Numerical Modeling of Water Exchange through the Kerch Strait for Various Types of the Atmospheric Impact

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Water exchange through the Kerch Strait plays a fundamental role in formation of the hydrological, hydrochemical and hydrobiological regimes in the adjacent sea areas. This article examines features of water exchange through the Kerch Strait for various types of the atmospheric impact. The numerical hydrodynamic model ADCIRC was used. The results of numerical modeling of currents and sea level in the Azov – Black Sea basin on the non-uniform computational grid concentrated in the strait were used as the input data. The authors identified the ranges of wind directions at which water exchange through the strait is the most intense; and revealed the relationship between the maximum values of forward and reverse water flux with wind speed. The characteristics of free oscillations in the strait that occur after the wind stops were studied. Simulations show that the wind field generated by an atmospheric cyclone intensifies the total water exchange through the strait when of the cyclone passage speed decreases. The results of calculating water flow in the strait for real synoptic situations are consistent with the estimates obtained by other authors from the field data. The data from the WRF mesoscale meteorological model were used as atmospheric forcing. It was shown that the maximum water flux during storm period is 11000-16000 m^3/s at the mean currents velocity ~ 0.6-0.9 m/s.

Keywords: the Sea of Azov, the Black Sea, the Kerch Strait, wind currents, sea level, water exchange, numerical simulation, ADCIRC.

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Introduction. The Kerch Strait is the most important shipping line and one of the richest fishing areas in the Azov – Black Sea basin. Water exchange through the Kerch Strait plays a fundamental role in formation of the hydrological, hydrochemical and hydrobiological regimes in the adjacent sea areas.

The results of the study of water exchange features through the Kerch Strait on the basis of field observations are given in [13]. In these works measurements of currents in the northern narrowness of the Kerch Strait (Port Krym – Port Kavkaz section) were used for water flux estimation. Analysis of calculation results showed that water exchange through the Kerch Strait intensifies during storms caused by the cyclones or by the action of stable winds, which have predominant meridional velocity component. Currents velocity measurements are scarce and are absent throughout the strait cross section, which makes the water flux computations based on field data quite complicated. Moreover, the measurements in the strait are mostly carried out under calm weather conditions. Hydrodynamic modeling of water exchange through the Kerch Strait can help close this gap in the necessary data.

A number of publications [4-9] were devoted to modeling the dynamics of the Kerch Strait waters where a computational domain with two liquid boundaries, the northern and southern ones, is used. Depending on the wind direction and the sea level differences on the liquid boundaries, certain boundary conditions that introduce distortions into the simulation results are applied. In this article, the problem of liquid boundaries is solved by using the entire Azov-Black Sea basin as the computational domain. The problem requires large amounts of computation and high-performance computing systems for its solution.

The purpose of this work is to study water exchange through the northern narrowness of the Kerch Strait for various types of the atmospheric impact within the range of synoptic variability on the basis of model data.

Numerical model. To calculate the fields of currents and sea level in the Azov – Black Sea basin, the numerical hydrodynamic model Advanced Circulation Model for Shelves Coasts and Estuaries (ADCIRC) is applied. A detailed description of the model and the results of its application are given in [10-13]. The model ADCIRC validation according to the observations of the Azov Sea level was carried out in [14, 15]. The basic equations are defined as follows

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}-fV=-g\frac{\partial}{\partial x}\left[\eta+\frac{P_{\mathrm{a}}}{g\rho_0}\right]+\frac{\tau_{sx}-\tau_{bx}}{\rho_0 H}+\frac{M_x}{H}, \tag{1}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+fU=-g\frac{\partial}{\partial y}\left[\eta+\frac{P_{\mathrm{a}}}{g\rho_0}\right]+\frac{\tau_{sy}-\tau_{by}}{\rho_0 H}+\frac{M_y}{H}, \tag{2}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0, \tag{3}$$

here x, y and t are horizontal coordinates and time; U, V are the mean depth components of the current velocity vector along the x and y axes, respectively; η is the deviation of the free surface of the sea from the undisturbed state; f is the Coriolis parameter; g is the gravity acceleration; P_{a} is atmospheric pressure; ρ_0 is the mean water density; $H=h+\eta$ is the dynamic depth, h is the sea depth; $M_x = A_{\mathrm{h}}\Delta q_x$, $M_y = A_{\mathrm{h}}\Delta q_y$ are the components of horizontal turbulent viscosity; A_{h} is the coefficient of horizontal turbulent viscosity, Δ is the Laplace operator with respect to variables x and y; $q_x = UH$, $q_y = VH$ are the components of the water flux.

The tangential stress components in (1), (2) are defined by the following expressions:

$$\tau_{sx}=\rho_{\mathrm{a}}C_{\mathrm{a}}W_x\sqrt{W_x^2+W_y^2}, \quad \tau_{sy}=\rho_{\mathrm{a}}C_{\mathrm{a}}W_y\sqrt{W_x^2+W_y^2}, \tag{4}$$

$$\tau_{bx}=\rho_0 C_{\mathrm{d}}U\sqrt{U^2+V^2}, \quad \tau_{by}=\rho_0 C_{\mathrm{d}}V\sqrt{U^2+V^2}, \tag{5}$$

where ρ_{a} is the air density; W_x, W_y are the components of the near-surface wind velocity; C_{a}, C_{d} are the surface and bottom friction coefficients.

The numerical algorithm is based on the finite element method, using triangular elements and linear basic functions. To prevent the appearance of computational noise in the numerical integration of the system (1) – (3), the last equation is written in the form of the so-called Generalized Wave Continuity Equation (GWCE) [11]

$$\frac{\partial G}{\partial t} + \tau_0 G = 0,$$

where $G \equiv \frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y}$, τ_0 is a positive parameter. After some differential transformations, the *GWCE* is reduced to the following equivalent form:

$$\frac{\partial^2 \eta}{\partial^2 t} + \tau_0 \frac{\partial \eta}{\partial t} + \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} = 0, \quad (6)$$

where

$$J_x = -q_x \frac{\partial U}{\partial x} - q_y \frac{\partial U}{\partial y} + f q_y - \frac{g}{2}\frac{\partial \eta^2}{\partial x} - \frac{H}{\rho_0}\frac{\partial P_\mathrm{a}}{\partial x} + \frac{\tau_{sx} - \tau_{bx}}{\rho_0} + M_x + \tau_0 q_x + U\frac{\partial \eta}{\partial t} - gH\frac{\partial \eta}{\partial x},$$

$$J_y = -q_x \frac{\partial V}{\partial x} - q_y \frac{\partial V}{\partial y} - f q_x - \frac{g}{2}\frac{\partial \eta^2}{\partial y} - \frac{H}{\rho_0}\frac{\partial P_\mathrm{a}}{\partial y} + \frac{\tau_{sy} - \tau_{by}}{\rho_0} + M_y + \tau_0 q_y + V\frac{\partial \eta}{\partial t} - gH\frac{\partial \eta}{\partial y}.$$

Practically, the optimal value of the parameter τ_0 is chosen on the basis of numerical experiments. The following condition is usually used $1 < \tau_0 / \tau_{\max} \leq 10$, where $\tau_{\max} = \max \left| C_\mathrm{d} \sqrt{U^2 + V^2} / H \right|$.

Results of the numerical experiments. Numerical simulation was carried out for the entire Azov – Black Sea basin on an unstructured grid of ~ 158.000 nodes. The size of the sides of the finite elements varied from 60 m in the Kerch Strait to 4.900 m in the deepwater part of the Black Sea. The friction coefficients in the expressions (4) and (5) were given by formulas $C_\mathrm{a} = 0.001\left(0.75 + 0.067\sqrt{W_x^2 + W_y^2}\right)$ and $C_\mathrm{d} = gn^2 / H^{1/3}$, where $n = 0.025$ is Manning's roughness coefficient. The horizontal turbulent viscosity coefficient $A_\mathrm{h} = 10$ m^2/s, the time integration step was 3 s. Taking into account the mentioned limitations, the weight factor τ_0 in equation (6) was taken to be 0.005. To simplify the problem, the contribution of the river discharge in the simulation of hydrodynamic fields was not taken into consideration.

Port Krym – Port Kavkaz section position is shown in Fig. 1. Length of section L is approximately 4 km. Water exchange calculations were carried out according to the computed hydrodynamic fields in the following way. First, the components of the water flux vector and the sea level in the section were defined by linear interpolation. Then, the instantaneous water flux (Q), the mean currents velocity (V_N) and mean sea level (SL) were calculated by integration along the right line L:

$$Q(t) = \int_L q_\mathrm{N}(l,t)dl, \quad V_\mathrm{N}(t) = \frac{Q(t)}{\int_L H(l,t)dl}, \quad SL(t) = \frac{1}{L}\int_L \eta(l,t)dl,$$

where $q_\mathrm{N} = \sqrt{q_x^2 + q_y^2}\cos(\varphi_\mathrm{N} - \varphi)$ is the projection of the water flux vector onto the normal to the line L, $\varphi_\mathrm{N} = 52°$ is the positive normal direction to the section, φ is the direction of the water flux vector. Hereinafter, all the angles are measured with respect to the x axis, directed to the east counter-clockwise. Thus, when $Q > 0$, the total water flux is directed to the Sea of Azov (direct flux), when $Q < 0$ – to the Black Sea (the reverse flux). For the direct and reverse fluxes, the notations Q_A and Q_B are used, respectively.

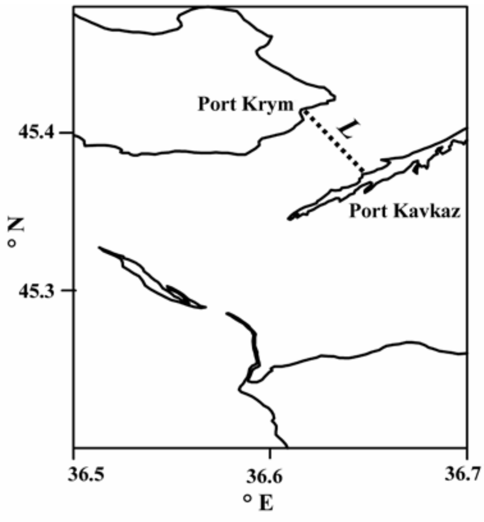

Fig. 1. Pattern of the northern narrowness of the Kerch Strait. Dotted line is Port Krym – port Kavkaz section

In the first cycle of numerical experiments, the effect of the direction (θ) of the space-homogeneous wind over the water exchange through the Kerch Strait was analyzed. The problem was solved with zero initial conditions. We assumed that when $t > 0$, the wind starts to act on the basin surface; its velocity increases linearly from 0 to W_0 within 12 hours and then remains unchanged. For each fixed θ, the total integration time was 48 h, which corresponds to the typical time of action of stable winds over the Azov – Black Sea basin.

Fig. 2 shows the dependencies of the water flux on the wind direction at $t =$ $= 48$ h for different wind velocities W_0. As can be seen, the curves presented have a well-pronounced sinusoidal character. The angular range $60° \leq \theta \leq 105°$ corresponds to the maximum direct fluxes, the angular range $240° \leq \theta \leq 285°$ corresponds to the maximum indirect fluxes. The angular ranges $165° \leq \theta \leq 175°$ and $345° \leq \theta \leq 355°$ correspond to the minimum values of the fluxes, as well as to the change in their direction. W_0 increase causes an intensification of water exchange through the strait. Thus, with W_0 variation within the range of 5 – 20 m/s, the maximum values of Q_A and Q_B increase by 5.7 and 6.6 times, respectively. The relationship between the maximum values of the direct and reverse fluxes with the wind velocity W_0 in the indicated range can be approximated by the following linear equations:

$$\max Q_A = 1013W_0 - 2008, \quad \max Q_B = -1207W_0 + 3324.$$

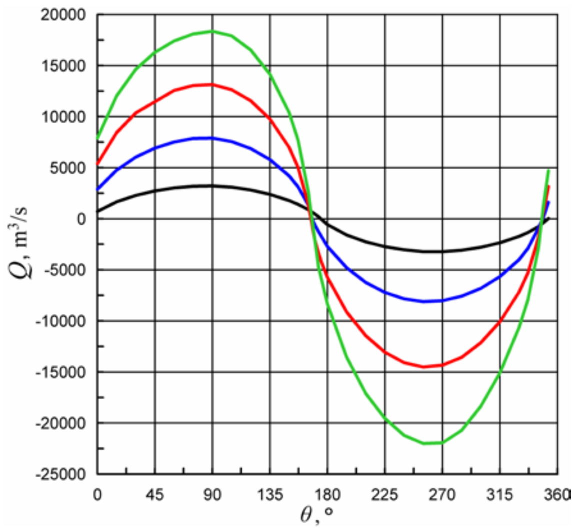

Fig. 2. Dependencies Q on θ at t = 48 h and at various values of W_0. The black curve corresponds to W_0 = 5 m/s; the blue one – to W_0 = 10 m/s; the red one – to W_0 = 15 m/s and the green one – to W_0 = = 20 m/s

Fig. 3 presents the dependencies of Q on time for the characteristic values of θ at W_0 = 10 m/s. Curves B1 and B2 correspond to the maximum values of Q (wind direction is close to the meridional one). One can see that in the time interval 0 – 12 h a Q increases to ± 7500 m^3/s, followed by stabilization. These curves show slight fluctuations with an inertial period due to the rotation of the Earth. The curves C1 – C4 correspond to the minimum values of Q, when the wind direction is close to the zonal one. The inertial fluctuations are also traced on these curves, but their sweep is much larger as compared to the curves B1 and B2.

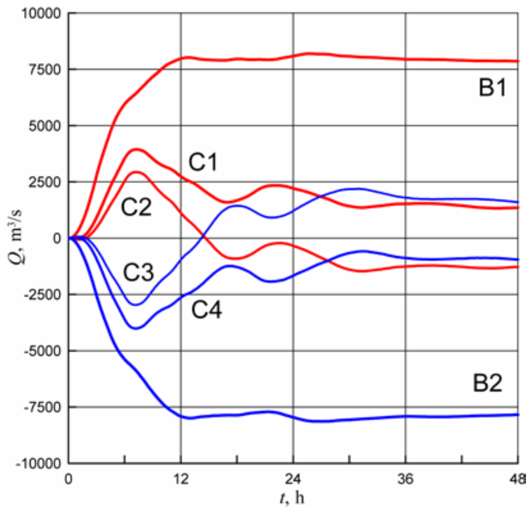

Fig. 3. Time dependencies Q at W_0 =10 m/s. The curve B1 corresponds to θ = 75°; the curve B2 – θ = 240°; the curve C1 – θ = 165°; the curve C2 – θ = 175°; the curve C3 – θ = 355° and the curve C4 – θ = 345°

Thus, wind direction greatly affects the water exchange in the Kerch Strait. The ranges of wind directions with the maximum and minimum values of Q_A and Q_B are found. When the wind direction is close to the zonal, the water exchange is minimal. In this case, the role of inertial oscillations increases. For all the considered values of W_0, the qualitative form of the time dependence Q does not change.

Water exchange features through the Kerch Strait, which appeared after the abrupt termination of the wind, were also analyzed. As in the previous calculations, for the first 12 hours wind velocity increased linearly from 0 to W_0 and further remained constant for 36 hours. After that it was assumed to be zero and the integration was carried out for 72 hours of model time.

Fig. 4 shows time dependencies of Q after the wind effect termination ($48 \text{ h} \leq t \leq 120 \text{ h}$). Analysis of the curves shows that during the first day there are sharp changes of Q due to the abrupt termination of the wind effect and accompanied by a change in the sign of Q. Then there is a regime of free oscillations with attenuation.

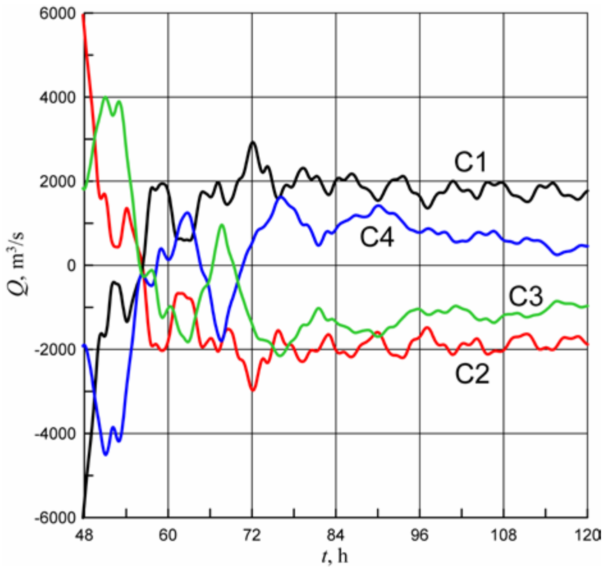

Fig. 4. Time dependencies Q at W_0 = 10 m/s after wind effect termination. The curve C1 corresponds to θ = 90°; the curve C2 – to θ = 270°; the curve C3 – to θ = 0°; the curve C4 – to θ = 180°

Under the meridional direction of the wind (the curves C1 and C2), the period of these oscillations is 10-12 hours. Under the zonal winds (the curves C3 and C4), the period of oscillations is close to the inertial one. In both cases, the range of Q oscillations is relatively small. In the middle currents, these oscillations manifest themselves in the form of V_N fluctuations, equal to ~ 0.02-0.03 m/s. It can be assumed that the period τ is induced by longitudinal seiche oscillations of the Sea of Azov.

In the next cycle of numerical experiments, we considered the situation when an atmospheric cyclone spreads over the Azov – Black Sea basin. Wind velocity in the cyclone was calculated using the following formula of the gradient wind

$$W_{\mathrm{g}}(r) = \left[\frac{r}{\rho_a} \frac{dP_{\mathrm{a}}}{dr} + \left(\frac{fr}{2} \right)^2 \right]^{1/2} - \frac{fr}{2},$$

where $r = \sqrt{r_x^2 + r_y^2}$ is the distance from the cyclone center (x_{c}, y_{c}) to the point (x, y), $r_x = x - x_{\mathrm{c}}$; $r_y = y - y_{\mathrm{c}}$. The atmospheric pressure P_{a} was set by the expression from [4]

$$P_{\mathrm{a}}(r) = \begin{cases} P_0 - \delta P_{\mathrm{a}} \cos^2\left(\dfrac{\pi r}{2R} \right) & \text{at } r < R, \\ P_0 & \text{at } r \geq R, \end{cases}$$

where P_0 is the background value of the atmospheric pressure; δP_{a} is the differential pressure between the cyclone center and periphery; R is the cyclone radius. It was assumed that the wind direction in the near-surface layer of the atmosphere due to friction deviates from the tangents to the isobars by an angle $\gamma = 20°$ counterclockwise and its velocity is less than the velocity of the gradient wind. Taking into account these assumptions, the components of the wind velocity vector in the near-surface layer of the atmosphere were defined at $\alpha = 90° + \gamma$, $\mu = 0.7$, in the following way:

$$W_x = -\frac{\mu W_{\mathrm{g}}}{r}(r_x \sin\alpha + r_y \cos\alpha), \quad W_y = \frac{\mu W_{\mathrm{g}}}{r}(r_x \cos\alpha - r_y \sin\alpha).$$

The calculations were carried out under the following cyclone parameters: $R =$ $= 300$ km, $\delta P_{\mathrm{a}} = 10$ hPa, $x_0 = 22°$E, $y_0 = 46.75°$N. The cyclone moved eastward along the zonal trajectory ($x_{\mathrm{c}} = x_0 + c\,t$, $y_{\mathrm{c}} = y_0$) at a velocity c. The total integration time was 10 days.

Time dependencies Q at various cyclone velocities are shown in Fig. 5, *a* – *c*. Fig. 5, *d* presents the time dependencies on the total water exchange between the basins:

$$Q_{\mathrm{S}}(t) = \int_0^t Q(\xi) d\xi .$$

Since in all the three cases the cyclone trajectory is the same, the curves Q for various values of c are similar – they have the same number of maxima and minima. An increase in the cyclone velocity is manifested in the compression of the curves on the graph along the time axis. Consequently, the time of the cyclone impact on the Kerch Strait water area is reduced. As a result, the total water exchange in the strait weakens, which is manifested in the $|Q_{\mathrm{S}}|$ decrease.

The final cycle of calculations is devoted to estimations of water exchange through the Kerch Strait for real synoptic situations that took place in the Azov – Black Sea basin., the wind velocity and atmospheric pressure fields from the mesoscale meteorological model WRF (ecobase.org.ua) with a spatial resolution of 7 km and a time resolution of 3 h were used as atmospheric forcing. The calculations were carried out for 5 monthly time intervals with different synoptic conditions.

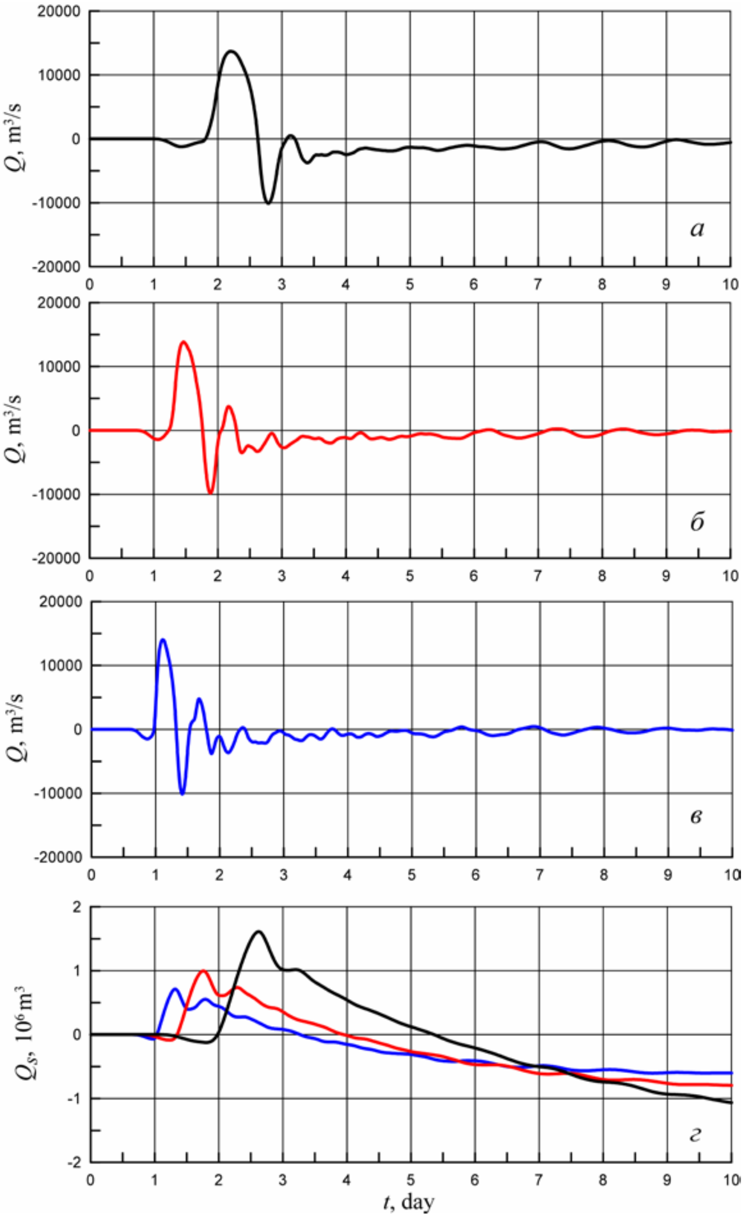

Fig. 5. Time dependencies Q and Q_S at various cyclone velocities: a – Q at c = 20 m/s; b – Q at c = = 30 m/s; c – Q at c = 40 m/s; d – Q_S at c = 20 m/s (the black curve), c = 30 m/s (the red curve), c = = 40 m/s (the blue curve)

Fig. 6 shows the results of calculations for November 2007, as an example. It is known that on November 11, 2007 there was a powerful storm in the Azov – Black Sea basin that had disastrous consequences in the Kerch Strait. Fig. 6, *a* shows the projection of the wind velocity on the normal to the section $W_N = \sqrt{W_x^2 + W_y^2}\cos(\varphi_N - \theta)$. The mean wind velocity and direction on the section were used to calculate W_N. Comparison of the curves shows that variations in the water flux (Fig. 6, *b*) and the mean currents velocity (Fig. 6, *c*) occur in phase with variations in projection of wind velocity on the normal to the section (Fig. 6, *a*). At that, the mean sea level changes in antiphase with the aforementioned features. Such course of dependencies is common for all 5 time intervals.

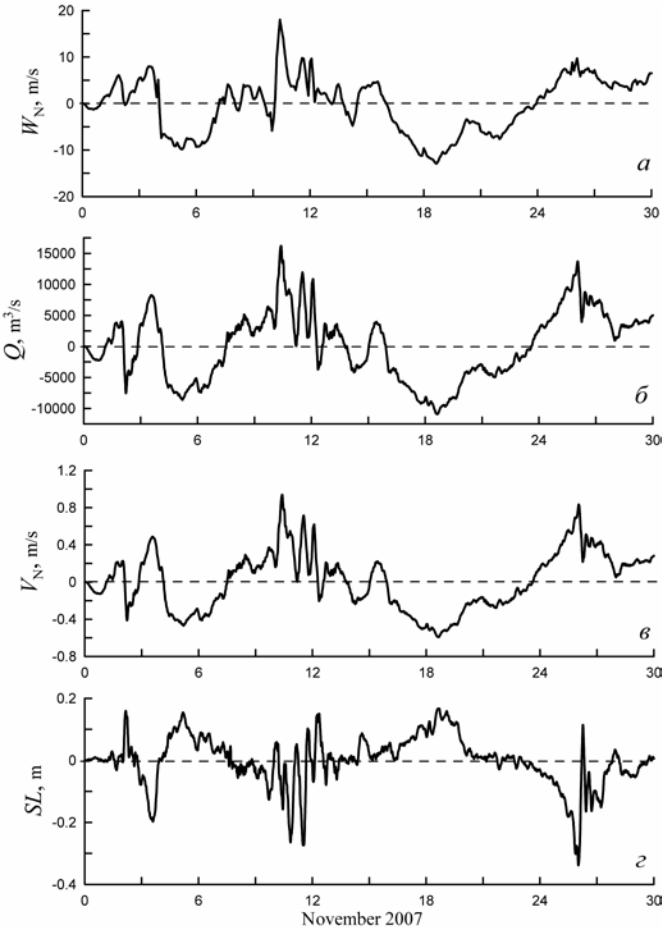

Fig. 6. Time dependencies W_N, Q, V_N and SL for November 2007

The table shows the extreme values of Q, V_N and SL in the northern narrowness of the Kerch Strait for the considered monthly time intervals. One can see that the maximum positive values of Q (the Black Sea flux) reach 12000-16000 m^3/s, the maximum negative values of Q (the Azov flux) are 11000 m^3/s. The mean currents velocities from the Black Sea to the Sea of Azov are 0.9 m/s. The currents from the Sea of Azov to the Black Sea have slightly lower velocities (~ 0.6 m/s). The maximum sea level increase and decrease are within the range of – 0.4 ... 0.4 m. The data in the table is consistent with the results of water exchange calculations using field measurements from [3], where it is shown that the maximum water flux during storm period is 11000 – 15000 m^3/s at the mean currents velocity ~ 0.45-0.47 m/s.

Extremes of Water Flux *Q*, the Normal component of the Mean Currents Velocity of V_N and Mean Sea Level *SL* in the Northern Narrowness of the Kerch Strait for Monthly Time Intervals

Assessment months	max*Q*, m^3/s	min*Q*, m^3/s	maxV_N, m/s	minV_N, m/s	max *SL*, m	min *SL*, m
November 2007	16220	–10909	0.93	–0.59	0.17	–0.34
March 2013	12880	–9700	0.79	–0.52	0.23	–0.38
July 2013	6604	–8043	0.38	–0.43	0.14	–0.13
September 2013	9543	–7586	0.56	–0.41	0.17	–0.17
September 2014	14990	–1392	0.92	–0.61	0.41	–0.39

Conclusion. Calculations of water exchange through the northern narrowness of the Kerch Strait for various types of the atmospheric impact are carried out. The results of numerical modeling of currents and sea level in the entire Azov – Black Sea basin on the non-uniform computational grid concentrated in the strait are used as the input data. Analysis of the calculations allows to draw the following conclusions.

Wind direction θ has a significant effect on water flux value *Q*. The ranges $60° \leq \theta \leq 105°$ and $240° \leq \theta \leq 285°$ correspond to the maximum values $|Q|$, the ranges $165° \leq \theta \leq 173°$ and $345° \leq \theta \leq 353°$ – to the minimum values $|Q|$. After wind effect termination in the Kerch Strait seiche oscillations *Q* with the periods of 10 – 12 hours appear.

When the atmospheric cyclone spreads over the Kerch Strait, the intensity of water exchange is defined by its movement speed *c*. When *c* decreases, the cyclone effect time on the Kerch Strait water area increases, resulting in the total water exchange intensification through the strait.

Values $|Q|$ for real synoptic conditions can reach 11000-16000 m^3/s, which is well-matched with the *Q* calculation results obtained according to the field data.

The calculations were carried out on the computational cluster of Marine Hydrophysical Institute.

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