Numerical Study of Storm Surge Processes and Currents of the Sea of Azov During a Period of Extreme Winds

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Magnitudes of storm surge fluctuations of the Azov Sea level occurring in this region during extreme winds and called "chernomorka" (reverse surface wind) are studied. These phenomena constitute a reason of floods in the coastal regions of the sea and the Taganrog Bay. Having been analyzed, the simulation results and the observation data of the sea level regime show their good compliance for the periods of strong storm cyclones moving from the northeast of the Black Sea. Interrelation between the parameters of the eastern and western storm winds observed in the Sea of Azov during the strong storms in 2013–2014 and the amplitudes both of the current velocities and the sea level fluctuations are defined. Hydrodynamic simulation is performed using the three-dimensional nonlinear Princeton Ocean Model (POM); at that real atmospheric forcing SKIRON corresponding to extreme storms is preset. Study of the storm surge frequency in different regions of the Azov Sea reveals the fact that the regions both of the sea eastern coast and the Taganrog Bay are exposed to catastrophic surges. Analysis of the currents induced by the storm winds demonstrates that in the sea surface layer the currents' maximum velocity exceeds 2 m/s (2.12 m/s in March, 2013 and 2.45 m/s in September, 2014). At the same time, the current velocities in the sea bottom layer achieving 0.59 and 0.44 m/s can cause intense lithodynamic processes in the coastal zone. The Taganrog Bay is subjected to the most intense forcing of the surge processes at the extreme winds over the Sea of Azov; at that the maximum sea level deviations here mount to 1.8 m.

Keywords: the Sea of Azov, the Taganrog Bay, sea level, extreme winds over the Sea of Azov, currents, surge phenomena processes, numerical simulation, storm cyclones.

Introduction

Among the global climate change manifestations in recent years the increase of the number of dangerous (DP) and natural hydrometeorological (NHP) phenomena in the coastal zones of the oceans and seas stands out. According to the data of [1], from 1970 to the present day, the number of intense hurricanes of 4 and 5th categories almost doubled.

The DP and NHP consequences in the Sea of Azov are often catastrophic. Storms are often accompanied by numerous tragedies, such as the loss of ships, the coastal infrastructure destruction and human victims [2–5]. The analysis of the gathered data of coastal observations at marine hydrometeorological stations (MH) of the Azov coast showed that the greatest frequency in percentage of the total number of phenomena that reached the DP and NHP criteria had the phenomena associated with storm activity, sea disturbance (30 %), storm surges (46 %) and lowering sea level (21 %). The physics and geographical conditions of the basin contribute to the development of surge level fluctuations in the Azov Sea: a sufficiently large sea area (39.000 km^2) with the insignificant average depth

(~ 7 m), as well as essential storm activity (average number of days with a storm wind velocity of 15 m/s and over is 24–34 days per year) [3, 5 and 6].

The effect of the characteristic Azov Sea winds causing the greatest surges in the sea level is the determining factor for the safe operation of the marine economy, including the sea transport. At abnormal falls of the level, the approach channels to the ports become shallower, storm surges lead to the flooding of coastal areas, shore storage facilities, including the loss of ships and people [3, 5].

The study of the surge repeatability in the Sea of Azov areas revealed that the most frequent are catastrophic negative (48 % of all cases) and positive surges (60 %) of the eastern coast of the sea and the Taganrog Bay [5]. The amplitude of the surge level fluctuations in these areas of the Sea of Azov often reaches values of 2.0–3.5 m. In Taganrog, where the Don River runoff has a meaningful effect, the amplitude of the surge fluctuations is maximal and is 6.87 m.

In a number of cases (in the years of 1739, 1831, 1843, 1877, 1914 and 1969) the storm positive surges led to numerous human victims in the coastal areas of the Temryuk Bay and the eastern part of the Sea of Azov [2–4, 7]. Over the last decade, as a result of storm activity, catastrophic floods are regularly observed in the Taganrog Bay and the Don estuary (12 April 1997, 1 March 2005, 30 September 2010, 23–24 March 2013 and 24 September 2014) [8–11]. The present paper will focus on the last two floods in the Taganrog Bay (23–24 March 2013 and 24 September 2014). These events, like the storm situation of 1997, were characterized by the maximum sea level rise over the entire historical period observations (1882 – 2015). In this study, the spatial and temporal variability of water dynamics in the Bay during these DPs was based both on the data of in situ observations and on the results of numerical experiments by means of mathematical modeling.

Theoretical research of water dynamics, extreme surges in the natural basin are based on the application of mathematical models. A series of studies [12 ± 14] is devoted to the numerical modeling of the water dynamics of the Sea of Azov. In these works the main characteristics of wind currents and surge processes for typical stationary wind fields are studied on the basis of the three-dimensional nonlinear sigma-coordinate *POM* (*Princeton Ocean Model*) model [15] adapted to the area of the Sea of Azov [16]. In [12], the conclusions about the effect of the parameters of model cyclones (direction, movement velocity, geometric characteristics) on the maximum velocity of the currents generated by them and extreme sea level fluctuations were drawn.

The results of numerical simulation of currents and level fluctuations during the extreme storm that caused the DP in the Kerch Strait, when 13 vessels crashed (11 November 2007), are shown in [13]. These studies were carried out using data from the *SKIRON* atmospheric model [17] (http://forecast.uoa.gr). The verification of the model based on direct measurements of the level at MH Genichesk and Mariupol was performed.

Using the two-layer mathematical model and the materials of hydrometeoro-logical observations at the coastal base of the Southern Scientific Center of the Russian Academy of Sciences, the case of the anomalous flooding of the Don estuary from 20 to 26 March, 2013 was considered [8, 10]. Applying *ADCIRC* and

SWAN numerical models, the calculations of storm positive surges and wind waves in the Taganrog Bay of the Sea of Azov were carried out in [11], and mechanisms for the Don estuary flooding were studied.

Using mathematical modeling, the present paper studies the effect of stationary currents on the surge phenomena caused by the action of the wind, which near-surface fields are calculated by the method using the assimilation of meteorological observations (*SKIRON*). The results of numerical calculations and the data of in situ observations obtained during extreme storms at a number of hydrometeorological stations on the coast of the Sea of Azov and the Taganrog Bay are compared.

Problem statement. Boundary and initial conditions.

The mathematical model is based on the system of equations of turbulent motion of a viscous fluid [15] in Cartesian coordinates, where the x axis is directed to the east, y – to the north and z is upward vertically:

$$\frac{du}{dt} - fv + \frac{1}{\rho}\frac{\partial P}{\partial x} = 2\frac{\partial}{\partial x}\left(A_{\text{M}}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left[A_{\text{M}}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left(K_{\text{M}}\frac{\partial u}{\partial z}\right), \qquad (1)$$

$$\frac{dv}{dt} + fu + \frac{1}{\rho}\frac{\partial P}{\partial y} = 2\frac{\partial}{\partial y}\left(A_{\text{M}}\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial x}\left[A_{\text{M}}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left(K_{\text{M}}\frac{\partial v}{\partial z}\right), \qquad (2)$$

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

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

where u, v and w are the velocity projections along x-, y- and z-axes; t is the time; $P(x, y, z, t) = P_{\text{atm}} + g\rho_0(\zeta - z)$ is the pressure at z-depth on the basis of vertical integrating of the equation (3); $P_{\text{atm}} = 1013.25$ gPa is the standard atmospheric pressure at 0°C at a latitude of 45°; ρ is the density; g is the free fall acceleration; f is the Coriolis parameter; $d/dt = \partial/\partial t + u\partial/\partial x + v\partial/\partial y + w\partial/\partial z$ is the total derivative. Parametrization of the vertical viscosity coefficients K_{M} in the equations (1) and (2) is carried out in accordance with the semi-empirical Mellor-Yamada differential model [18]. The horizontal viscosity factor A_{M} is calculated using the subgrid viscosity model [19], depending on the horizontal velocity gradients.

The boundary conditions on the free surface have the following form

$$w\big|_{z=\zeta} = \frac{\partial\zeta}{\partial t} + u\frac{\partial\zeta}{\partial x} + v\frac{\partial\zeta}{\partial y}, \quad K_M\left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z}\right)\bigg|_{z=\zeta} = \left(\tau_{0x}, \tau_{0y}\right), \qquad (5)$$

where $\zeta(x, y$ and $t)$ is the deviation of the free surface from the unperturbed horizontal plane; $\tau_{0x} = C_{\text{a}}W_x|\mathbf{W}|$ and $\tau_{0y} = C_{\text{a}}W_y|\mathbf{W}|$ are the projections of the tangential wind stresses, $\mathbf{W}$ is the wind velocity vector at an altitude of 10 m above

sea level, C_a is the empirical coefficient of surface friction [20] for the wind velocity less than 22 m/s, in the other cases C_a is the constants proposed in [21]:

$$10^3 C_a = \begin{cases} 2.5, & |\mathbf{W}| > 22 & \text{m/s}, \\ 0.49 + 0.065|\mathbf{W}|, & 8 \le |\mathbf{W}| \le 22 & \text{m/s}, \\ 1.2, & 4 \le |\mathbf{W}| \le 8 & \text{m/s}, \\ 1.1, & 1 \le |\mathbf{W}| \le 4 & \text{m/s}. \end{cases} \quad (6)$$

The boundary conditions in the bottom layer have the form [15]

$$\left(w + u \frac{\partial H}{\partial x} + v \frac{\partial H}{\partial y} \right)\bigg|_{z=-H} = 0, \quad K_M \left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right)\bigg|_{z=-H+h_b} = (\tau_{1x}, \tau_{1y}), \quad (7)$$

where $\tau_{1x} = C_b u \sqrt{u^2 + v^2}$; $\tau_{1y} = C_b v \sqrt{u^2 + v^2}$; C_b is the coefficient of bottom friction, which is found from the formula $C_b = k^2 / (\ln^2 h_b / z_0)$; h_b is the vertical step in the bottom layer; $z_0 = 0.003$ m is the roughness parameter characterizing the hydrodynamic properties of the underlying bottom surface. The value of z_0 is determined using the Grant-Madsen theory [22], which describes the mechanism of the effect of waves on the currents in the near-bottom boundary layer.

At the lateral boundaries, adhesion conditions are fulfilled. As initial (at $t = 0$) ones, the conditions of the absence of fluid motion and the horizontal nature of the free surface before the beginning of atmospheric disturbances are assumed

$$u(x,y,z,0) = 0, \quad v(x,y,z,0) = 0, \quad w(x,y,z,0) = 0, \quad \zeta(x,y,z,0) = 0. \quad (8)$$

Numerical experiments were carried out applying the *POM* model. For this purpose the transition from the z-coordinate to the σ-coordinate was fulfilled [15] in the original equations (1)–(4), the boundary conditions (5), (7) and the initial conditions (8). Selection of the integration steps for time and space coordinates was carried out in accordance with the stability criterion for barotropic waves [23]. The bottom topography is interpolated to a model grid using an array of depths shown on the navigation maps. Its latitude and longitude resolution is $1/59 \times 1/84°$. In this case the linear dimensions of the cell are $\Delta x = \Delta y = 1.4$ km, the number of nodes of the horizontal grid is 276×176, there were 11 grid levels vertically. The equations were integrated over time with a step $\Delta t = 18$ s to find the averaged two-dimensional velocity and level components, and also with the step $\Delta t_A = 10\Delta t = 3$ min to calculate the deviations from the found mean and vertical velocity components. The source of the data for constructing the computational grid was the bathymetry map and the configuration of the shoreline of the Sea of Azov, built on the basis of the digitization of the recent large-scale hydrographic charts of the Hydrographic Service.

Atmospheric forcing, used in computational experiments

Storm surge fluctuations of the Azov Sea level occurring in this region during extreme storms moving from the north-east of the Black Sea and called "chernomorka" (reverse surface wind) in the terminology of local fishermen are studied.

The long-lasting action of winds from the south-south-east to south-south-west, with moderate or hurricane velocity, leads to extreme level surges, being the cause of destructive floods on the Azov coast. To understand the features of these recurring phenomena, an analysis of meteorological situations demonstrating the destructive power of storm surges and leading to catastrophic floods in the Taganrog Bay and the Don estuary (23–24 March, 2013 and 24 September, 2014) was carried out.

As follows from the observation data, the DP of 23–24 March, 2013 appeared during the passage of a deep cyclone over the southern European part of Russia and the strengthening of the south-west wind over the water area of the Sea of Azov. The passage of the cyclone was accompanied by a storm surge and flooding of the vast territories of the Don estuary and the eastern coast of the Sea of Azov [1, 9 and 10]. Extremely dangerous phenomenon on September 24, 2014 was caused by a powerful cyclonic eddy formed in the Crimean region in a deep tropospheric trough, oriented from the Arctic to the south of Europe. The eddy formation was promoted by the great thermodynamic instability of the atmosphere, appeared as a result of a collision of cold air from the north and from the middle troposphere, and warm moist air from the Black Sea. During the cyclone transition at night of 24 September, an intensification of the eddy took place. It was accompanied by a hurricane, intense precipitation and wind waves, as well as storm surge on the east coast of the Sea of Azov and Taganrog Bay.

In computational experiments reproducing DP as atmospheric forcing, the near-water wind and atmospheric pressure fields, obtained from the data of the *SKIRON* regional atmospheric model, were used. This model, based on the *Eta* one, was originally created at the University of Belgrade [24] and was further developed on the *NCEP* basis at the University of Athens by the *Atmospheric Modeling and Weather Forecasting Group* [17]. The *SKIRON* model forecast results used in the present study were obtained by Marine Hydrophysical Institute as the *MFSTEP* project full participant. This model version presents a detailed 72-hour forecast of meteorological parameters for the Azov-Black Sea and Mediterranean basins. During the first 48 hours the data output is carried out 2 hours later, and then the values are taken 6 hours later. The parameters are calculated on a grid with a step of 0.1° along the x and y axes. 16 different parameters, including the atmospheric pressure and wind velocity data, are totally displayed. These data are interpolated to the computational grid of the Azov basin with the specified horizontal resolution. The data is also used to specify the boundary conditions (5) using the equation (6). Based on the *SKIRON* data meteorological information analysis, the conclusions about the nature of the wind regime over the water area of the Sea of Azov during the extreme events of 23–24 March, 2013 and 24 September, 2014, and also during the month preceding them, were drawn. The wind velocity averaged over space during the development of extreme reverse surface wind was found by the following formula

$$\left|\overline{\mathbf{W}}(t)\right| = \frac{1}{N}\sum_{k=1}^{N}\left|\mathbf{W}_{\text{SKIRON}_k}(t)\right|,$$
(9)

where N is the number of computational grid nodes; $\left|\mathbf{W}_{\mathrm{SKIRON}_k}(t)\right| = \sqrt{W^2_{\mathrm{SKIRON}_x}(t)_k + W^2_{\mathrm{SKIRON}_y}(t)_k}$ – is the wind velocity module in its k-node. The mean wind velocity (10.2 m/s) calculated in this way range within its largest (2.7 m/s) and the smallest (17.6 m/s) value in March 2013. For September 2014 it is 13.6 m/s (within the smallest and largest values, 2.5 and 24.7 m/s respectively), which is 1.3 and 1.8 times higher than its mean annual climatic value [6]. Fig. 1 shows the mean wind velocity evolution.
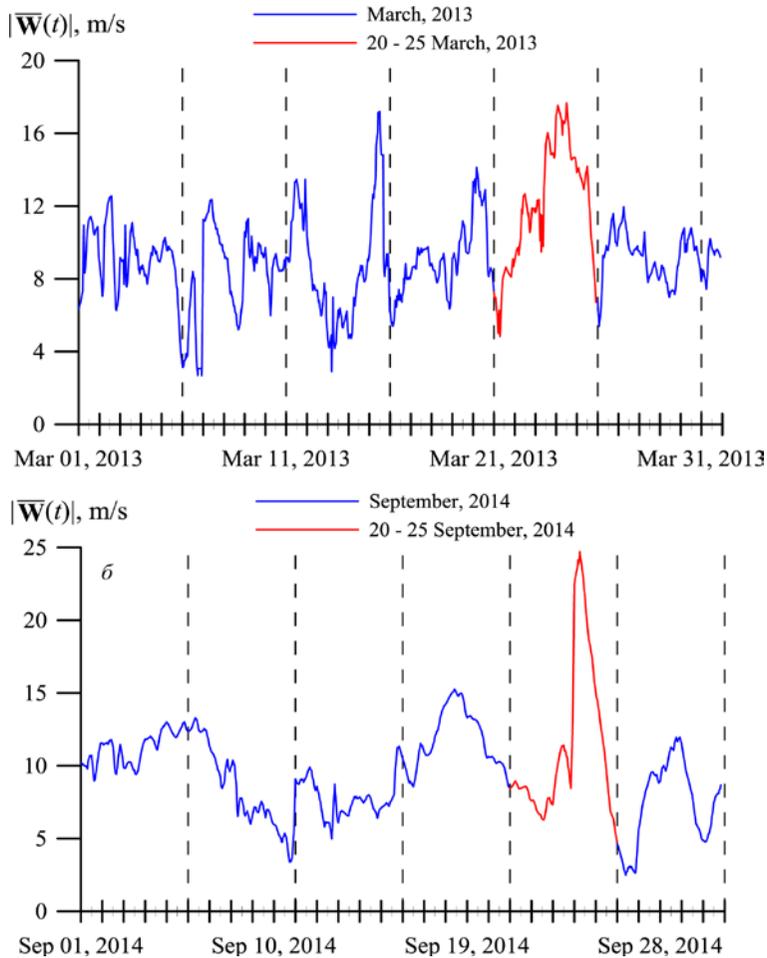
Fig. 1. The mean wind velocity along the Azov water area during the stormy months: 1–31 March, 2013 (*a*); 1–30 September, 2014 (*b*). Vertical dotted lines are held with a discreteness of 5 days

Note that in March, 2013 (Fig. 1, *a*), the comparable with the maximum but short-term (within 3 h) increase of the mean wind velocity from 16 to 17.2 m/s (14 March, 2013) didn't appear to be the reason of extreme sea level fluctuations. The long-lasting action of the wind at almost the same velocity (from 16 to 17.6 m/s) within 12 hours led to the DP on 23–24 March, 2013.

According to Fig. 1, *b*, moderate winds generally dominated over the Sea of Azov during the whole month (September 2014). The mean wind velocity increase to 24.7 m/s occurred during the cyclone transition on 24 September, 2014. In this case, the effect of wind with a velocity exceeding 16 m/s during 22 hours caused extreme surge phenomena on the coast of the Sea of Azov. Thus, the effect of a storm wind of less than 3 hours does not lead to the storm surges.

According to observations at the MH Taganrog and Temryuk, the mean wind velocity of the south-western direction on 23–24 March, 2013 was 9–13 m/s at the maximum values of 21–22 m/s. At the MH Yeisk and Dolzhanskaya, the maximum wind velocities were 21 and 19 m/s, respectively, with mean values of 9–10 m/s. On the western and southern coasts of the Sea of Azov (Genichesk and Mysovoye), the mean wind velocity of the western and north-western directions was 16–22 m/s at the maximum values of 23–28 m/s. It should be noted that the data of in situ observations are close to or exceed the calculated *SKIRON* values.

Under the mean wind velocity in the water area of 11–15 m/s, its maximum values at the MHs in Taganrog, Dolzhanskaya and Temryuk reached 33–37 m/s. Such extreme wind velocity values at these stations were recorded for the first time in the entire historical period of observations. As a result of the hurricane wind on the coast of the Taganrog Bay, power lines were damaged, trees were, the roof of houses were broken, electricity pylons were damaged, power towers and a high-altitude crane were dropped in the ports of Yeisk and Taganrog.

The spatial distribution of the near-surface wind fields over the Sea of Azov, obtained from the model data ($\mathbf{W}_{SKIRON}$) during the storm situations in March 2013 and September 2014, is shown in Fig. 2. It is noteworthy that in the considered situations a significant spatial heterogeneity of wind fields over the sea both in velocity and direction was observed.
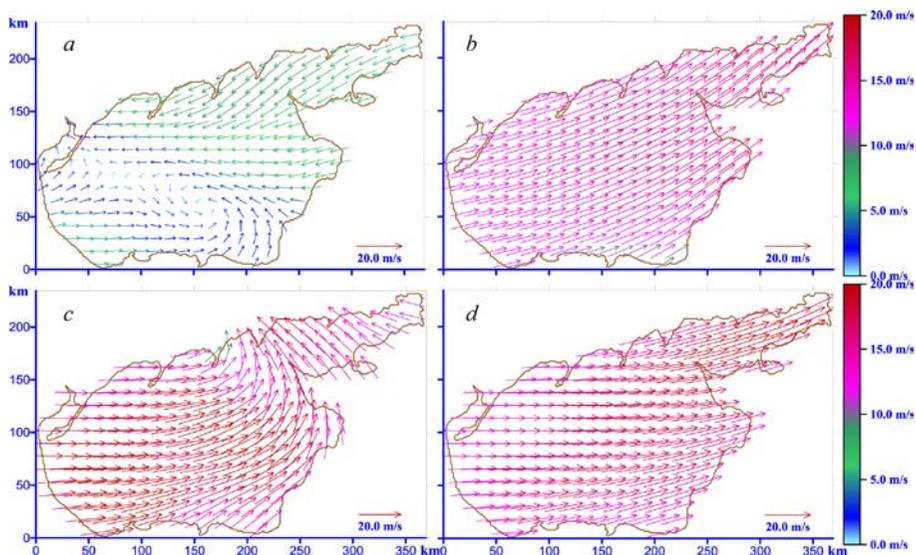
Fig. 2. The near-surface wind fields on 23–24 March, 2013: 23 March, 12:00 (*a*); 24 March, 20:00 (*b*); during the storm on 24 September, 2014: at 12:00 (*c*); 20:00 (*d*)

Wind intensification to 10 m/s occurred at 12:00 on 23 March, 2013, when the cyclone passed through the central part of the sea. At this time the wind changed its direction from the north-east to the south-west. The next velocity maximum took place in the middle of the day on 24 March, 2013. Fig. 2, b shows the transition of extensive cyclonic formation with a high (up to 20 m/s) wind velocity from the Black Sea north-east. Direction of this formation is inhomogeneous in different parts of the Sea of Azov. The maximum storm development occurred on the following day (24 March, 2013). In this case the wind did not change its direction and acted along the axis of the Taganrog Bay (south-south-western direction (Fig. 2, *b*)), and the maximum wind velocity reached 25 m/s.

Fig. 2, *d*, *e* shows direction of the wind fields during the storm on 24 September, 2014, according to the *SKIRON* reanalysis data. During the day, as in the case of the storm of 2013, a steady wind of the south-south-western direction (along the axis of the Taganrog Bay) was observed with a velocity exceeding 28 m/s. According to the *SKIRON* data, the obtained wind fields on the whole agree well with the data of in situ observations on coastal MHs and confirm the fact that the greatest increase of wind velocity was over the water area of Taganrog and Temryuk Bay.

The variation in surface atmospheric pressure was studied, its sharp drop accompanied by a strong wind at the sea surface, leads to the significant sea level elevation. The time course of the mean atmospheric pressure values ($\overline{P}(t)$), averaged over the area of the Sea of Azov, calculated according to a formula similar to (9), during the storms of 2013 and 2014, is shown in Fig. 3.
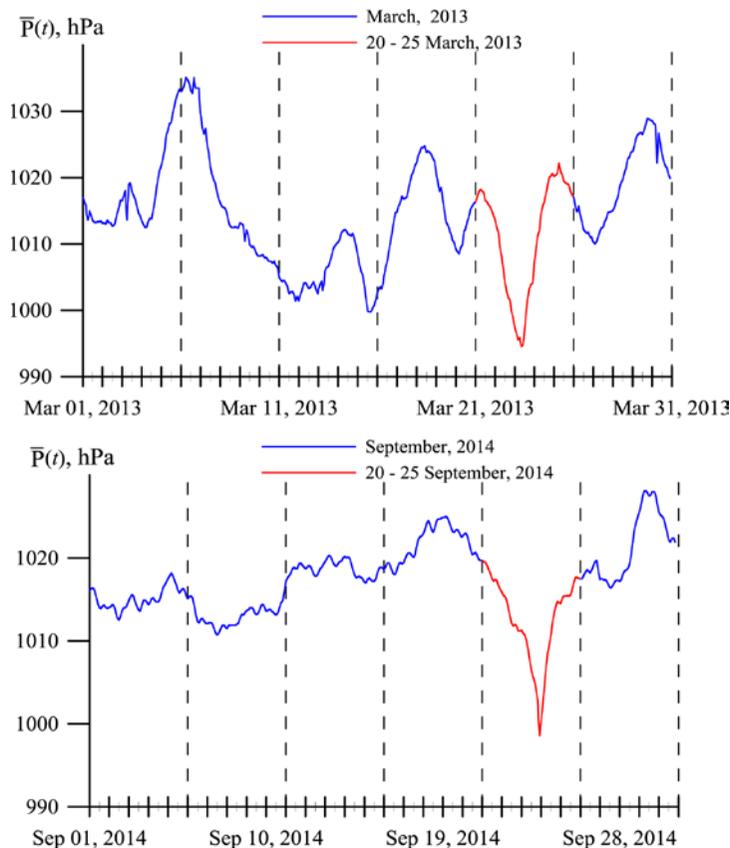
Fig. 3. The atmospheric pressure according to the *SKIRON* model data, averaged over the Azov water area in March 2013 (*a*) and September 2014 (*b*). Vertical dotted lines are made with a discreteness of 5 days

As follows from an analysis of the curves noted in Fig. 3 in red (during the period from 20 to 25 the number of time intervals considered), storm situations were accompanied by a significant drop in atmospheric pressure. It is seen that in March 2013 the atmospheric pressure varied from the minimum (995 hPa) to the maximum value of 1035 hPa. During September 2014, the atmospheric pressure difference was insignificant, but a sharp decrease in atmospheric pressure to 998 hPa is shown in the graph (Fig. 3, *b*) during the cyclone transition on September 24.

The analysis of numerical experiments and observational data

In order to describe and study the features of the Sea of Azov water circulation at extreme phenomena of the Sea of Azov area, the studies on the basis of observational data analysis and modeling results were carried out. Forecast of recurring severe storm consequences (March 23–24, 2013 and September 24, 2014) and identification of their causes is based on the determination of the atmospheric effect critical parameters within the framework of numerical modeling.

1. A comparative analysis of the *current velocity maximum values* ($|\mathbf{U}|_{max}$) during the storms in March 2013 and September 2014 was performed on the basis of the analysis of the numerical calculation results presented in Table 1. Here the

horizons and coordinates of points in which the highest velocities during the entire computational period t ($0 \le t \le 744$ and $0 \le t \le 720$ h) were recorded, as well as a time for obtaining the maximum velocity values, are given.

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Current velocity maximum values ($|U|_{max}$) at different horizons of the Sea of Azov, a time to reach them (t_{max}) and (x_{max}, y_{max}) coordinates corresponding to them during the periods of extreme storms

Computational period	Horizon, m	$|U|_{max}$, m/s	x_{max}, km	y_{max}, km	t_{max}, h
March 1 – 31, 2013	1	2.12	230.23	42.85	March 24 17:00 MSK.
	3	1.37	240.32	168.72	March 24 17:30 MSK
	5	1.33	150.37	41.511	March 24 23:00 MSK
	10	0.59	235.34	173.00	March 24 05:00 MSK
September 1 – 30, 2014	1	2.45	221.52	100.43	March 24 05:00 MSK
	3	1.57	220.18	100.43	March 24 17:00 MSK
	5	0.89	285.96	194.17	March 24 17:00 MSK
	10	0.44	89.951	14.73	March 24 19:00 MSK

The analysis of velocity maxima of currents (Table 1) caused by the effect of storm winds at a significant atmospheric pressure drop showed that $|\mathbf{U}|_{max}$ values in the surface layer exceeded 2 m/s (2.12 m/s in March 2013 and 2.45 m/s in September 2014). The velocity of currents in the near-bottom layer was somewhat smaller (0.59 and 0.44 m/s) but it reached the values which are able to cause intensive lithodynamic processes in a sea coastal zone. Surface current velocity extrema were observed in the Taganrog Bay and in the area of the Dolzhansky Strait. The maximum velocity of currents in the near-bottom layer was recorded near the Taganrog Bay and in Genichesk area.

In Fig. 4 and 5 spatial distributions of current velocities in the Sea of Azov at different horizons in time moments corresponding to the extreme values of current surface velocities given in Table 1 are represented.
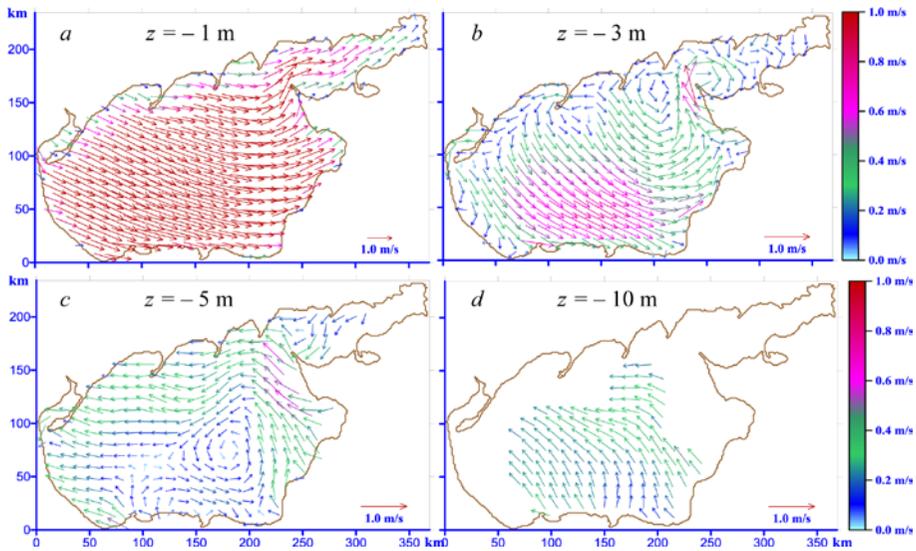
Fig. 4. Fields of currents during the storm on March 24, 2013 at 1 m (*a*), 3 m (*b*), 5 m (*c*) and 8 m (*d*) horizons
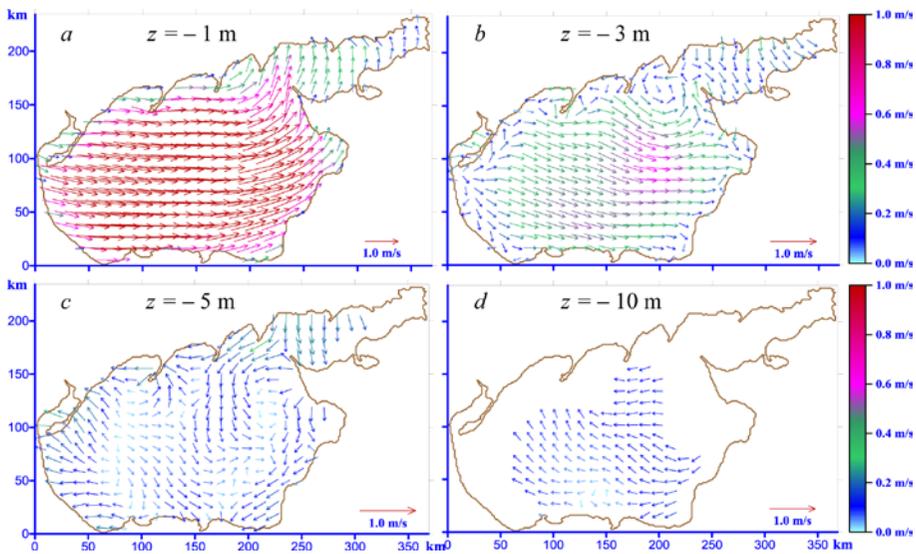
Fig. 5. Fields of currents during the storm on September 24, 2014 at 1 m (*a*), 3 m (*b*), 5 m (*c*) and 8 m (*d*) horizons

When a steady southwestern storm wind blows all over the sea area (Fig. 2, *d*), the direction of currents in the surface layer coincides with the wind direction (Fig. 4, *a*). From 3 m depth (Fig. 4, *b*) the currents deviate from wind direction by 90° and more, eddies of different signs are traced at the Taganrog Bay entrance (in the Dolzhansky Strait). In the central part of water area in 5 m layer a well-pronounced compensation current directed against the wind is formed. At 8 m depth the currents deviating from the direction of the ones in the surface layer and from the direction of the blowing wind (Fig. 4, *d*) by 135° and more are observed.

As follows from Fig 4, the currents of the surface (1–3 m) and near-bottom (5–8 m) layers are directed oppositely.

2. Now we turn to the analysis of the *extreme surge fluctuations of the Sea of Azov level* and their consequences. According to the data of Roshydromet and Russian Emergency Ministry, the flood that took place on March 14, 2013 (DP on March 23–24, 2013) covered the territory of the Don delta (538 km^2) and the eastarn coast of the Taganrog Bay. 21 settlements in Azovsky, Neklinovsky and Myasnikovsky districts of Rostov region got into the flooding zone, the suburbs of Rostov-on-Don, Taganrog and Azov were flooded. The total damage to the population and administrative facilities amounted to about 76 million rubles. The maximum level increase on March 24 reached the following markings: at MH Taгатгog – 7.51 m, Ochakov Spit – 7.41 m, Azov – 7.40 m, Yeysk – 6.10 m and in Primorsko-Akhtarsk – 6.04 m. At surge, the maximum level exceeded the long-term annual average value for March by 3.40 m in Kagalnik, 2.84 m in Taganrog, 1.40 m in Yeysk and 1.30 m in Primorsko-Akhtarsk. In Genichesk a negative surge with 0.81 m level decrease was observed.

During the storm surge on September 24, 2014 in Taganrog, Eysk and Azov the absolute maximums of level (7.96 m, 7.81 m and 6.56 m, respectively) over the entire observation time were recorded. In September, the maximum level exceeded the long-term annual average value by 3.60 m in Kagalnik, 3.35 m in Taganrog, 1.93 m in Yeysk and 1.85 m in Primorsko-Akhtarsk. According to the Russian Ministry for Emergencies in the Krasnodar region, in the flood zone there were five settlements (Sadki, Morozovsky, Dolzhanskaya, Yasenskaya crossing, Yeisk). According to a release from Russian Emergency Ministry in Krasnodar Krai, five settlements (Sadki, Morozovsky, Dolzhanskaya, Yasenskaya crossing, Yeysk) were in the flooding zone. In the Rostov region 26 settlements (Azov, Taganrog, Neklinovsky, Myasnikovsky and Azov districts) were in the flood zone, 3091 houses were flooded and the population was evacuated (971 people).

Observational data are compared with positive and negative surge (caused by the effect of severe storms) values at the Sea of Azov coastal stations obtained from the modeling. In Table 2 the values of the largest positive and negative surges during the storms in 2013 and 2014, obtained from the observations (taking into account the average long-term values) and numerical calculations, depending on wind velocity and direction at coastal stations are shown. The data on wind are represented on the basis of Roshydromet and Russian Emergency Ministry information. The values given with the negative sign correspond to negative surge.

From the represented data it is obvious that under effect of wind with 17 to 32 m/s velocity the greatest deviations (1.81 m and 1.36 m) in Taganrog occur at WSW and SSW wind directions. According to computational data, the maxumal negative surges are observed in Genichesk and Mysovoye (0.99 m and 0.49 m, respectively). It should be pointed out that despite higher wind intensity according to *SKIRON* data, the values of positive and negative surges caused by the storm that took place on March 23 – 24, 2013 exceeded the extreme level fluctuations during DPon September 24, 2014. Such difference is explained by longer duration of storm wind effect (see Fig. 1).

T a b l e 2

Dependence of the Sea of Azov level extreme deviations (m) on the direction and velocity of blowing wind during the storms in 2013, 2014 according to the data of network of coastal hydrometeorological stations and modeling results

Coastal stations	March 23–24, 2013				September 24, 2014			
	Wind velocity, m/s	Wind direction, degrees	Sea level deviation		Wind velocity, m/s	Wind direction, degrees	Sea level deviation	
			ζ_{extr}^{observ}, m	ζ_{extr}^{mod}, m			ζ_{extr}^{observ}, m	ζ_{extr}^{mod}, m
Genichesk	28	NW, WNW (315, 292)	–0.94	–0.99	25	SW, W (250, 270)	—	–0.87
Berdyansk	19	SSW, W (200, 270)	0.39	0.28	24	SW, W (250, 270)	—	–0.52
Mariupol	19	W, WNW (270, 292)	0.95	0.82	25	SSW, SW (225, 250)	—	0.88
Taganrog	22	WSW, SSW (200)	1.58	1.81	32	SW (205, 225)	—	1.36
Yeysk	21	SSW, W (200, 270)	—	0.96	27	SW, WNW (225, 290)	1.12	1.06
P.-Akhtarsk	17	W (270)	0.61	0.79	24	SSW, SW (225, 250)	1.20	1.11
Temryuk	22	SSW, W (200, 270)	0.32	0.31	30	SW, W (250, 270)	0.45	0.51
Opasnoye	20	W, WNW (270, 292)	–0.19	–0.27	28	SSW, W (200, 270)	—	–0.47
Mysovoye	28	W, WNW (270, 292)	–0.61	–0.49	25	SW (225, 250)	—	–0.53

From the analysis of the sea level isoline maps it is obvious that when the storm develops (Fig. 6, *a*), level decrease area follows the geometry of wind field anticyclonic eddy (see Fig. 2, *a*) along the western coast, has an elliptical shape and shifts from the center.

The area of the increased level values (up to 0.7 m) is concentrated near the entrance to the Taganrog Bay (near the Dolzhansky Strait). In 8 h after the beginning of the storm (Fig. 6, *b*) the isoline of level zero amplitudes shifts eastward away from the center. Positive surge area moves to the Don delta and the areas of significant level decrease shift to the northwestern region of the sea (near Genichesk). Subsequent DP development and peak of the storm in March 2013 (Fig. 6 *c, d*) result in the water area division into separate parts of level rise and decrease in the western and eastern parts of the basin separated by zero amplitude line (oriented in meridional direction). It can be seen that the Taganrog Bay is affected by the strongest surge processes. The maximum sea level deviations here reach 4 m.

In Fig. 6 *e, f* the Sea of Azov level isolines at DP in September 2014 are given. It is noticeable (Fig. 6, *e*) that complex level fluctuations are formed in the Taganrog Bay. Here, in rather shallow (average depth of the bay is 9 m) semi-enclosed basin level fluctuations (whch are different in sign) with a nodal line passing throug its center take place.
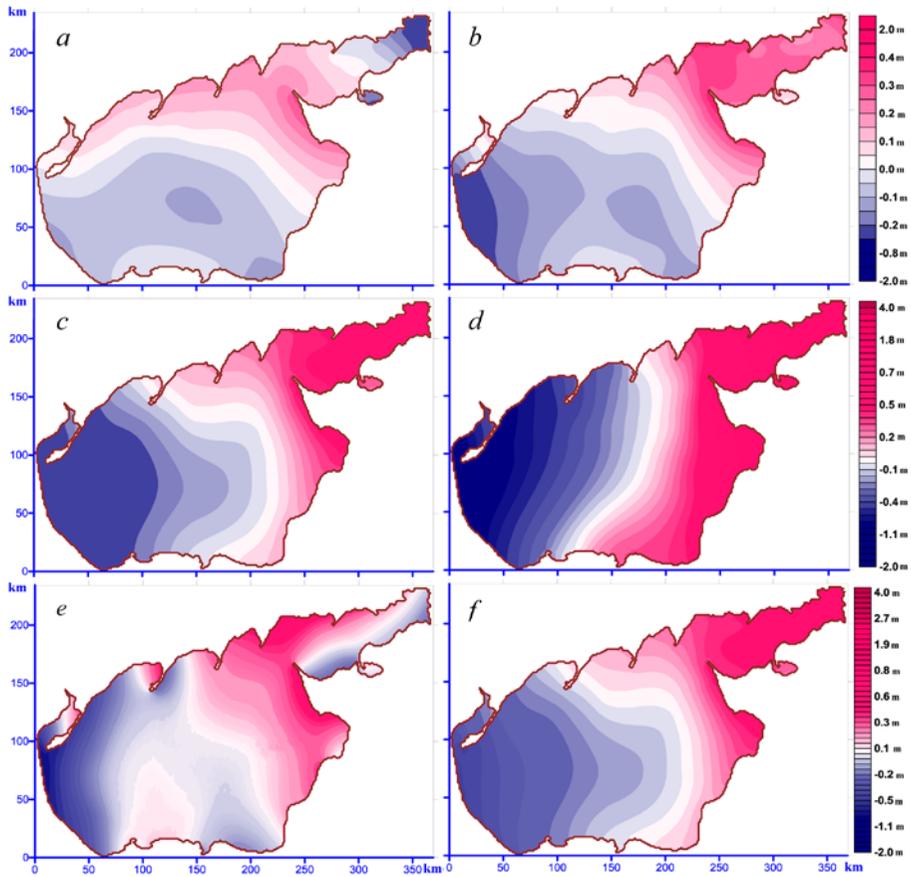
Fig. 6. The Sea of Azov level fields at the same moments of time as in Fig. 2

The highest level increase occurs at the estuary entrance. Under effect of southwestern wind with 25 m/s velocity (Fig. 6, *f*) the fields of sea level deviations acquire similarities with the maps of storm level (the storm took place in 2013) (Fig. 6, *d*) with the water area division into increase and decrease areas (in the eastern and western parts of the sea).

3. A comparison of positive and negative surge values (obtained from the modeling) with field measurement data over the same period, which are given in the State Hydrometeorological Service tables of hourly sea level height values, has been carried out. For this purpose the data of level observations at coastal hydrometeorological stations and posts of the Sea of Azov and the Taganrog Bay in March 2013 and September 2014 were involved. The observations are the level measurements performed by recorders at MH Taganrog, Temryuk, Yeysk and Primorsko-Akhtarsk, as well as measurements with 6 hour discreteness by a tide-gauge at other coast points of the Sea of Azov basin.

The graphs of sea level course during the March 2013 at Taganrog and Primorsko-Akhtarsk stations obtained from the observational data and modeling are represent-ted in Fig. 7. The analysis of level graphs reveals relatively good corresponddence of fluctuation trends. Some differences, such as the ones on the

values of positive and negative surge maxima, are explained by certain errors in measurements and calculations. For example, in Taganrog (2013) the calculated positive surge maximum is 14 % higher than the one according to observational data. In Primorsko-Akhtarsk (2014) the maximum value of positive surge is 8 % less than the measured value.
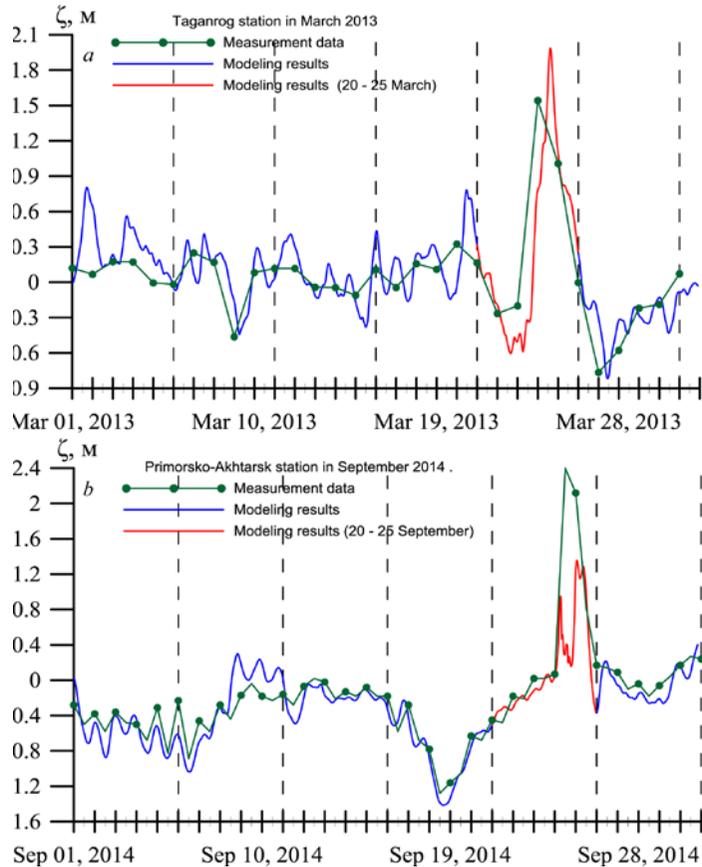
Fig. 7. Sea level deviations (m) according to direct measurement data and modeling results at: Taganrog station in March 2013 (*a*); at Primorsko-Akhtarsk station in September 2014 (*b*). Vertical dashed lines are drawn with 5 day discreteness

Conclusion

On the basis of observational data and modeling result analysis, the study of the Sea of Azov water circulation features occurring at extreme phenomena of the Sea of Azov region is performed. The investigation of the surge repeatability in the Sea of Azov areas revealed that the most frequent are catastrophic negative (48 % of all cases) and positive surges (60 %) of the eastern coast of the sea and the Taganrog Bay. Computational data indicated that during DP in 2013–2014 under effect of storm wind the entire water area of the Sea of Azov is divided into separate rise and decrease parts in western and eastern parts of the basin. They are divided by meridionally-oriented line of zero amplitudes. The Taganrog Bay,

where the maximum sea level deviations make up 1.8–2.2 m according to numerical computations, is affected by the strongest positive surge effect.

Wind fields obtained by *SKIRON* regional atmospheric model data generally corresponds well with field observations at MH and confirm the fact that the strongest wind velocity increase during DP in March 2013 and September 2014 took place above the water areas of the Taganrog and Temryuk Bays.

The analysis of the maximum velocity values of currents caused by the effect of storm winds during these DP indicated that in the surface layer the maximum current velocity values exceeded 2 m/s (2.12 m/s in March 2013 and 2.45 m/s in September 2014). The velocity of currents in the near-bottom layer was somewhat lower (0.59 and 0.44 m/s) but it reached the values which are able to cause intensive lythodynamic processes in the sea coastal zone. Surface current velocity extrema were observed in the Taganrog Bay and in the Dolzhansky Strait. The maximum current velocity values were recorded near the Taganrog Bay and in Genichesk region.

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