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Original article

Study of Seiche Oscillations in the Sevastopol Bay System Based on Field Observations and Mathematical Modeling

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Abstract
Purpose. The purpose of the study is to determine the parameters of seiche oscillations with periods less than 1 hour and their actual mode composition in the system of interconnected bays located in the coastal zone of Sevastopol, based on *in-situ* sea level observations and mathematical modeling results.
Methods and Results. Three ultrasonic sea level gauges (developed and manufactured at Marine Hydrophysical Institute, RAS) were deployed in Gollandiya, Karantinnaya and Kruglaya bays for *in-situ* observations (with a measurement resolution of 10 s). The observations were conducted from July to December 2024. Spectral analysis of the obtained time series revealed peaks in the spectra at periods of 54, 48, 42, 29.7, 23, 17, 12.5, 11, 9.6, 6.8, 4.0 and 2.4 min, corresponding to the natural oscillations of the Sevastopol bays. A series of numerical experiments was carried out using the non-tidal linear version of the hydrodynamic model Advanced Circulation Model for Shelves Coasts and Estuaries (ADCIRC). The computational domain encompassed the entire system of bays and part of the adjacent coastal waters of Sevastopol. “Red noise” was applied as the forcing disturbance. Satisfactory agreement with the *in-situ* observation data was achieved. Analysis of the modeling results allowed investigation of interactions between the bays and interpretation of the field observation data.
Conclusions. The eigenmodes of elongated narrow bays readily penetrate into neighboring bays within the system of interconnected bays. The Helmholtz mode of Sevastopol Bay (period ~ 50 min) is prominent throughout the system and exhibits high intensity. The eigenmodes of Kruglaya Bay, which has a nearly circular shape, virtually do not penetrate into neighboring bays. The eigenmodes of larger bays are strongly represented in the neighboring smaller bays (Pesochnaya, Abramova) included in the system, with relatively high intensity.

Keywords: long-wave sea level oscillations, seiches in bays, coupled system of oscillations, Sevastopol bays, ADCIRC model

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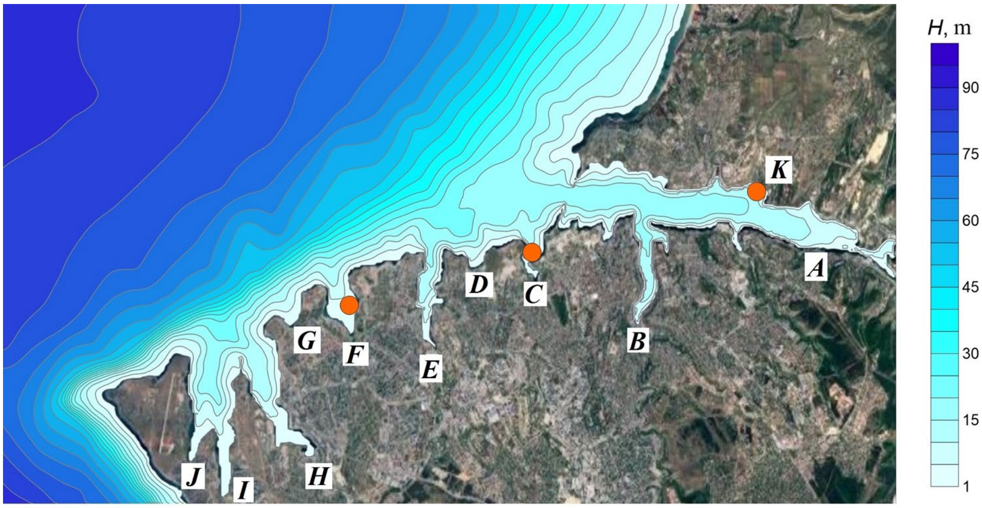
Introduction

A significant part of the territory occupied by Sevastopol includes a unique system of interconnected bays (Fig. 1) actively used in the city’s life. Sevastopol and Kamyshovaya bays accommodate ports for handling various cargoes and ship repair enterprises. Many bays in the system are protected from wind wave influence by hydraulic structures. However, these structures are not very effective for protecting the bays from long-wave disturbances penetrating from the open sea, which lead to the generation of seiche oscillations. Some inner Sevastopol bays are also equipped with protective structures. For example, as shown in [1], Mayachnaya Bay has a protective mole, but this does not save it from the impact of certain seiche modes of Sevastopol Bay, where they can reach high intensity and pose a danger to ships.



F i g. 1. Bathymetry of the study area. The bays are marked with Latin letters: A – Sevastopol, *B* – Yuzhnaya; *C* – Karantinnaya, *D* – Pesochnaya, *E* – Streletskaya, *F* – Kruglaya, *G* – Abramov, *H* – Kamyshovaya, *I* – Kazachia, *J* – Solenaya, *K* – Gollandiya. Orange markers indicate the positions of sea level gauges

Sevastopol bays form a system of interconnected water bodies; their interaction occurs at various temporal and spatial scales. This phenomenon has mainly been studied using the example of adjacent bays [2–5]. However, interaction also occurs for larger water bodies, as shown, for example, in [6]. The connection between bays leads to an expansion of the seiche modal composition due to the penetration of eigenmodes of adjacent bays into individual bays.

In partially enclosed water areas, there is a special type of oscillation – Helmholtz mode (zero, fundamental mode), analogous to the fundamental tone of an acoustic resonator, absent in enclosed water bodies. This mode has no nodal lines in the bay water area. As field observation data reveal, in bays and harbors with a narrow entrance, the Helmholtz mode usually dominates all other types of natural oscillations and determines the general nature of movements in the inner water area [7, p. 104].

The presence of a large bay in the system of interconnected bays, exceeding others in size, leads to its zero mode manifestation in all bays of the system. In [8], it is shown that the Helmholtz mode of Sevastopol Bay manifests itself with high intensity in Karantinnaya Bay, and according to [9], it is also observed in Kruglaya Bay. A similar pattern occurs at the island of Menorca (Balearic Islands), where the Helmholtz mode of Platja Gran Bay penetrates into the adjacent Ciutadella Bay and has high intensity there. This periodically leads to catastrophic consequences and hinders port operations [2].

The problems of seiche oscillations for complex water areas containing an outer harbor connected with the sea and an inner harbor [10] are of particular interest. Among Sevastopol bays, Dvoinaya Bay belongs to such type of water areas. It includes the inner Kazachia and Solenaya bays (Fig. 1).

Despite the importance of Sevastopol bays for the city's life, they remained poorly studied for a long time. There were only a small number of oceanographic studies [11–14] devoted to Sevastopol Bay. However, in recent years, through the efforts of staff of Marine Hydrophysical Institute (MHI), significant progress has been made in the study of Sevastopol bays, especially in the field of resonant oscillation research using mathematical modeling. Both modern numerical hydrodynamic models Advanced Circulation Model for Shelves Coasts and Estuaries (ADCIRC) [1, 8, 15] and Simulating WAves till SHore (SWASH) [9], as well as analytical solutions [16], were used; this provided sufficiently accurate estimates of the natural periods of real bays [15, 17]. The ADCIRC model is described in studies [1, 2], SWASH – in [18].

Field observations were previously performed extremely rarely. Most of them were carried out at the hydrometeorological post located at Cape Pavlovsky in Sevastopol Bay. The results of these observations are summarized in [11]. Field data on currents in Sevastopol Bay are given in [13, 14]. Significant progress has been achieved through the use of an inexpensive and highly efficient Ultrasonic Level Fluctuation Meter (ULFM), developed at MHI [9]. Previously, this device was successfully used for studying long-wave sea level oscillations in Kruglaya Bay [9].

This paper presents the results of processing *in-situ* observation data obtained using the MHI ULFM. The instruments were installed in Gollandiya Bay (part of Sevastopol Bay), Karantinnaya Bay, and Kruglaya Bay (Fig. 1), providing synchronous measurements. Such observations were conducted for the first time. Mathematical modeling based on the ADCIRC model was applied to interpret the observation results.

This work aims to determine the parameters of seiche oscillations and their actual modal composition in the system of Sevastopol bays, based on field observation data and mathematical modeling.

[1] Luettich, R. and Westerink, J., 2004. *Formulation and Numerical Implementation of the 2D/3D ADCIRC. Finite Element Model Version 44.XX*, 74 p. [online] Available at: http://adcirc.org/adcirc_theory_2004_12_08.pdf [Accessed: 10 August 2025].

[2] Luettich, Jr., R.A., Westerink, J.J. and Scheffner, N.W., 1992. *ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries. Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL*. Dredging Research Program. Technical Report DRP-92-6. Vicksburg, MS: U.S. Army Engineers Waterways Experiment Station, 137 p.

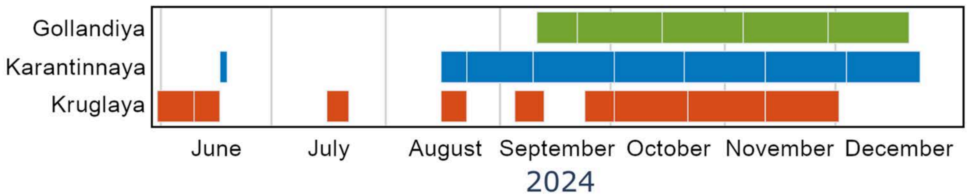
Materials and methods

Research object. Fig. 1 represents the system of Sevastopol bays and the bathymetry of adjacent water area. In the Sevastopol area, the shelf length is ~ 47 km. Its depth can be approximated by a linear dependence $h(x) = \alpha x$, where α = 0.00426. The resonant periods of such a shelf are calculated using the formula from [7, p. 183]:

$$T_n = 8\sqrt{L} / \left(n\sqrt{g\alpha}\right),$$

where L is shelf width; n = 1, 3, 5 ... is a number of mode; g is gravitational acceleration.

Sea level observations. Sea level fluctuation observations were carried out from June to December 2024 (Fig. 2). For this purpose, MHI ULFM meters were applied. The tide gauge is an acoustic rangefinder based on the widely used JSN-SR04 sensor. The sensor is controlled by an Arduino Pro Mini microcontroller, which is responsible for initiating the probing pulse, measuring the return time of the echo signal, and recording the measurement result (an integer value in microseconds) on a memory card. The pulse repetition frequency is 10 Hz. In the absence of a reflected signal, a zero value is recorded. The charge of six lithium-ion batteries used for power is sufficient for 21 days of operation. To compensate for errors associated with changes in the speed of sound, primarily caused by temperature fluctuations, an additional measurement channel (a second similar transceiver) is provided. This channel measures the time for a pulse to travel to a stationary target located at a distance of 0.7 m from the transceiver and back. Simultaneously, the air temperature is recorded on each measurement cycle by an external sensor.



F i g. 2. Diagram of measurement data availability

The resolution of ULFM meter in range is determined by the accuracy of measuring the time of flight (1 μs), which is equivalent to ~ 0.2 mm in distance (considering the speed of sound in air to be 340 m/s). The random error of the initial measurements, estimated from test measurements of the distance to a stationary smooth surface, turned out to be approximately 100 times greater, ~ 2 cm. At the post-processing stage, the average sea level value over one minute was calculated, which significantly reduced the random error. Before averaging, unsuccessful (zero) readings corresponding to cases where the reflected signal was not recorded against the background noise were discarded. If the proportion of successful measurements was less than 10%, such an averaged value was discarded, and the average value was interpolated from neighboring points (such measurements in the overall statistics are negligible, < 0.25%). Thus, for calculating the average, at best no more than 600 correct readings were used and at worst – no less than 60. The statistical error of the mean of a normally distributed quantity is $\sqrt{N}$ times (where N is a number of correct readings) less than its standard deviation. This provides an average level error no better than 0.8 mm (with a full set of 600 readings) and no worse than 2.5 mm (with 60 measurements). The latter value can be interpreted as the final error of the analyzed one-minute average sea level series. A detailed description of the device is given in [9].

Sea level observations were performed in Gollandiya, Karantinnaya, and Kruglaya bays for half a year (Fig. 1). However, due to technical problems (damage to sensors during a storm, inability to replace batteries in time), a continuous series of simultaneous measurements at all points covers only 39 days (from September 12 to November 2, 2024). This period was used for subsequent analysis.

Methods for processing *in situ* observation data. Time series of one-minute averaged sea level were studied by standard methods of spectral analysis. In particular, we used the Welch method to estimate the power spectra of sea level fluctuations. The time series was divided into fragments of 234 hours duration (corresponding to a quarter of the length of the entire series, spectral resolution 0.0042 1/h), overlapping each other by half the duration. To supress spectral "leakage" (to suppress side lobes associated with the finite fragment duration), a Hann window was applied; it was multiplied by each fragment of the record, after which the Fast Fourier Transform was calculated. The power spectrum estimate was obtained by averaging the square of the modulus of the Fourier transforms, $S_{xx} \sim < FFT\left(x(t)\right) conj\left(FFT\left(x(t)\right)\right) >$, where x is a fragment of the time series, FFT is the Fast Fourier Transform operator, angle brackets indicate averaging over fragments.

For shorter model time series, the fragment duration corresponded to the entire recording length (6 h) to ensure the highest possible frequency resolution (0.167 1/h).

Similarly, cross-spectra of time series in three possible bay combinations were calculated: Gollandiya – Karantinnaya, Gollandiya – Kruglaya, Karantinnaya – Kruglaya, $S_{xy} \sim < FFT\left(x(t)\right) conj\left(FFT\left(y(t)\right)\right) >$, where x and y are fragments of time series in a pair of bays, the complex amplitude angle S_{xy} corresponds to the phase difference between two signals.

Numerical hydrodynamic model and numerical experiment scheme. Numerical experiments were based on the hydrodynamic finite element model ADCIRC [1, 2] [19]. A version of the model based on depth-averaged linearized equations of motion in the long-wave approximation was applied. Since the seiche periods in Sevastopol bays do not exceed 1 h, Earth's rotation was not taken into account. In this case, the system of equations takes the following form:

$$\frac{\partial U}{\partial t}+g\frac{\partial \zeta}{\partial x}=A_h\frac{\Delta q_x}{H}, \quad \frac{\partial V}{\partial t}+g\frac{\partial \zeta}{\partial y}=A_h\frac{\Delta q_y}{H}, \quad \frac{\partial \zeta}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0.$$

Here U, V are depth-averaged components of the current velocity vector along the x and y axes respectively; ζ is sea level; $H = h + \zeta$ is dynamic depth; Δ is the Laplace operator in spatial variables; A_h is the coefficient of horizontal turbulent viscosity; $q_x = UH$, $q_y = VH$ are components of the total flow vector.

The ADCIRC model numerical algorithm is based on the finite element method using triangular elements and linear basis functions. To reduce the computational noise level during numerical integration of the original system, the continuity equation is represented in the form of the Generalized Wave Continuity Equation (GWCE) [2]. The computational noise level in GWCE is regulated by the parameter τ_0. In the calculations performed in this study, $\tau_0 = 0.005$.

The calculations were carried out in two stages. In the first stage, lasting for 6 hours of model time, wave generation was carried out by feeding a "red noise" type disturbance [20] into the computational domain through its liquid boundary:

$$\zeta_b = \begin{cases} \zeta_p, & t \le t_p, \\ 0, & t > t_p, \end{cases}$$

where $\zeta_p(x,y,t)$ is a random function with a "red" noise spectrum; t_p is the time interval duration of disturbance action.

In the second stage, lasting for 6 hours of model time, the problem of free oscillations with initial conditions obtained in the first stage of calculations was solved. A free wave passage condition was set at the liquid boundary of the computational domain. At the solid boundaries of the computational domains, an impermeability condition was set. The calculated series of sea level oscillations at control points were subjected to spectral analysis. Scripts presented in work [3] were employed. Using the Fourier transform, energy spectra of level oscillations were obtained, resulting in the determination of the most energy-carrying periods.

Two numerical experiments were performed. In the first one, the computational domain represented the water area of individual bays (Sevastopol, Karantinnaya, and Kruglaya), with the liquid boundary located across the bay entrances. This approach allows to obtain the natural periods of the bays determined by their shoreline profile and bathymetry without accounting for the connection between the bays. In the second numerical experiment, the computational domain, according to [15], included all bays and a part of the coastal zone in the form of a sector with a radius of 8 km. The mesh was refined in the bays (lengths of triangle sides here were ~ 50 m), time integration step $\Delta t = 0.025$ s, $A_h = 3$ m^2/s, bottom friction coefficient

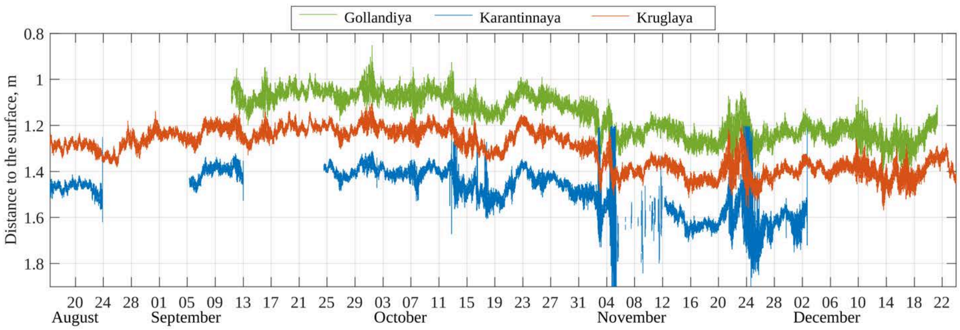
[3] Winde, H.P., 2012. *Wave Height from Pressure Measurements*. Bachelor Thesis. Delft University of Technology, 49 p. [online] Available at: https://resolver.tudelft.nl/uuid:e3b07efd-1ce9-4fd1-b051-c794c72959ca [Accessed: 12 December 2024].

$C_d = C_0\left[1+\left(H_b/H\right)^{\alpha}\right]^{\beta/\alpha}$, where $C_0 = 0.0025$, $\alpha = 10$, $H_b = 1$ m, $\beta = 1/3$. The values of all the aforementioned coefficients were chosen by recommendations outlined in studies [1, 2].

With this approach, it is possible to obtain a comprehensive picture of seiche oscillations, taking into account the interconnections between the bays in the system.

Results and discussion

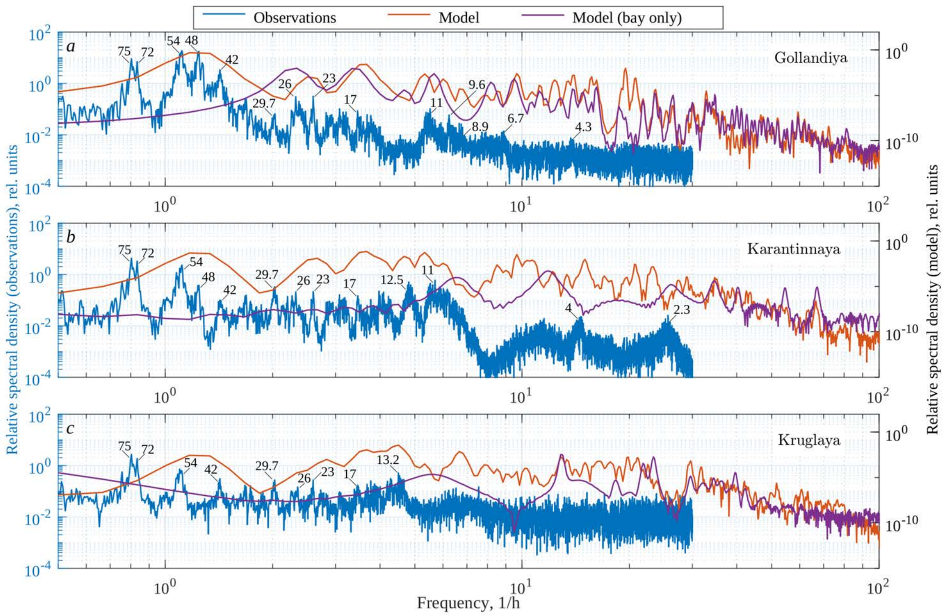
Modal composition of level oscillations and resonant periods. Time diagrams of the measured distance from the sensor to the sea surface, simulating tide gauge records, are given in Fig. 3. It can be seen that on time scales exceeding several days, the sea level oscillation records demonstrate a high degree of consistency.



F i g. 3. Time diagrams of the measured distance from a sensor to the sea surface for three stations. Time scale is calibrated in days, data averaging is 1 min

In this study, we will limit our analysis to sea level oscillations in the period range up to one hour, as these mainly correspond to the natural modes of the Sevastopol Bay system. Fig. 4 presents graphs of spectral density, Fig. 5 shows the phase difference between spectral components of level oscillations. As can be seen from Fig. 4, there is satisfactory correspondence for the resonant peaks obtained from observation and modeling data.

In the low-frequency region, according to observation data (Fig. 4), intense peaks at periods of 75, 54, 48 and 42 min are distinguished at all stations. The presence of an oscillation with 75 min period in Sevastopol Bay is indicated in [11]. This mode was not identified during mathematical modeling for the Sevastopol Bay system, and it can be attributed to high-frequency global seiches of the Black Sea water area. Oscillations with periods of 54, 48 and 42 min are due to the presence of Sevastopol Bay in the bay system. As the results of study [21] show, in coupled bays both antiphase and in-phase oscillations with periods close to the natural period of one of the bays can exist. Moreover, the period of in-phase oscillations is greater than the bay natural period, and that of antiphase oscillations is less than the specified period.



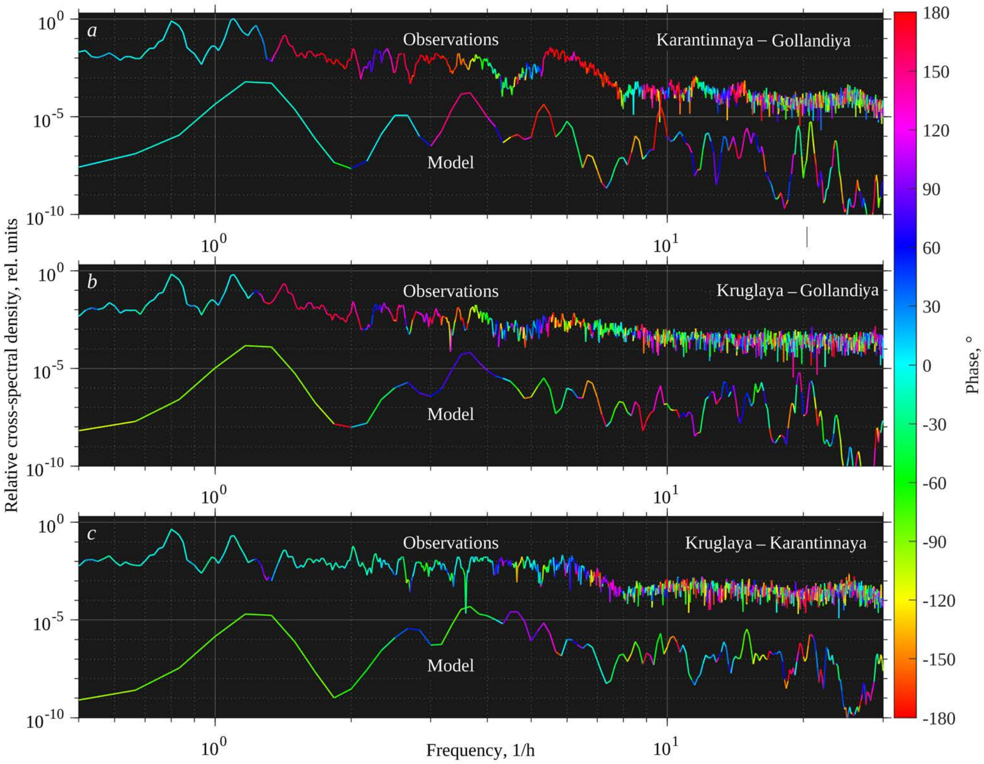
F i g. 4. Spectral density of sea level fluctuations in the Sevastopol bays calculated both for the whole system of Sevastopol bays and for the individual ones based on *in situ* observations and modeling results. Periods in minutes are indicated above the peaks

According to theoretical estimates from [22], the period of the zero mode (Helmholtz mode) of Sevastopol Bay is ~ 50 min. From Fig. 5 it can be seen that, according to observation data, sea level oscillations with 54 min period in Kruglaya and Karantinnaya bays are in-phase with oscillations in Gollandiya Bay, and oscillations with 42 min period are antiphase. It can be concluded from this fact that, due to the connection between bays, the Sevastopol Bay zero mode manifests itself in Karantinnaya and Kruglaya bays in the form of in-phase or antiphase oscillations. Also, in Gollandiya and Karantinnaya bays (which are closely adjacent to Sevastopol Bay), there are level oscillations with 48 min period, absent in Kruglaya Bay. Apparently, this occurs when the connection between the bays of the system is weak. Calculations based on the model reveal (Fig. 4) the presence of an intense peak at ~ 50 min period in all three considered bays, indicating the penetration of Sevastopol Bay Helmholtz mode into Karantinnaya and Kruglaya bays with high intensity.

According to observation data (Fig. 4), a peak at 29.7 min period is distinguished. It is not identified through modeling, so it can presumably be associated with the fifth mode of shelf seiches, which has 28 min period.

In the mid-frequency region of seiches, intense peaks at periods of 17, 12.5, 11, 9.6 min are recorded in all considered bays according to observation and modeling data (Fig. 4). The peak at 17 min period corresponds to the natural mode of Sevastopol Bay. The belonging of this mode to the mentioned bay is confirmed by Fig. 5, from which it can be seen that this oscillation is absent between Kruglaya and Karantinnaya bays and has an antiphase character (characteristic of seiches) between Gollandiya Bay and Kruglaya and Karantinnaya bays.

Interestingly, the natural mode of Sevastopol Bay with 12.5 min period is more intense in Karantinnaya Bay than in Sevastopol Bay. The presence of a peak at ~ 11 min period is due to the zero mode of Karantinnaya Bay. Level oscillations between Gollandiya and Karantinnaya bays have an antiphase character at this period (Fig. 5). We should also note that modeling and observation data record the Helmholtz mode manifestation in Kruglaya Bay with ~ 13.5 min period, which is not distinguished in adjacent bays.



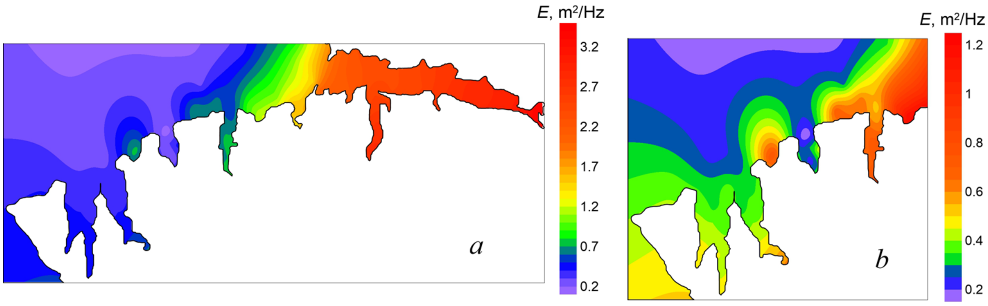
F i g. 5. Cross-spectrum modulus in the following pairs of bays: Gollandiya – Karantinnaya (*a*), Gollandiya – Kruglaya (*b*), and Karantinnaya – Kruglaya (*c*). Phase difference between the spectral components is indicated by color

Among the high-frequency seiche modes in Gollandiya Bay, there is a natural mode of Sevastopol Bay with 6.8 min period, as well as a natural mode of Karantinnaya Bay with ~ 4.0 min period (Fig. 4). In Karantinnaya Bay, its natural modes with 4.0 and 2.4 min periods are distinguished.

The Table presents periods of seiche oscillations in the largest Sevastopol bays resulted from mathematical modeling and field observation data. Here T_0, T_1, T_2, T_3, T_4 are periods of natural oscillations of Sevastopol Bay (values are given for the Gollandiya Bay area) and Yuzhnaya, Karantinnaya, Streletskaya, and Kruglaya bays. The indicated periods of the studied bays are known from [15], where they were obtained using analytical solutions according to formulas for rectangular basins with an open entrance of constant depth, as well as with a parabolic bottom profile. "Alien" periods A_1, A_2, A_3, A_4, A_5 are the ones of natural modes that penetrate from neighboring bays and the coastal zone. In the table they are arranged in order of decreasing oscillation energy.

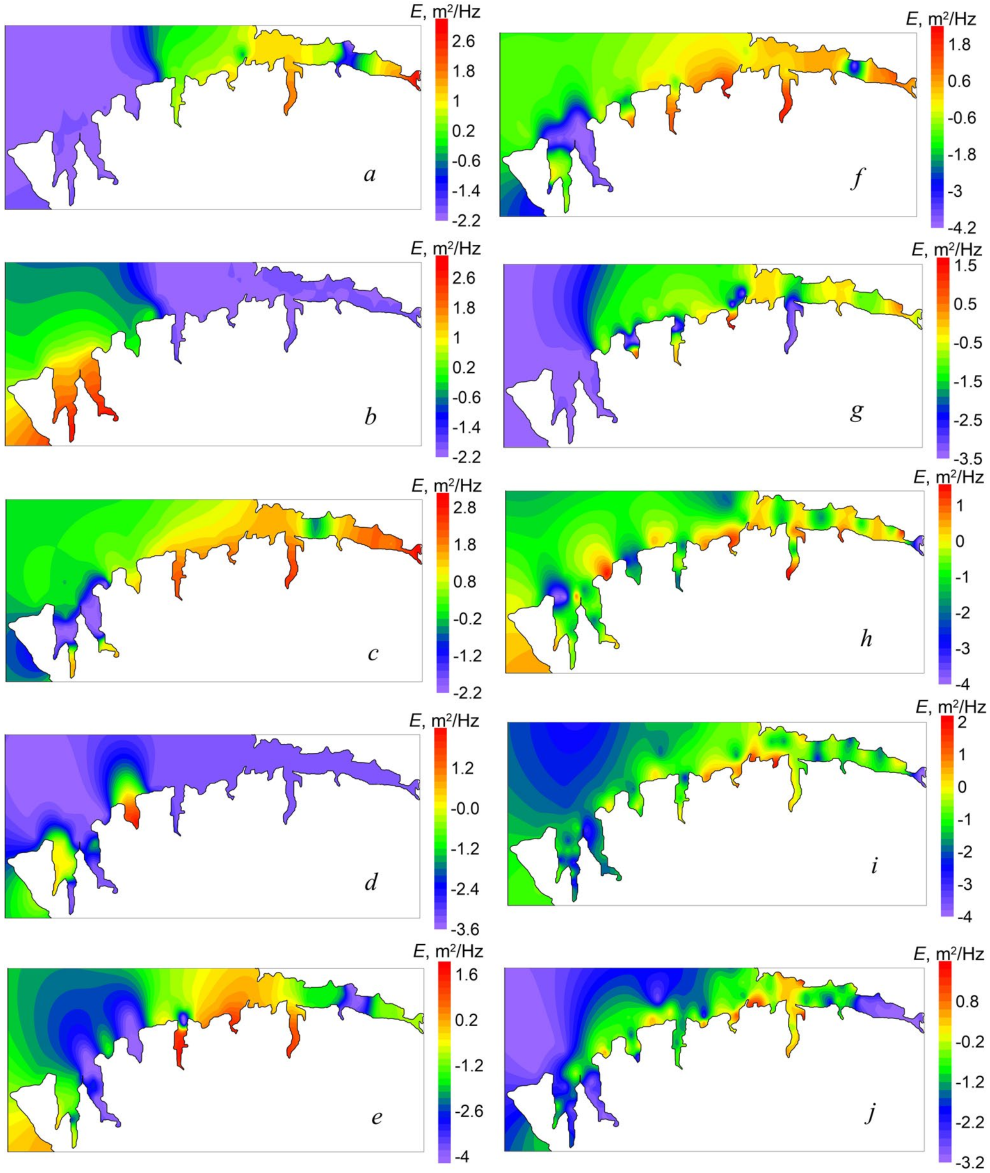
Periods of seiche oscillations in the largest Sevastopol bays resulted from mathematical modeling and *in-situ* observation data

Bay	Eigenperiods (mathematical modeling results / *in-situ* data), min					"Alien" periods, min				
	T_0	T_1	T_2	T_3	T_4	A_1	A_2	A_3	A_4	A_5
Sevastopol Bay (including Gollandiya)	51.4 / 54.0	22.5 / 23.0	16.4 / 17.0	10.0 / 9.6	6.1 / 6.7	11.3	3.0	4.3	2.8	3.8
Yuzhnaya	16.4	4.3	2.8	2.2	–	51.4	11.3	22.5	6.1	12.9
Karantinnaya	11.3 / 11.0	4.0 / 4.0	2.6 / 2.3	–	–	16.4	51.4	6.1	12.9	22.5
Streletskaya	12.9	4.4	2.8	–	–	16.4	14.4	11.3	51.4	22.5
Kruglaya	13.3 / 13.2	4.6	2.8	–	–	16.4	9.0	51.4	4.4	21.2
Kamyshovaya	21.2	6.9	4.4	2.7	–	10.3	16.4	3.6	9.2	51.4



F i g. 6. Spatial distribution of the spectral density of sea level oscillations (period is 51.4 min) in the Sevastopol bays based on the results of numerical modeling for the whole system of Sevastopol bays (*a*) and for the ones remote from Sevastopol (*b*)

From the Table and Figs. 4, 5 it can be seen that Sevastopol Bay has a significant influence on all bays of the system. At the same time, these bays also affect Sevastopol Bay. In particular, due to the connection between bays, the natural modes of Karantinnaya Bay (with 11.0 and 4.0 min periods) and Streletskaya Bay (with 4.4 min period) penetrate into Sevastopol Bay with high intensity. As for bays more remote from Sevastopol Bay, the wavelengths of their natural modes are relatively small compared to the distance to Sevastopol Bay, so upon exiting the bays they attenuate quite quickly, not reaching the water area of Sevastopol's main bay. Note that all bays of the system interact with each other to one degree or another. Natural modes of Streletskaya Bay (with 4.4 min period) and Kamyshovaya Bay (with 7.5, 21.2 min periods) penetrate into Kruglaya Bay, and the natural mode of Karantinnaya Bay (with 11.0 min period) penetrates into Streletskaya Bay. Analysis of calculation results revealed that in the small Abramova and Pesochnaya bays the natural modes of larger adjacent bays are widely represented.



F i g. 7. Spatial distribution of the spectral density of main energy-carrying oscillations of sea level in the Sevastopol Bay system with periods 22.5 min (*a*); 21.2 min (*b*); 16.4 min (*c*); 13.3 min (*d*); 12.9 min (*e*); 11.3 min (*f*); 10.0 min (*g*); 6.1 min (*h*); 4.0 min (*i*); 2.8 min (*j*)

Spatial structure of the main seiche modes of the Sevastopol bay system. Fig. 6 represents the spatial distribution of spectral density of level oscillations with 51.4 min period in the Sevastopol bay system obtained through numerical modeling. The specified period corresponds to the Helmholtz mode of Sevastopol Bay. It can be seen that the oscillation energy is maximum in Sevastopol and Karantinnaya bays. At the same time, this mode is present in all other bays of the system but in the bays most remote from Sevastopol one (Kamyshovaya and Dvoinaya) its intensity is noticeably weaker. Note that this oscillation also occurs in the small Pesochnaya and Abramova bays.

The spatial distribution of spectral density of level oscillations of other most energy-carrying periods, identified on the basis of processing the mathematical modeling results, is given in Fig. 7.

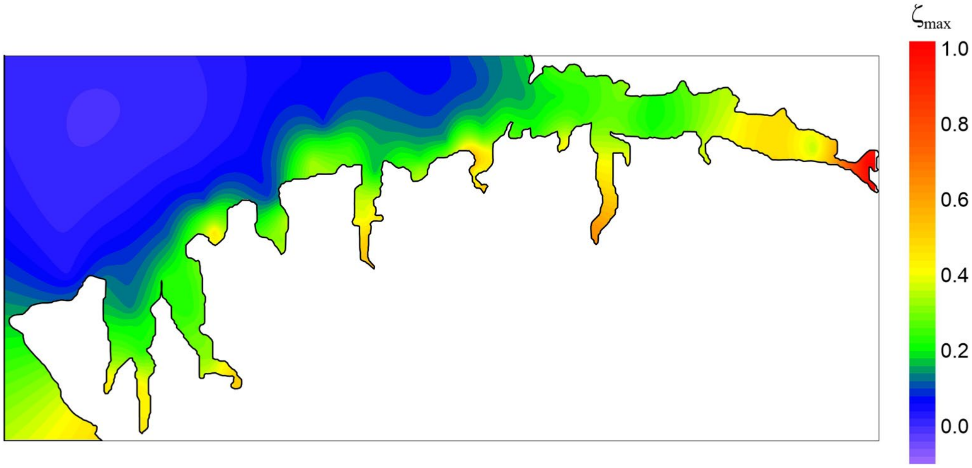
Oscillations with 22.5 min period (Fig. 7, *a*) are most intense in Yuzhnaya Bay and at the head of Sevastopol Bay; this period corresponds to the first mode of Sevastopol Bay. The period of 21.2 min (Fig. 7, *b*) is the natural period of Kamyshovaya Bay, and it also manifests itself with high intensity in Dvoinaya Bay. The periods 22.5 and 21.2 min are close in value, so the corresponding modes can enhance each other.

Periods 16.4, 12.9, 10.0, 6.1 min are due to the presence of Sevastopol Bay in the bay system. As can be seen from Fig. 7 *b*, *d*, *f*, *h*, these modes are noticeably pronounced in most bays of the system.

The period of 13.3 min (Fig. 7, *d*) belongs to the Helmholtz mode of Kruglaya Bay. Due to the specific shape of this bay's water area, the oscillation energy is weakly radiated into the open sea and practically does not manifest itself in the bays of the system.

The period of 11.3 min (Fig. 7, *e*) corresponds to the Helmholtz mode of Karantinnaya Bay, which manifests itself with high intensity in all bays of the system, except for Kamyshovaya Bay. This also applies to another natural mode of Karantinnaya Bay, with a period of 4.0 min (Fig. 7, *g*).

Fig. 8 represents the spatial distribution of relative (normalized to the maximum value) amplitudes of seiche level oscillations in the bays, generated by the "red" noise impact and containing all the modes considered above. It can be seen that the largest amplitude values occur at the heads of the bays, with a maximum in the main one – Sevastopol Bay.



F i g. 8. Spatial distribution of the relative amplitudes of seiche sea level fluctuations in the Sevastopol Bay system

Conclusion

Long-term (more than 7 months) observations of level oscillations were carried out in Gollandiya Bay (located in Sevastopol Bay), Karantinnaya, and Kruglaya bays, which are part of the Sevastopol Bay system. However, the continuous, concurrent dataset suitable for analysis was constrained to 39 days (12 September – 2 November 2024) due to adverse weather and technical issues. This period was therefore selected for detailed analysis. To interpret the field observation data, mathematical modeling of seiche oscillations was performed based on the ADCIRC model.

Analysis of level oscillations and mathematical modeling results made it possible to identify the following most energy-carrying periods of long-wave oscillations (up to 1 h) in the Sevastopol Bay system: 54, 48, 42, 29.7, 23, 17, 13.2, 12.5, 11.0, 9.6, 6.8, 4.0 and 2.4 min.

Sevastopol bays actively interact with each other through connections at their entrances, thereby expanding the modal composition of seiche oscillations in the bays. The largest, Sevastopol Bay, has a significant effect on all bays of the system, but adjacent bays also affect it. According to observation data, the Helmholtz mode of Sevastopol Bay penetrates with high intensity into Karantinnaya and Kruglaya bays in the form of antiphase oscillations with 42 min period and in-phase oscillations with 54 min period. The mathematical modeling results reveal the presence of a powerful peak at ~ 50 min period in all bays of the system. Other natural modes of Sevastopol Bay with periods of 23, 17, 12.5 and 9.6 min are also distinguished according to observation data in Karantinnaya and Kruglaya bays; according to modeling data, they are distinguished in all bays of the system.

The Helmholtz mode of Karantinnaya Bay with ~ 11 min period manifests itself with high intensity in Gollandiya Bay.

The Helmholtz mode of Kruglaya Bay, with 13.3 min period, is identified from observation and mathematical modeling data, while this mode practically does not penetrate into adjacent bays.

The natural modes of elongated narrow bays easily penetrate into neighboring bays. The natural modes of Kruglaya Bay, which has a nearly circular water area, practically do not penetrate into adjacent bays.

In the small bays of the system (Pesochnaya, Abramova), the natural modes of larger neighboring bays are widely represented, having a fairly high intensity.

In general, the results obtained through numerical modeling agree reasonably well with field observation data. They made it possible to obtain the spatial structure of level oscillations of the entire system of interconnected Sevastopol bays.

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