MEDWIN PUBLISHERS
Committed to Create Value for Researchers

International Journal of Oceanography & Aquaculture
ISSN: 2577-4050

Seiches in the Semiclosed Seas of the Continental Shelf

Inzhebeikin Yu I*

Russian Academy of Sciences, Russia

***Corresponding author:** Inzhebeikin Yu I, Russian Academy of Sciences, Southern Scientific Center, Rostov-on-Don, Russia, Email: uinzheb@mail.ru

Research Article
Volume 4 Issue 3
Received Date: September 18, 2020
Published Date: October 23, 2020
DOI: 10.23880/ijoac-16000199

Abstract

Seiche movements in two small areas of semi-closed seas on the Continental Shelf (the White Sea and the Sea of Azov) with very different morphometric characteristics are considered in this paper. In addition, tidal movements are highly developed in the White sea, while in the Azov sea tides are virtually absent. We've used morphometric characteristics of the seas, including the ones recently obtained by the Azov Sea, as well as methods of numerical hydrodynamic simulation based on the theory of shallow water, and spectral analysis of the observation data of the sea level fluctuations.

Keywords: Continental Shelf; Semi-Closed Seas; White Sea; Sea Of Azov; Seiche; Numerical Hydrodynamic Simulation; Spectral Analysis; Flood

Introduction

In August 2006, on the Dolzhanskaya spit of the Azov sea, the water level rose sharply, people and cars washed away in the sea, the spit broke in several places. At the same time there was no storm warning. In June 2010 on the Yeisk spit of the same sea of Azov at full calm across the sea suddenly appeared powerful current washed away children, wandering on the spit knee-deep in water. In both cases, there are victims. Analysis of observations above sea level, showed that these phenomena were caused by the seiches. It is known that any natural system brought out of the state of equilibrium under the influence of any power is able to mobilize some internal mechanisms to restore the state of equilibrium. When the driving force is terminated, the system continues to produce free oscillations for some time. Being characterized by the system properties, the fluctuations depend on the initial impact of the driving force. After a certain time they terminate under the influence of the friction force as the system returns to the state of equilibrium. Such free oscillation of fluid in a closed or semi-closed basin is called a seiche. Seiche movements character and their role in the ecosystem functioning can vary greatly in different seas. Let us consider seiche movements in the two semi-closed seas of small area (in the White Sea & the Sea of Azov, located in the Northern and South-Western boundaries of the European part of Russia respectively (Figure 1).

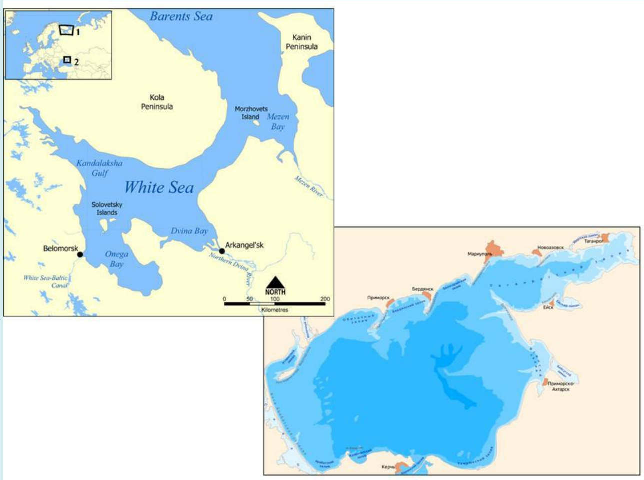

Figure 1: Map of the White and Azov seas. On the inset their location on the map of Europe.

The White Sea is located entirely in Russia between the latitudes 68° 40' and 63° 48' North, and the longitudes 32° 00' and 44° 30' East. As forthe Azov sea, it is located between the latitudes 45° 12′ 30″ and 47° 17 30″ North and the longitudes 33° 38′ and 39° 18′ East, and belongs to Russia and Ukraine. The area of the White sea is 90.000 km2, the volume is 6.000 km3, the average depth is 67 m, the maximal depth is 350 meters. The same parameters for the Azov sea are correspondingly 39.000 km2, 290 km3, about 7 m and 14.4 m. The greatest length of the White sea from Cape Kanin Nos to Kem-port is 600 km, and the greatest width between the cities of Arkhangelsk and Kandalaksha is 450 km [1]. The maximal length of the Azov sea from the Arabatskaja strelka spit to the Don delta is 380 km and the maximal width from the North to the South between the vertices of the Temryuk and Belosaraisk Bays is 200 km [2].

There are not many publications about seiche oscillations of the White sea level, and until recently [3] characteristics of seiche fluctuations haven't been studied. On the one hand, this is due to proximity of periods between seiche and strong tidal oscillations in the White sea and, on the other hand, due to complexity of its coasts and seabed topography. Indeed, two directions can be distinguished in the study of seiche level fluctuations in natural basins. The first one is spectral analysis of time series of levels observations data. The second one is calculation of eigen fluctuations based on analytical dependences for basins with simple morphometric characteristics or numerical modeling. There are strong tidal movements of water in the White Sea with a significant number of additional overtones, frequencies of which are close to those of seiche oscillations. This makes it difficult to distinguish seiche variations in the spectrum of total level fluctuations. On the other hand, complexity of the coastline and seabed topography made it impossible to apply simple formulas or analytical methods for solution of equations which describe seiche fluctuations.

As for the Azov Sea, in spite of the fact that seiches represent one of the most widespread types of level oscillations in this sea, they remained insufficiently studied. Both frequency and spatial characteristics of these oscillations, as well as their role in formation of extreme sea-levels, remained poorly studied [4], although some publications [1] and other articles [5,6] etc. consider some aspects of this phenomenon. This is partly explained by complex configuration of the shoreline due to development of numerous narrow barrier spits and firths extending far seaward, extreme shallowness of the basin or, to be more exact, the extended shoals, which, combined with the hydrometeorological factors and river runoff, form complex sea-level oscillations, highly variable in space and time.

Materials and Methods

Bathymetry data were taken from navigation maps. They were also specified by means of sonar sounding in some areas of the Azov sea. The data of observations on sea level at the coastal hydrometeorological posts of the Russian Hydrometeorological Service and of the Southern scientific center of the Russian Academy of Sciences were used for the study.

The main methods for calculating natural oscillations in basins of arbitrary complex shape on the rotating Earth were proposed by Platzman [7], Shwab and Rao [8]. Platzman's method is based on the "resonance iteration," while in Shwab and Rao's one, two sets of orthogonal functions are numerically selected and solved. These methods are relatively labor-intensive. In their work, Wubber and Krauss [9] numerically calculated the natural oscillations in the basin based on numerical solution of shallow-water equations with subsequent spectral analysis of the obtained data.

Greenberg [10] used a different method for calculating the natural period of the "Bay of Fundy – Gulf of Maine" system. He proceeded from the assumption that the wave energy, transferred across the open boundary of a semi-closed basin, should be maximal when the periods of the wave and natural oscillations coincide. The performed calculations provided results that accord well with the observations and are interpretable from the physical standpoint. We also used this approach to study seiche movements in the White Sea [3] and the Sea of Azov [4].

To calculate seiche oscillations in basins of arbitrary shape Maramzin [11] applied the method of finite elements, which was later used to study seiche variations of sea-level of the Sea of Azov [12,13]. At the same time, since the models, based on the method of finite elements at the "liquid" boundaries with the Black sea, use the condition of impermeability, and the so-called "mouth correction" is not taken into account, the amplitude and frequency characteristics of seiches, calculated in the last three works, differed notably from their real parameters.

Seiches in the Azov and White Seas may be induced by abrupt changes in the wind or atmospheric pressure fields immediately above the Azov and White Seas during cyclones and anticyclones rapidly moving above them. In the Sea of Azov seiches are also induced by storm surges from the Black Sea, and in the White Sea – by the analogous storm surges from the Barents Sea. A comparatively small amount of energy is enough to cause seiches. That is why one of the reasons that cause seiche oscillations in the hyper-shallow basin of the Azov Sea can also be local abundant rainfall over a part of the sea area, short-term spring or rain floods in the rivers of Don or Kuban, as well as water discharges from the Tsimlyansk and, to a smaller extent, Krasnodar reservoirs. The morphometric features of each of the seas influence characteristics of seiche oscillations. And the latter can be characterized by notable amplitudes if the periods of natural fluctuations in the Sea of Azov or in the White Sea, in some of their bays, or their systems coincide with the periods of the forcing impact.

The following system of motion and continuity equations is used in the proposed models, based on the shallow-water theory:

$$\frac{\partial u}{\partial t} - fv + g\frac{\partial \zeta}{\partial x} + \frac{ru}{H+\zeta}\sqrt{u^2+v^2} = 0 \qquad (1)$$

$$\frac{\partial v}{\partial t} + fu + g\frac{\partial \zeta}{\partial x} + \frac{rv}{H+\zeta}\sqrt{u^2+v^2} = 0, \qquad (2)$$

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial}{\partial x}(H+\varsigma)u + \frac{\partial}{\partial y}(H+\varsigma)v = 0 \qquad (3)$$

in which u and v are components of the depth-averaged current velocities along the X and Y axes, H is the depth under the undisturbed level, ζ is the deviation of the sea level from its undisturbed state, f=2ω sinφ is the Corriolis parameter, ω is the angular velocity of the Earth rotation, φ is the latitude, r is the coefficient of the bottom friction, and t is the time. The derivation of equations (1–3) is demonstrated in many works. It is based on the application of the approximations of the long waves theory to the motion and continuity equations of the uniform incompressible liquid subject to the Earth rotation (although, on the f plane) while ignoring the effects of advective nonlinearity. Indeed, according to Le Blon and Mysak [14], the equations for the f plane that ignore the changes in the local vertical component of the Earth rotation's angular velocity through the latitudes are applicable when the following condition is fulfilled:

$$\frac{L\cos\varphi_0}{R} < 1, \qquad (4)$$

in which R is the radius of the Earth, L is the basin size, and φ0 is the latitude. Since the maximal length of the Sea of Azov from the Don River delta to the Kamenskoe Settlement (the Kerch Peninsula) is 380 km, and the average latitude is φ0=46.15°, this ratio for the movements under study is less than , which is much less than unity. Thus, in the model of the Sea of Azov f is assumed to be equal to 1.052×10^{-4} s^{-1}. The maximal length of the White sea from the Kanin Nose cape to Pongoma Settlement (the Onega Bay) is 580 km, and the average latitude is φ0 = 66.50. These make the ratio equal to about 4·10-2, which is also much less than unity. Thus, in the White sea model f is assumed to be equal to 1,335×10-4s-1. The free fall acceleration was also taken constant in these models: g = 9.82 m/s2. Similarly, the density of seawater was assumed to be constant and equal to 1000 kg/m3 in the models. In the adopted formulation of the problem, the nonlinear terms are taken into account by the changing depth of the level fluctuations and by the quadratic bottom friction.

On the basis of the recent field data of the Azov sea, the morphometric characteristics obtained in SSC RAS [15] and the data from navigation maps for the White sea, the seas were approximated by the net domains. Before introducing the obtained water depths into the model, they were smoothed using the following filter:

$$H_{i,j} = H_{i,j}\beta + \frac{1-\beta}{4}\left(H_{i,J} + H_{i,j-1} + H_{i-1,j} + H_{i+1,j}\right) \qquad (5)$$

where $\beta = 0{,}7$.

The distinct finite-difference scheme constructed on the spaced network [11] was selected to solve the system of primary shallow-water equations numerically:

$$\varsigma_{i,j}^{n+1} = \varsigma_{i,j}^{n} - \frac{\Delta t}{\Delta h}\left[\left(Du\right)_{i,i}^{n} u_{i,j}^{n} - \left(Du\right)_{i,j-1}^{n} u_{i,j-1}^{n} + \left(Dv\right)_{i-1,j}^{n} v_{i-1,j}^{n} - \left(Dv\right)_{i,j}^{n} v_{i,j}^{n}\right], \qquad (6)$$

$$u_{i,j}^{n+1} = u_{i,j}^{n} + \Delta t\left\{ f\tilde{v}_{i,j}^{n} - \frac{g}{\Delta h}\left(\varsigma_{i,j+1}^{n+1} - \varsigma_{i,j}^{n+1}\right) + \frac{\left(\tau_x\right)_{i,j}^{n+1}}{\left(Du\right)_{i,j}^{n+1}} - \frac{1}{\rho}\left(\frac{\partial P_a}{\partial x}\right)_{i,j}^{n+1} - \frac{ru_{i,j}^{n+1}}{\left(Du\right)_{i,j}^{n+1}}\sqrt{\left(u_{i,j}^{n}\right)^2 + \left(\tilde{v}_{i,j}^{n}\right)^2}\right\}, \qquad (7)$$

$$v_{i,j}^{n+1} =$$

$$= v_{i,j}^{n} + \Delta t\left\{ -f\tilde{u}_{i,j}^{n+1} - \frac{g}{\Delta h}\left(\varsigma_{i,j}^{n+1} - \varsigma_{i+1,j}^{n+1}\right) + \frac{\left(\tau_y\right)_{i,j}^{n+1}}{\left(Dv\right)_{i,j}^{n+1}} - \frac{1}{\rho}\left(\frac{\partial P_a}{\partial y}\right)_{i,j}^{n+1} - \frac{rv_{i,j}^{n+1}}{\left(Dv\right)_{i,j}^{n+1}}\sqrt{\left(\tilde{u}_{i,j}^{n+1}\right)^2 + \left(\tilde{v}_{i,j}^{n}\right)^2}\right\}, \qquad (8)$$

$$\left.\begin{aligned}(Du)^n_{i,j} &= \frac{1}{2}\left(H_{i,j} + \varsigma^n_{i,j} + H_{i,j+1} + \varsigma^n_{i,j+1}\right)\\ (Dv)^n_{i,j} &= \frac{1}{2}\left(H_{i,j} + \varsigma^n_{i,j} + H_{i+1,j} + \varsigma^n_{i+1,j}\right)\end{aligned}\right\} , \qquad (9)$$

$$\left.\begin{aligned}\tilde{u}^n_{i,j} &= \frac{1}{4}\left(u^n_{i-1,j-1} + u^n_{i,j-1} + u^n_{i-1,j} + u^n_{i,j}\right)\\ \tilde{v}^n_{i,j} &= \frac{1}{4}\left(v^n_{i+1,j} + v^n_{i+1,j+1} + v^n_{i,j} + v^n_{i,j+1}\right)\end{aligned}\right\} . \qquad (10)$$

In formulas (6) - (10), $(Du)^n_{i,j}$ and $(Dv)^n_{i,j}$ indicate the total depths respectively in u - and v nodes; i, j are integer indexes along the Y & X axes; n is an integer index of time; Δh is a space step, identical both along the X and the Y axes; Δt is a time step, which was chosen from the condition of stability of the numerical scheme of Courant–Friedrichs–Levy

$$\Delta t < \frac{\Delta h}{\sqrt{2gH_{\max}}}$$

where $\beta = 0{,}7$. In oceanology Sielecki [16] applied a similar scheme with forward–backward differences; other researchers [17-19]used it for modeling storm surges.

The level rise and the components of the depth-averaged current velocities at the initial moment were assumed to be of zero value. The impermeability condition was accepted for the solid boundaries, whereas for the liquid ones it was the condition of taking into account “external” surges (formed in the Black Sea or in the Barents sea). For the Sea of Azov the «liquid» border passed through the Kerch Strait, and for the White Sea it passed through the section from the Svyatoy Nose Cape to the Kanin Nose Cape. Thus, both liquid and solid boundaries were drawn through the u and v nodes parallel to the X and Y axes, respectively.

According to different authors, the coefficient of the bottom friction in different seas varies from 10–2 до 10–3 (Ramming & Kowalik,1980). By analogy with (Ramming & Kowalik,1980), in this work we assume r as a function of the depth (the equivalent of the bottom relief roughness parameter) in the form of

$$r = \frac{1}{32}\left[\ln\left(\frac{14.8H}{z*}\right)\right]^{-2} \qquad (11)$$

where H is the depth, $z* = \Delta h \cdot 10^{-3}$ is the parameter of the network “roughness,” and Δh is a step of the network. For the White sea, the bottom friction coefficients were selected by means of model calculations of the amplitude of tidal wave M₂. Its smallest deviation from the observed values was obtained, if the bottom friction coefficient values depended on the depth in form of the formula (11) for the Onega Bay, and r equal to $1.4 \cdot 10^{-3}$ for the rest of the sea.

To evaluate the effect of driving forces of certain frequency on the Azov Sea waters, we performed a series of calculations, based on the assumption that surges at the open border in the Kerch Strait are in the form of:

$$\zeta\text{H}(t) = \frac{B}{2}Cos(\sigma t) \qquad (12),$$

the period of waves being from 3 to 50 hours and the time step being 0.1 hour. In equation (12), B is the surge value assumed as 1.0 m in our calculations; σ =2π/T is angular velocity; T is a time period (duration) of the surge.

Since the overwhelming majority of storm surges from the Barents to the White sea are propagated as Kelvin waves (8), the White sea waters response to the driving forces of certain frequency was assessed by a series of calculations, in which surges at the open border were defined as the Kelvin waves:

$$\varsigma_{\text{H}}(t) = \varsigma_{SN}(t)\exp\left[-\frac{f\,y}{(g\,H)^{1/2}}\right] \qquad (13)$$

with the period of waves from 3 to 48 hours and the time step of 0.1 hour. In equation (13) $\zeta SN(t)$ is a surge component of sea levels at the Cape Svyatoy Nos cape, assumed as 1 m in our calculations (a typical value of surge waves from the Barents sea); y is the distance from Cape Svyatoy Nos to this or that point at the open border along the OY axis.

To assess the response of the Azov & the White Sea waters to forcing oscillations and to define resonance frequencies, we calculated and compared the time-averaged sum of the oscillations energy ES = Ek + Ep. This energy is evident to be maximal when natural and forcing oscillations periods coincide (Figure 2). Thus, the kinetic component of the total energy was calculated proceeding from the dependence:

$$E_k = \frac{\rho}{2T}\int_T\int_S (h+\varsigma)(u^2+v^2)\,dS\,dt \qquad (14)$$

while the potential one was derived from the expression:

$$E_p = \frac{\rho g}{2T}\int_T\int_S \varsigma^2\,dS\,dt \qquad (15)$$

where ρ is the density of seawater (assumed to be constant and equal to 1000 kg/m3 in the model), T is the period and S is the size of the area.

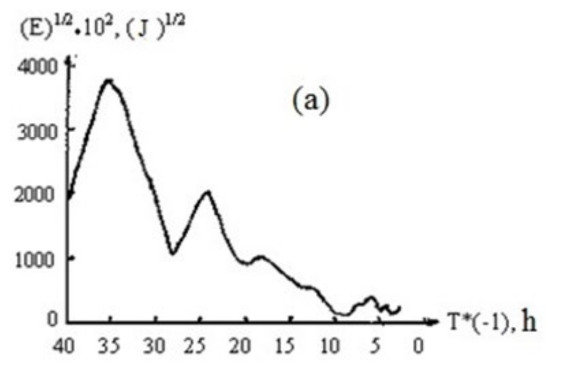

Figure 2: Change of total energy depending on frequency (period) of forcing action (a) in the White sea.

Results

The Sea of Azov. The periods of one-, two-, three-, four- and five-node seiche oscillations are 38.4, 23.7, 12.1, 8.8, and 5.1 hours, respectively (Figure 3). All the five modes identified in the observations at different sea coast parts are detected in the sea-level fluctuations spectra (Figure 4) that supports the obtained results. Let us consider the contribution of seiche movements to formation of levels and currents in the Sea of Azov in more detail.

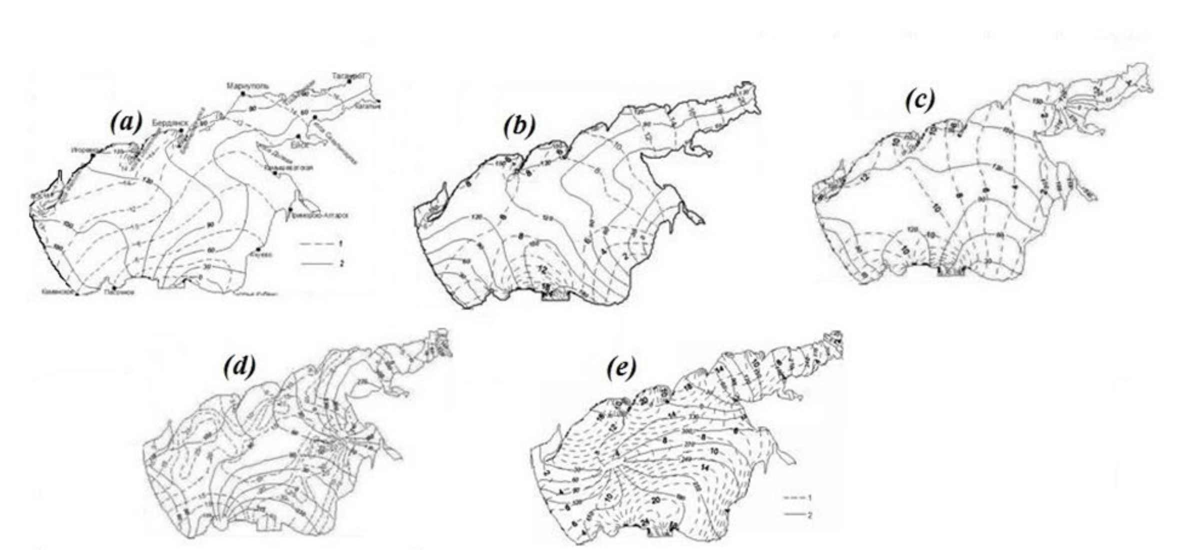

Figure 3: The distributions of isoamplitudes (1, cm) and isophases (2, degrees) of the one- (a), two- (b), three- (c), four- (d) and five-node (e) seiches in the sea of Azov.

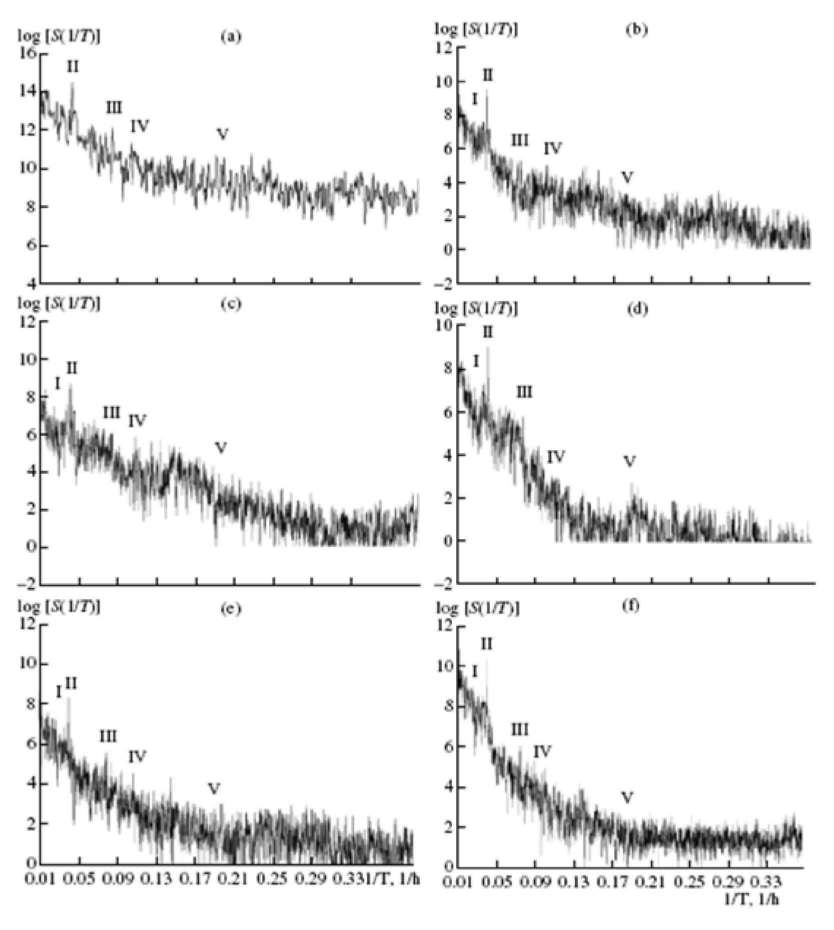

Figure 4: Spectra of sea level fluctuations of the Azov sea from observations at the points of Kagalnik (a) for the period from June to October 2007; Yeisk (b); Primorsko-Akhtarsk (c); Genichesk (d); Mariupol (d) and Taganrog (e) for the period from April to September 1977.
Roman numerals indicate peaks corresponding modes seiche oscillations.

One-nodal seiche. Figure 3b shows the distribution of coamplitudes and cophases of water level variations, whereas Figure 5a represents the distribution of maximal current velocities during one seiche period. The center of the degenerate amphidromic system of oscillations at the resonance frequency corresponding to the one-node seiche is located in the western part of the Kerch Strait (Figure 3b). The solution for first mode demonstrates a cyclonic rotation of the isophasal lines about the amphidromic center (Figure 3b). Thus, while the wave moves through the northern, shallower part of the sea, the phase velocity decreases, which results in the formation of the "apron" of delay of wave isophases (Figure 3b). Under the assigned values of the driving forces, the one-node seiche provides the maximal sea-level fluctuations (above 35 cm) at the head of the Taganrog Bay and at the northwestern sea coast near the Igorevka Settlement area.

Significant oscillations are observable near the western sea coast, East of the Obitochna Spit (up to 0.3 m), and Northeast of the Berdyansk Spit (up to 0.25 m). At the same time, in the areas where the wave crest of the one-node seiche approaches long protruding barrier spits, the sea-level oscillations behind the latter (in the head part of the bays formed by the barrier spits) appeared to be 15-35% lower as compared with their counterparts, which are observable, according to the calculations, in front of their seaward parts. It happens due to hyper-shallowness of the sea.

In the Taganrog Bay, under natural conditions, when seiche fluctuations are generated by perturbations in the atmospheric pressure or wind right above the sea water area, one should expect higher values of a one-node seiche and its contribution to the extreme levels in the area.

In regard to the currents in the movements corresponding to a one-node seiche, one can notice that the main trend in the distribution of the maximal speeds for the seiche period is growth of their values as they approach the amphidromic center where, according to the calculations, speed increases up to 1-1.3 m/sec (Figure 5a). In the Eastern half of the Kazantip Bay (located relatively close to the amphidromic center), velocities amounted to 60-70 cm/sec, at the Eastern tip of the Cape in front of the entrance to the Bay they grew up to 2 m/sec, while at the Western Cape - up to 1.5 m/sec. The calculations showed relatively high velocities of currents at the western (north-western) coasts of the Spits: the Obitochna - 30-40 cm/sec (maximum of 60 cm/sec to the west of the spit tip); the Berdyansk- 25-30 cm/sec (maximum up to 45 cm/sec to the west of the spit tip); the Belosaraysk – 25-30 cm/sec (maximum up to 50 cm/sec); the Krivaya – 15-20 cm/sec (maximum 30 cm/sec); the Beglitskaya - 10-20 cm/sec (maximum 25 cm/sec); the Dolgaya – 10-15 cm/sec (maximum more than 20 cm/sec) (Figure 5a). For this mode calculated speeds are significant in the Strait before Utlyuksky Firth (20-30 cm/sec, maximum is up to 0.5 m/sec to the west of the tip of the Biryuchy island spit). Along the eastern shore of the sea the velocities are approximately 10 cm/sec, and only at the Cape to the south-west of the settlement of Achuevo they increase up to 25 cm/sec. Along the eastern part of the southern coast of the sea velocities are mostly 7-10 cm/sec, only at the Cape near the Kuban mouth they increase up to 20 cm/sec and reach 0.3-0.5 m/sec the closer it gets to the Strait of Kerch (the amphidromic center) (Figure 5a). Away from spits, bottlenecks and the amphidromic center, seiche velocities of 4-8 cm/sec prevail in the Sea of Azov.

The be-nodal seiche. For the second mode of resonance oscillations corresponding to a two-nodal seiche with a period of 23.7 h, the node of one amphidromy which represents a degenerate amphidromic system, is located in the southeastern part of the Azov Sea, in the area between the mouth of the Kuban river and the settlement of Achuevo (Figure 3c). Another amphidromy is also a degenerate amphidromic system, its nodal area being located in the extreme Western part of the sea near the Arabat Spit. The rotation of the both amphidromic systems is of cyclonic nature; thus, the isophasal lines of the first amphidromy in the sorthern shallow part of the sea also form an «apron» of delay.

For the oscillations corresponding to the two-nodal seiche, the highest values can take place in the vast antinode area between the two amphidromic systems: from 12 - 16 cm in the central areas of the sea to 0.3 - 0.5 m to the North-West of the Kerch Strait, as well as at the top of the Taganrog Gulf (over 0.4 m). The level variations can attain observable quantities (15-20 cm) near the North-Western and North-Eastern coasts of the sea (Figure 3c). In other parts of the sea level fluctuations of this resonance frequency are insignificant; they reach not more than 10 cm in the western part of the sea, near the Arabat spit, and 4-8 cm – along the south-eastern coast of the sea.

The maximal speeds of currents for the seiche period, arising due to the resonance movements of water and corresponding to the two-nodal seiche, increase up to 15-20 cm/sec near the center of the first amphidromy (between the mouth of the Kuban river and the settlement of Achuevo) and reach their maximum of 35 cm/sec near the cape to the South-West of the settlement of Achuevo (Figure 5(b). In the area of the second amphidromic center (adjacent to the Arabat Spit) the velocities are from 8 to 10 cm/sec, which increase up to 15-20 cm/sec towards the NNW to the Utlyuksky Firth and reach the maximum of more than 60 cm/sec to the West of the tip of the Biryuchy Ostrov spit. The velocities of currents calculated for this mode of oscillations in the Utlyuksky Firth itself are 12-15 cm/sec. Regardless of the area close to the open border, where there are large velocities as shown in Figure 5b, but where there can be significant distortions under the influence of boundary conditions, according to the calculations, the maximal velocities of currents of this mode in the whole sea took place in the eastern part of the Kazantip Bay. The maximal current velocities here are 50-70 cm/sec, at the eastern tip of the Cape, in front of the entrance to the Bay they increase to up to 1.5-1.7 m/sec, and to the East of the Bay – to 1.5 m/sec. (Figure 5b). In the western part of the Kazantip Bay the velocities are 0.3-0.7 m/sec, and to the West of the Bay they increase up to 1.5 m/sec.

Since the zones of lower levels (as compared to the levels generated on the side of the crowding of the wave front) are generated in the bays, formed by the Obitochna, the Berdyansk, the Belosaraysk and the Krivaya Spits, short-term currents characterized by increased instantaneous velocities and directed to these zones appear at the western and north-western coasts of these spits. At the western shores of these spits, the maximal for the period of this seiche velocities are 30-40 cm/sec near the Obitochna spit (maximum of more than 55 cm/sec to the West of the spit tip), 30-40 cm/sec near the Berdyansk spit (up to the maximum of 75 cm/sec to the West of the spit tip); 25-30 cm/sec at the Belosaraysk spit (up to the maximum of 55 cm/sec), 15-20 cm/sec at the Krivaya spit (the maximum is 35 cm/sec), 10-15 cm/sec at the Beglitskaya spit (the maximum is 25 cm/sec) (Figure 5b). In the central part of the sea away from spits, bottlenecks, and amphidromic centers, as well as in the Taganrog Bay, the dominating velocities are 5-10 cm/sec.

Three-nodal seiche. For three-nodal seiche fluctuations (with a period of 12.1 hours) amphidromic systems are: the first one in the western part of the Taganrog Bay with the amphidromic point at 8 miles toward South-West from the tip of the Krivaya Spit, the second one near the north-eastern shore of the Crimean Peninsula, and the third one in the western part of the sea near the Utlyuksky Firth (Figure 3d). The last two amphidromies are degenerate amphidromic systems. All three amphidromic systems have cyclonic nature. For this mode seiche variations may reach maximum values of up to 25-30 cm on the coastal area to the North-West of the Fedotov Spit, and up to more than 20 cm near the coastal area to the South-West of Berdyansk spit, and in the western part of accumulative Panov Plain, which is the wide antinode zone. In the zone of antinodes, located in the central and partially in the eastern half of the sea, level variations designed according to the model amounted to 10-16 cm (Figure 3d). In the waters adjacent to the eastern coast and in the Taganrog Bay these values were from 4 to 8 cm.

For this mode of resonant oscillations the zones of the largest and maximum velocities in the sea during the seiche period, are also, for the most part, confined to the amphidromic centers. In the Taganrog Bay as we approach the amphidromic point in the western part of the Gulf velocities are increasing from 3-5 at the periphery to 10-15 cm/s at the amphidromic center (Figure 5c). In the nodal area of the second amphidromic system to the North-East of the Crimean Peninsula velocities increase up to 40-70 cm/s; in the area between the Bulganak Bay and Cape Borzovka, near the Eastern Cape of the entrance to the Kazantip Bay, and the Western Cape of the entrance in the same Bay highest speed values are correspondingly 90, 130, and 125 cm/s (Figure 5c). In the area of the third amphidromic center near the entrance to the Utlyuksky Firth velocities amounted to 20-40 cm/s; maximum speed was 80 cm/s to the West of the tip of the Biryuchy Ostrov Spit. In the Utlyuksky Firth itself speeds were 10-20 cm/s (Figure 5c).

For this oscillation mode in the western or north-western coastal area of Spits: Obitochna, Berdyansk, Belosaraysk, and Krivaya maximum current speeds were quite significant. Thus, in the waters to the West of these spits speeds were correspondingly 20-50 cm/s, 20-40 cm/s, 20-40 cm/s, 10-15 cm/s (Figure 5c); in area to the West of tips of the spits: Obitochna, Berdyansk, Belosaraysk, and Krivaya maximum velocities are correspondingly more than 70 cm/s, 90 cm/s, 60 cm/s, and 35 cm/s. Relatively high velocities were also observed in the water area to the South-East of Mariupol where they amounted to 15-20 cm/s; maximum is 50 cm/s. In area along the South-West coast of the Dolgaya Spit speeds turned out to be significant, 15-20 cm/s; maximum velocities are more than 40 cm/s near the north-western tip of this spit. Along the south-eastern sea coast offshore speeds are 20-30 cm/s, maximum 50 cm/s near the cape to the South-West of the settlement of Achuevo. In the antinode areas occupying almost the entire central part of the sea, as well as in the eastern part of the Taganrog Bay maximum current velocities for the three nodal seiche period did not exceed 5 cm/s. In the Western part of the Taganrog Bay maximum current speeds for this mode amounted to 5-10 cm/s (Figure 5c).

Four-nodal seiche. In case of oscillations at the resonance frequency corresponding to the four-nodal seiche with a period of 8.8 h, all four amphidromic systems have cyclonic nature (Figure 3e). The amphidromic point of the first system is located in the eastern part of the sea 20 miles to the West-South-West from the Kamyshevatsk settlement in the northern part of the Achuevsk Trough. In the center of this amphidromy isoamplitudes of water level variations form an ellipse kind of clenched by banks: the Achuevsk to the North-East of center, and the Zhelezinsk to the South-West of it. Centers of the other three amphidromies representing degenerate amphidromic systems are located: in the top of the Taganrog Bay in the area of Taganrog, in the Bay of Kazantip to the North of the Kerch Peninsula, and in the extreme west area of the sea near the entrance to the Utlyuksky Firth (Figure 3e). In a small water area in the zone of antinodes over the Zhelezinsk Bank the fourth mode may cause fluctuations of more than 1.5 m, which is the absolute maximum of the values obtained for oscillation from the first to the fifth modes in all areas of the Azov Sea under the influence of perturbations arising on the «liquid» boundary. In antinodal areas: at the western border of Panov accumulative plain (10-13 miles to the East of the Fedotov Spit), to the South of the Berdyansk Spit, and in the area adjacent to the central part of the Arabat Spit for this mode the magnitudes of the level variations can reach respectively 0.7; 0.5, and 0.4 m. In the other regions the sea values of level variations during the fourth mode are small; they are less than 0.15 m in the central areas of the sea, and less than 0.1 m in the areas along the eastern coast of the sea, and in the Taganrog Bay (Figure 3e).

For a four-nodal seiche, the trend - which consists in that zones of greatest current velocities maximal for the seiche period are adjoining the amphidromic centers - remains in the entire area of the sea. Thus, as we approach the amphidromic point in the eastern half of the sea (in the northern part of the Achuevsk Trough) speeds are increasing from 5-15 on the periphery to up to 50-60 cm/s in the centre. In the area of the second amphidromy's node in water area adjacent to the Bay of Kazantip, in the Bay itself speeds amounted to 50-70 cm/s; maximum speed was 90 cm/s directly to the West of this Bay. In the area to the East of the Bay maximum current velocities for the seiche period were 70-90 cm/s.

In the water area before the entrance to the Utlyuksky Firth, where the node of the third amphidromy is situated, speeds amounted to 20-50 cm/s; maximum - more than 90 cm/s in the Strait to the west tip of the Biryuchy Ostrov Spit. In the Utlyuksky Firth itself speeds were within 10-20 cm/s. And, finally, in the water area adjacent to the coast between

Taganrog and Petrushino near the centre of the fourth amphidromic system velocities amounted to 15-20 cm/s, though across all of the rest of the Taganrog Gulf maximum current speeds for this mode did not exceed 5 cm/s.

In the waters to the West of the Obitochna, Berdyansk and Belosaraysk Spits significant maximum current velocities for the seiche period were 20-50, 10-20, 15-20 cm/s correspondingly. To the West of the tips of the above spits highest speed values are 80, 50 and 40 cm/s respectively. In the rest, the greater part of the sea the velocities are dominantly 10-15 cm/s; and only in the Taganrog Bay they fall to 5 cm/s or less.

Five-nodal seiche. The fluctuations being at the five nodal seiche with a 5.1 h period, the first amphidromic system covers almost the entire deep southern part of the sea and has cyclonic character (Figure 3f). Its centre is located in the western half of the sea. he following four amphidromies are degenerate amphidromic systems. The center of the first one is located in the western base of the Obitochna Spit (at the top of the Bay formed by the spit). The amphidromy has anticyclonic character (Figure 3f). The following amphidromic system, the third one for this mode, also revolves clockwise around the Dolgaya Spit, i.e. has anticyclonic character. The fourth amphidromic system, which also has anticyclonic nature, revolves around the Sazalniksk Spit. The last, fifth (degenerate) amphidromic system at the top of the Taganrog Bay revolves counterclockwise around the Taganrog Peninsula (spit), i.e. has cyclonic nature (Figure 3f). Values of level fluctuations during a five-nodal seiche can reach up to 0.1 m in the Taganrog Bay and along the eastern coast of the sea, 0.4 m near the north-western coast of the sea, and exceed 0.5 m in the north-eastern coast of the Crimean Peninsula. In antinode areas covering a sizable central part of the sea the magnitude of level variations can reach 15-30 cm (Figure 3f).

For this oscillation mode the maximum velocities occurring within the seiche period increase from 5-10 on the periphery to 15-20 (maximum 30) cm/s in the center of the first amphidromy covering the whole southern part of the sea (Figure 5d). In the antinode area of the second amphidromic system, at the western coast of the Obitochnaya Spit the speed increases up to 30-50 cm/s (maximum - more than 70 cm/s). In the area of the third amphidromic system's center near the Dolgaya Spit maximum speed of currents during a five-nodal seiche amounted to 20-30 cm/sec (max. 60 cm/s). In the water area by the Sazalniksk Spit with the center of the fourth amphidromy, calculated maximum speeds were within 20-30 cm/sec; (max. 35 cm/s).

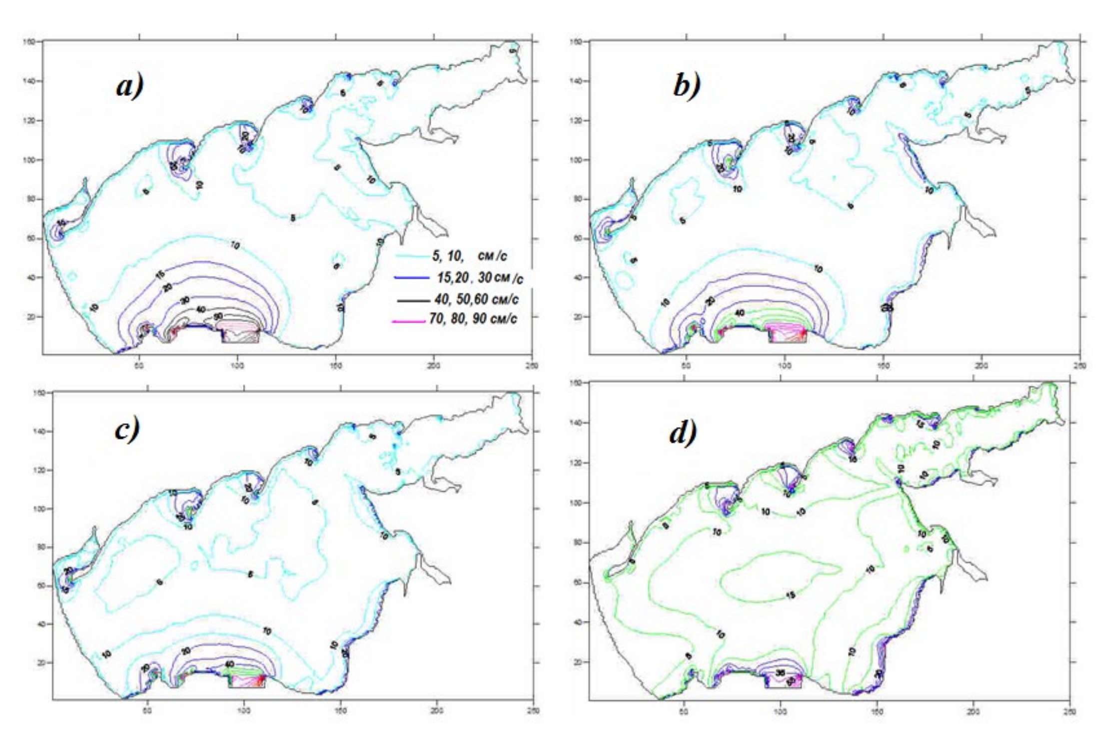

Figure 5: The distribution of maximum velocities of currents at one (a) two (b) three (c) and five-node (d) seiches in the sea of Azov.

As we approached the center of the fifth amphidromic system in water area near Taganrog maximum speed of currents for the seiche period increased from 5 cm/s in the periphery to 15 cm/s in the centre of the amphidromy (Figure 5d). In the Taganrog Bay relatively high speeds of currents for this oscillation mode (25 cm/s) were detected in the water area between the Chumbur Bank and the Ochakov Spit (including the area of the spit itself). High speeds were also measured at the top of the Bay (10-15 cm/s), and also near the settlement of Port Katon where the specified speeds amounted to 40-50 cm/s (max. above 70 cm/s). Along the Yeysk Spit speed of currents amounted to 30-40 cm/s from the direction of the sea, and 5-10 cm/s from the direction of the firth. In the strait at the entrance to the Yeysk Firth the considered speeds were within 10-15 cm/s, and in the greater part of the Firth – up to 5 cm/s (Figure 5d).

In narrow places and water areas before the capes the maximum current speeds for the seiche period were 30-40 cm/s for the Berdyansk (max. 115), 35-45 for the Belosaraysk (max. above 90), 25-40 for the Krivaya (max. above 70), and 10-15 cm/s;. In narrow water at the entrance to Utlyuksky Firth maximum speed is more than 15 cm/s, although at a small distance from cape in Firth speed fell to less than 5 cm/s (рис.5d).

In the eastern half of the Kazantip Bay water area prevailing maximum velocities of currents for the seiche period were 15-25 cm/s. The highest speed value was 90 cm/s near the Cape at the entrance to the Bay. In the western half of the Bay they were 5-10 cm/s.

Near the Cape, which is still slightly to the East of the Bay, speed reached up to 110 cm/s. In the extreme South-West of the sea, in the area of the Kerch shore to the West of the Kamenskoe settlement, relatively high speeds were also measured - 20-30 cm/s (maximum 50 cm/s).

In general, seiche currents in the Sea of Azov are more variable both in space and time than level variations. It is noticeable by more intense “spottiness” even if we compare spatial variability of level fluctuations’ isoamplitudes to corresponding maximum current velocities for the seiche period. This is due to the fact that to ensure the conditions of continuity, the current velocity must fall to increase in rounding capes, spits, in straits and bottlenecks as well as when water moves from the deep zones to shallower ones. The results also showed that maximum speeds of seiche currents are comparable to or some may even exceed maximum wind currents speeds obtained in the work [2].

The White Sea

Strong tidal currents are always present in the tidal White Sea. That is why seiche movements don’t play such great role in functioning of its ecosystem as in the Sea of Azov. Studying seiches here matters only for explanation of mechanisms of extreme levels formation and accounting for their contribution to extreme levels of rare incidence. This is why we won’t consider currents occurring during seiches for the White Sea in this work. Results of total oscillations energy with different values of their period are presented in Figure 2. In this figure oscillation periods are marked along the X axis, and the square root derived from values of total energy is marked along the Y axis for clear demonstration. Calculations have shown that the oscillation period for the first mode is 35.7 h (Figure 6a). Oscillation periods corresponding to a 2-, 3-, 4-, and 5-nodal seiche constitute 18.5; 12.5; 7.5 and 6 hours correspondingly. The obtained values are confirmed by the spectrum of level fluctuations according to observations at Sosnovets hydrometeorological station for the period of May-November, 1977, as shown in Figure 7. Though their identification is complicated by closeness of frequencies of specified seiche variations modes to frequencies of tides observed in the sea. Only the peak at the frequency corresponding to the period of 35.7 h. is weakly expressed (see box on figure 7). It may be caused by proximity of the observation point to the amphidromic point of the one-node seiche and the character of synoptical processes within the observation period which were not bringing about oscillations of such frequency. The peak of total energy observed in Figure 2 at the frequency corresponding to the period of 24.5 h. is determined by the one-node seiche of the Kandalaksha Gulf – the Gorlo– the Mezen Bay system. Based on all above we may draw a conclusion that the calculated characteristics of seiche oscillations are supported by natural observations data.

The amphidromic point of the first oscillation mode at the resonance frequency corresponding to a one-node seiche is located in the north-eastern part of the Gorlo to the south-west of the middle of the line connecting Cape Voronov and Cape Danilov (Figure 6a). The amphidromic system forms a cyclonic rotation of phases. The one-node seiche may form the highest values of level fluctuations, up to 1.25 m, at the top of the Onega Bay, up to 1 m. at the top of the Kandalaksha and the Dvina Bay and up to 0.75 m. – at the top of the Mezen Bay. The second mode of resonance oscillations corresponding to a two-node seiche, has a period of 18.5 h. Thus, the first amphidromic point is located in the eastern part of the Basin close to the border between the strate Gorlo and the Basin (Figure 6b). The second amphidromy representing a degenerate amphidromic system is situated in the north-eastern part of the Voronka, to the south of Cape Kanin Nos. Both amphidromic systems have cyclonic nature. Highest values of oscillations during a two-node seiche may occur in the Mezen Bay - up to 55 cm., in the Voronka and the Onega Bay – up to 25 cm., and in the Kandalaksha and the

Dvina Bay – up to 15 cm.

The third oscillation mode at the “seiche” frequency with a period of 12.5 h. forms three amphidromic systems with centers: in the eastern part of the Voronka; in the south-westernmost part of the Gorlo closer to Cape Zimnegorskiy; a degenerate amphidromic system around Cape Letny Orlov in the north-eastern part of the Onega Bay (Figure 6c). All three amphidromic systems are of cyclonic character. Seiche variations can reach maximum values during this mode at the top of the Mezen Bay (up to 150 cm.), then in the Voronka, the Gorlo and the Onega Bay (40 cm.). In the Kandalaksha and the Dvina Bays they can be 30 and 45 cm. respectively.

All four amphidromic systems of oscillations at the resonance frequency corresponding to a four-nodal seiche with a period of 7.5 h. have cyclonic character. Their centers are situated: to the south-west of the Kanin Peninsula; at the border between the Voronka and the Mezen Bay along the line connecting Konushin Cape and Morzhovets Island closer to the latter; in the central part of the Basin; and also in the central part (towards the thalweg) of the Onega Bay, but closer to the Lyamitsk shore (Figure 6d). One should notice that in a small water area-at the top of the Mezen Bay – the fourth mode can cause fluctuations above 160 cm. which is the absolute maximum of all values obtained for oscillations from the first to the fifth mode in all areas of the White Sea. At the same time, values of level fluctuations during the fourth mode in other parts of the sea are relatively small and can reach in the Gorlo – 65 cm., at the top of the Kandalaksha Bay – 45 cm., in the Voronka (Figure 6e) and at the top of the Dvina and the Onega Bays – 25 cm., and in the Basin – 10 cm. (Figure 6d).

The period of fluctuations at a resonance frequency corresponding to a five-node seiche is 6.0 h. Amphidromies of cyclonic nature are located: before the entrance to the Gorlo along Cape Danilov-Morzhovets island line; in the northern part of the Mezen Bay; in the southern part of the Basin, to the north-east of Zhizhgin Island; in the southern part of the Onega Bay closer to the Lyaminsk shore; and also a degenerate amphidromic system in the north-eastern part of the Voronka. Values of level fluctuations during a five-node seiche may reach in the Kandalaksha and Mezen Bays up to 105 cm., in the Basin-25 cm. and in other parts-45 cm.

Short-Term Floods with Extreme Currents

Superposition of seiche oscillations with rises in the level due to other reasons (e.g. a storm surge) may lead to short-term catastrophic flooding of separate zones of shores and spits against the background of high current velocities. Let us consider this based on the example of resonance level variations corresponding to a five-node seiche as these are most revealing. Figure 8 shows instantaneous topography of the Sea of Azov level in two-dimension and three-dimension versions at a certain point of time (in this case at the 90^o. phase) of resonance oscillations corresponding to a five-node seiche (In Figures 8a, 9a and 10a water areas where sea level is higher than in undisturbed state are highlighted blue. The ones where sea level is lower than that - red). One may notice that there is a drop of 10-20 cm. between the levels of the western and the eastern coasts of the Obitochna Spit. This is due to the fact that the node of one of five-nodal fluctuations’ amphidromic systems with minimum variation amplitude is located at the western base of the Obitochna Spit. And as the crest of a wave of another amphidromic system approaches (having its centre in the western part of the sea) quite significant difference in levels appears, spit-wide. Thus, as seen in Figure 3f, the shift between isophases at different spit shores can constitute over 90^o I.e., for example, the crest of a wave at the east coast (maximum level) may correspond to even a fall of level below average (from the undisturbed state) at the west coast of the spit. If seiche oscillations occur against the background of a storm surge and the total level rise from the superposition of the surge and a seiche wave exceeds the lower marks of the spit’s topography, the spit (or, to be exact, its lower part) will be underwater. The speed with which the crest of the wave will move across the spit (current speed, u) will be almost equal to the phase speed of the wave, c, i.e.

$$u \approx c = [g(H+a)]^{\frac{1}{2}} \qquad (16)$$

and, for the Obitochna Spit area it may become almost 5 m/s. In the formula (16) g is free fall acceleration, m/s^2; H – depth, m; a – amplitude of a seiche wave, m. In the process of fluctuations in 30^o, (phase being 120^o.) a similar situation may occur at the Dolgaya Spit (Figure 9). But because here the amphidromic system revolves around the spit and the spit is entirely encircled by the node, the value of five-nodal seiche variations is insignificant. Flooding of the spit under this mode of fluctuations is less probable. Values of the difference between the level at the south-west and north-east coasts here are relatively small. Phase being 270^o. the same situation occurs at the Yeysk Spit (Figure 10). And we may notice that the crest of the wave approaching the spit creates a 10-cm. difference between the north-east and the south-west coasts of the spit. While the difference in level between the east and west coasts of the Fedotov, the Obitochna, the Belosaraysk and the Dolgaya Spits have changed signs. It is clear that values of seiche oscillations being higher (e.g., 40-60% from the magnitude of a storm surge), based on surge values of 0.5-3.0 m. in this region [2] such difference may make from 0.25 to 1.4 m. Current speeds at the Yeysk Spit during flooding of lower parts of the Spit, according to the formula (16) may exceed 2 m/s.

The situation of exactly this kind must have occurred at the Dolgaya Spits in August, 2006, when despite wind being quite weak, strong current washed away holiday-makers at the spit, their cars and broke the spit (created scours) in four places. One should note that the difference in level marks at the west and east coasts of the Fedotov and Belosaraysk Spits in Figure 8 and 9 is already determined not by proximity of nodes of seich variations amphidromic systems. Now it's determined by their position towards the surging crest of the wave: value of these variations is lower on a shore located in the rear side towards the surging front of the wave. Such a phenomenon is caused by the basin's hyper-shallowness and narrow spits protruding far seaward. It is characteristic not only of resonance oscillations corresponding to a five-node seiche but also of other, lower modes of oscillations. It can be traced by distribution of isoamplitudes in areas where some spits are located in figures 3b -3f. Thus, superposition of level rises and seiche oscillations my lead to short-term catastrophic floods with extreme currents which may cause human toll and spit scours. Studies have revealed that such flood mechanism may take place at five spits: the Obitochna, the Berdyansk, the Dolgaya, the Yeysk and the Fedotov (highlighted crimson in Figure 11) which are, by the way, quite popular recreation areas.

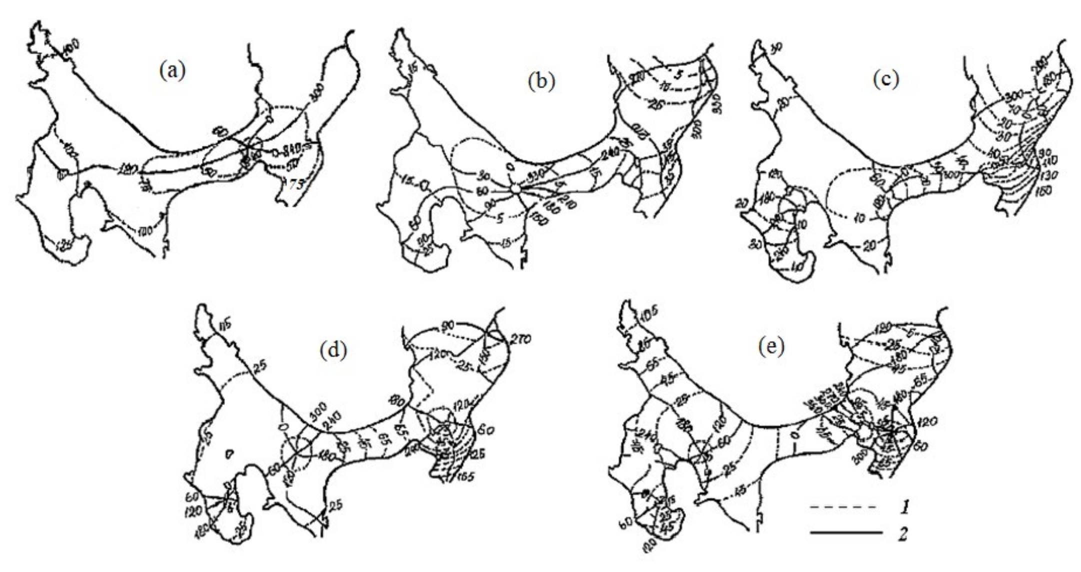

Figure 6: The distributions of isoamplitudes (1, cm) and isophases (2, degrees) of the one- (a), two- (b), three- (c), four- (d) and five-node (e) seiches in the White sea.

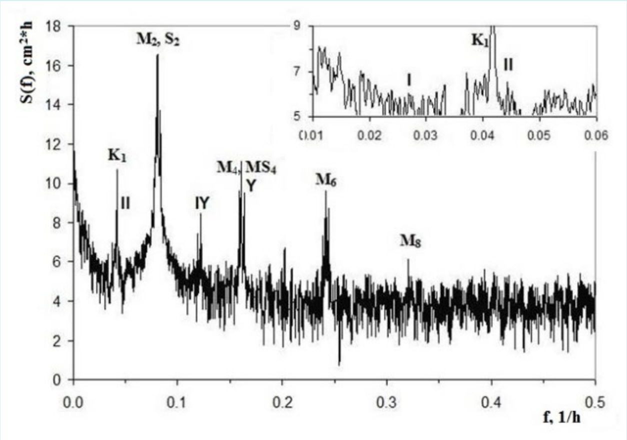

Figure 7: Spectrum of sea level fluctuations of the White sea from observations at the point Sosnowiec over the ice-free period 1977.

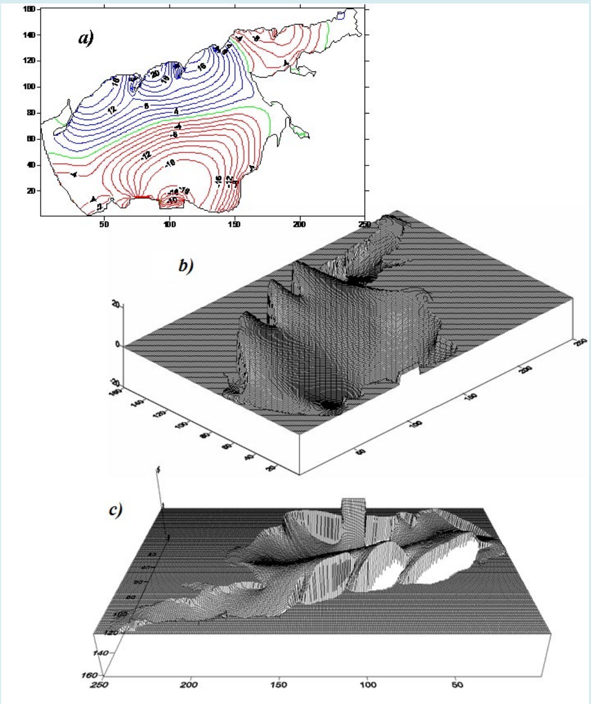

Figure 8: The relief of the instantaneous level (in cm) of the Azov sea at five nodal seiche in phase 90^0
a-two-dimensional representation; b, c-three-dimensional representation (b-top view from South-West; c-top view from North).

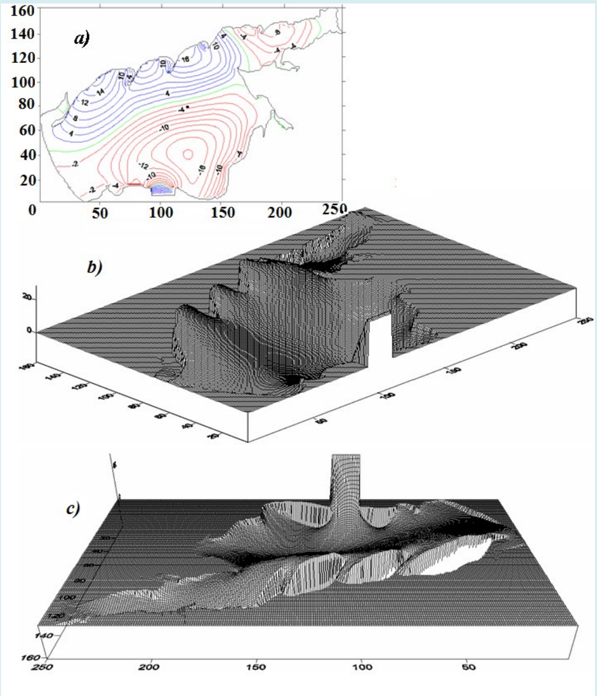

Figure 9: The relief of the instantaneous level (in cm) of the Azov sea at five nodal seiche in phase 120^0
a-two-dimensional representation; b, c-three-dimensional representation (b-top view from South-West; c-top view from North).

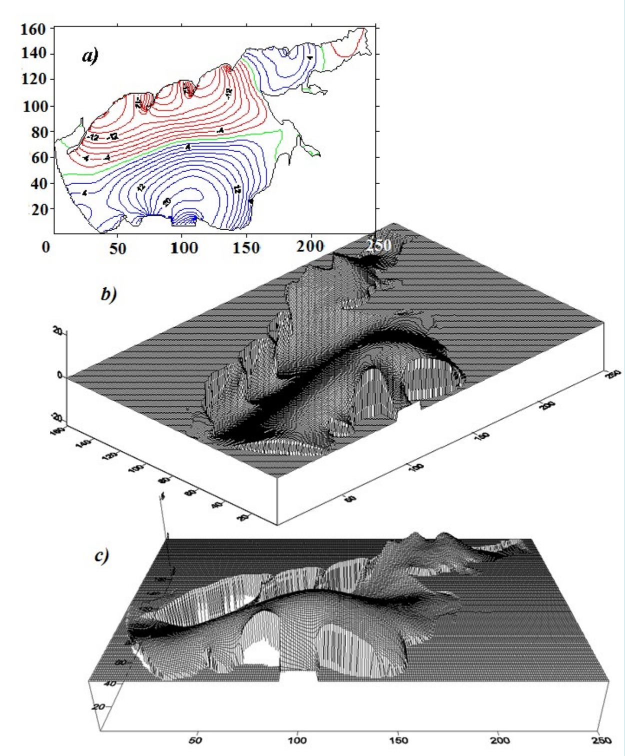

Figure 10: The relief of the instantaneous level (in cm) of the Azov sea at five nodal seiche in phase 270^0 a-two-dimensional representation; b, c-three-dimensional representation (b-top view from South-West; c-top view from South).

Storm surges caused by combined impact of strong wind and changing atmospheric pressure brought by passing cyclones and anticyclones, as well as seiches, relate to the class of long-wave movements. But the former: a) are usually predicted in advance; b) are characterized by bad weather when there are almost no holiday-makers on the beaches. So, it's possible to avoid casualties. But floods occurring during superpositions of seiche oscillations and rises in the average level may take place during not so strong winds and are hard to predict. Besides, when these phenomena occur at the above mentioned spits there is a difference in levels at different shores of a spit. Consequently, these floods will be almost always accompanied by strong currents which makes them more dangerous. Developing recreation zones at picturesque Sea of Azov spits one should keep in mind this mechanism of floods and take measures to limit danger for holiday-makers.

Discussion

In the accepted statement of the problem, the frequency characteristics and the spatial structure (the position of the amphidromic systems and the isophasal line) of seiche oscillations would correspond to their analogues of "true" seiches generated by the atmospheric impact. At the same time, certain errors of the amplitude values are observed in the areas immediately adjacent to the "liquid' boundary due to the influence of the boundary conditions. Besides, in the northeastern part of the hyper shallow sea of Azov, due to the strong dissipation of the wave energy when driving oscillations from the Kerch Strait pass through the shallow sea areas, the calculated values of oscillations should be slightly understated as compared with natural ones, when seiche oscillations were generated by changes in the fields of the atmospheric pressure or of the wind directly above the sea. This understatement is particularly significant for one- and two-node seiches. Therefore, for the above-mentioned modes of oscillations, the corresponding corrections were made in the distribution of the isoamplitudes in this part of the sea. These corrections take into account distribution of the values of the energetic spectrum of level oscillations at these frequencies in different parts of the sea. The calculated values of amplitudes (A=25 cm) and periods (T=23.7 h) for the two-node seisha showed a good correspondence with the observed values for the point Pereboyny (Figure 11) (from Gluhovsky, 1971): value 2A=50 cm; period T, ~24 h.

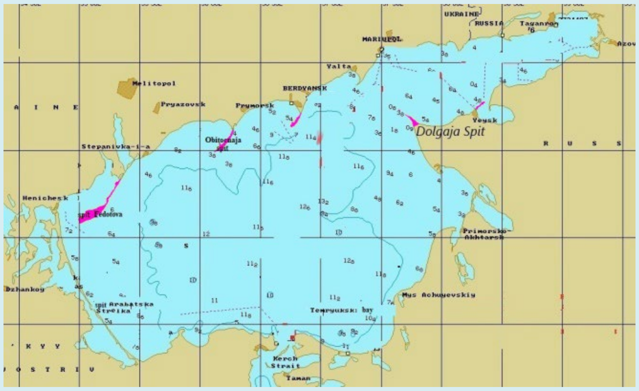

Figure 11: Areas of the Azov sea, where there may be a similar type of short-term catastrophic floods (marked in red).

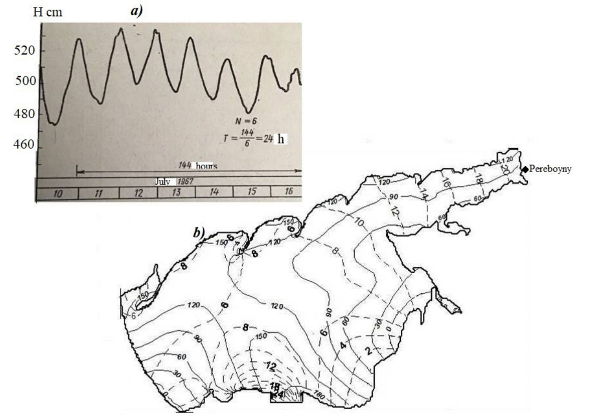

Figure 12: The distributions of isoamplitudes (1, cm) and isophases (2, degrees) of the two- node seiche (b) in the sea of Azov and seiche fluctuations of level on observations in p. Pereboyny (a).

Seiche level variations may turn out to be quite significant. In the sea of Azov, they can be 40-60% of the maximum surges, i.e. 0.5-1.5 m. In the work [20] according to observation data it was found out that amplitudes of seiche oscillations for particular months are comparable to those of storm surges and constitute 45-95% of the latter in the Sevastopol Bay located near the Sea of Azov,), i.e. 0.5-2.0 m . The measurement of the flow velocity near the amphidromic point of the single-node seisha in the Kerch Strait was 166 cm/s, which is close to the values calculated from the model.

The Role of Seiche Movements in Functioning Sea Ecosystems

The role of seiche movements in functioning of the White Sea ecosystem is insignificant. But draining large water areas in fish spawning zones they can severely damage fish populations [21-26].

Their negative impact on communal facilities and navigation destinations is more essential. Their superposition with storm surges may give birth to catastrophic floods causing destruction of port facilities, accidents at and shutdown of the heat electric-generating station. Salty seawater permeats to branches of the Northern Dvina river delta from which water intake for the heat station takes place.

Conclusion

Seiche oscillations may essentially contribute to variations of the Sea of Azov and the White Seas levels. They may be caused by abrupt wind field changes or changes in atmospheric pressure during cyclones and anticyclones rapidly moving above corresponding seas. One more reason may be storm surge waves coming from adjacent seas. Oscillation periods corresponding to the main one-node seiche are 38.4 for the Sea of Azov and 35.7 for the White Sea.

Oscillation periods corresponding to 2-, 3-, 4- and 5-node seiches are in the Sea of Azov - 23.7; 12.1; 8.8 and 5.1 h., and in the White Sea – 18.5; 12.5; 7.5 and 6.0 h. correspondingly. All the five identified modes in the spectrum of level fluctuations obtained through observations during the ice-free period are detected, which confirms credibility of the obtained results. The highest oscillations value corresponding to seiches from the first to the fifth mode, both in the Sea of Azov and the White Sea is observed during the fourth mode. It may reach up to 1.5 m. in the former in the antinode area above the Zhelezinsk Bank. In the latter it may go up to 1.6 m. at the top of the Mezen Bay. Nevertheless, across the rest of these seas oscillation values for the fourth mode are insignificant.

Seiches in the Sea of Azov seriously influence its hydrological and hydrochemical regimes and, consequently, its ecological condition setting the whole water mass of the sea in motion. The main mechanism of such influence are currents of periodic character with the period corresponding to the period of seiches.

On the most part of the Sea of Azov area prevailing speed values of maximum currents for a seiche period are 10-20 cm/s. In nodal zones of amphidromic systems they increase to 40-50 cm/s. At tips of capes and in bottlenecks for some modes of resonance oscillations they rise up to 90-110 cm/s. By the capes at the entrance to the Kazantip Bay at the Crimean shore during oscillations corresponding to a three-nodal seiche – up to 130 cm/s and to a one-nodal seiche – up to 150-200 cm/s. The latter values of maximum speeds for the period of a one-node seiche turned out to be the highest in the whole sea for all modes of resonance oscillations. So, maximum current speeds during seiches are comparable to and in some places may even exceed maximum speeds of wind currents.

In the White Sea tidal currents vary from 0.5 to 2.5 m/s depending on the sea part and play the dominant part in vertical mixing of waters. So, importance of seiches in functioning of its ecosystem is insignificant. Only in spawning areas seiche oscillations of sea level may lead to dying of young fish by increasing draining areas.

In the Sea of Azov, due to hyper-shallowness of the basin and presence of long narrow spits, a superposition of level rises (e.g. during surges) and seiche oscillations may lead to short-term catastrophic flooding of separate shore areas. Thus, it will be characterized by extremely fast currents in the flooding zone.

Conflict of Interest

There is no Conflict of Interest Statement in the Paper: Seiches in the semiclosed seas of the Continental Shelf by Yury Inzhebeikin.

Acknowledgement

This study was supported by the Russian Foundation for Basic Research, project no. 18-05-80010, Russian Academy of Sciences.

References

1. Gluhovskij B H (1991) Hydrometeorology and Hydrochemistry of the seas of the USSR. White Sea, Hydrometeorological conditions, Russia, 2(1): 240.

2. Simonov AI, Al'tman EN (1991) Hydrometeorology and Hydrochemistry seas of the USSR. Sea of Azov, Hydrometeorological conditions 4(1): 340.

3. Inzhebeikin YI (2005) The peculiarities of long-wave motions on the White sea. Oceanology 45(3): 332-338.

4. Matishov GG, Inzhebeikin Yu I (2009) Numerical Study of the Azov Sea Level Seiche Oscillations. Okeanologiya 49(4): 485-493.

5. Kurchatov IV (1925) Seiches in the Black Sea and the Sea of zov, Ed. Centre. Hydrometeorological Bureau, Moscow.

6. Manilyuk Yu V, Cherkesov L V (1995) Simulation of Seiche Oscillations in the Sea of Azov, Using the Finite Element Technique. Thermohydrodynamics of the Ocean 6(5): 325-329.

7. Platzman GT (1972) Two-Dimensional Free Oscillation in Nature Basin. J Phys Oceanogr 2(2): 117-138.

8. Shwab DJ, Rao DB (1976) Two-Dimensional Normal Modes in Arbitrary Enclosed Basins on Rotating Earth: Application to Lakes Ontario and Superior. Philos Trans R Soc 281A: 63-98.

9. Wubber C, Krauss W (1979) The Two-Dimensional Seiches of the Baltic Sea. Oceanol Acta 2(4): 748-755.

10. Greenberg DA (1979) A Numerical Model Investigation of Tidal Phenomena in the Bay of Fundy and Gulf of Maine. Mar Geod 2(2): 161-187.

11. Maramzin V L (1985) Calculations of Seiche Oscillations by the Method of Finite Elements in a Basin of Arbitrary Form," in Theoretical and Experimental Studies of Long-Wave Processes, Izd. DVNTs AN SSSR, Vladivostok, pp: 46-67.

12. Ivanov VA, Manilyuk Yu V, Cherkesov LV (1994) Seiches in the Sea of Azov. Meteorol Gidrol 6: 105-110.

13. Manilyuk Yu V, Cherkesov LV (1994) Mathematical Model Based on the Finite Element Technique is Applied to Study Seiche Oscillations in the Sea of Azov. Morsk Gidrof Zhurn 5: 3-8.

14. Le Blon P, Mysek L (1981) Ocean Waves, Mir, Moscow.

15. Matishov GG (2008) Climatic Atlas of Sea of Azov. IN: Matishov G, Levitus S, NOAA ATLAS NESDIS 65, U.S. Government Printing Office, Washington, DC, pp: 148.

16. Sielecki A (1968) An Energy-Conserving Difference Scheme for the Storm Surge Equations. Mon Weather Rev 96: 150-156.

17. Flather RA, Heaps NS (1975) Tidal Computations for Morecamble Bay. Geophys J R Astron Soc 42: 489-518.

18. Heaps NS (1972) On the Numerical Solutions for Tides and Storm Surges. Met Soc Roy Sci (Liege, Belgium) 2: 143-180.

19. Henry RF, Heaps NS (1976) Storm Surges in the Southern Beafort Sea. J Fish Res Board Can 33: 2362-2378.

20. Goryachkin Yu N, Ivanov VA, Repetin LN, Khmara TV (2002) Seiches in the Sebastopol Bay. Nauk Pratsi UkrNDGMz 250: 342-353.

21. Ivanov GS (1945) Fluctuations in the Sea of Azov Level Determined by Hydrometeorological Factors. Okl GOIN, No. 56: 1-11.

22. Kaminskii S T, Fedoseev VB (1975) Effect of Downward urrents on Seiche Formation in the Black Sea. Tr MGFI 1: 210-220.

23. Labzovskii NA (1994) Nonperiodic Sea Level Fluctuations Gidrometeoizdat, Leningrad, 1971) [in Russian to Study Seiche Oscillations in the Sea of Azov. Morsk Gidrof Zhurn 5: 3-8.

24. Mezinger F, Arakava A (1979) Numerical Methods Used in Atmospheric Models, Gidrometeoizdat, Leningrad.

25. Ramming HG, Kowalik Z (1980) Numerical Modellig of Marine Hydrodynamics. Application To Dynamic Physical Processes. Elsevier Oceanography Ser, Amsterdam, Oxford, New York.

26. Thorade H (1925) Seiches im Schwarzen und Asowschen Meer. Ann Hydrogr Marit Meteorol 53(10): 234-241.