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Original article

Sea Level Oscillations in the Adjacent Bays – Trade Port and Kholmsk-Severny (Sakhalin Island)

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Abstract
Purpose. The paper is purposed at studying long-wave processes in Kholmsk bays and on the adjacent shelf (including the interaction of bays) based on the theoretical concepts and the data of sea level field observations obtained in September 2022 – May 2023.
Methods and Results. Three autonomous wave meters ARW-14 K installed in the bays of Trade Port and Kholmsk-Severny, as well as on the shelf at an insignificant distance from the bays were used for observations. The measurement discreteness was 1 second. The time series both including the tides and without them were studied based on the spectral analysis using the Kyma program. Within the range of wave periods 1–30 h, the wave processes of a non-tidal origin and with the periods 1.6–6.7 h were found. They can be attributed to the shelf seiches, the Poincaré waves or the Tatar Strait seiches. Spectral analysis in the period range 1–10 min has shown the presence of seiches with the periods 1.83–8.17 min in Trade Port Bay and those with the periods 1.32–8.65 min in Kholmsk-Severny Bay.
Conclusions. It is established that in course of the whole series of field observations, the coupled oscillations at the periods ~ 8 min took place in the above-mentioned bays. These oscillations correspond to the Helmholtz mode of Kholmsk-Severny Bay. They are induced in this bay and then transmitted to Trade Port Bay due to interaction. At different times they had both in-phase and anti-phase spatial structures. During the periods of high eigen modes the interaction between the bays was not detected. Besides, the spectral analysis of the sea level oscillations under study made it possible to reveal the beats with a period 4.82 h (289.2 min), resulting from the interaction of modes with the close periods equal to 8.17 and 8.65 min. The stated facts, as well as correspondence of the distance between the bays' inlets to the proposed earlier interaction condition criterion allow us to assert that the coupled oscillations are present in two adjacent bays – Kholmsk-Severny and Trade Port.

Keywords: sea level oscillations, seiches, Poincaré waves, coupled oscillation system

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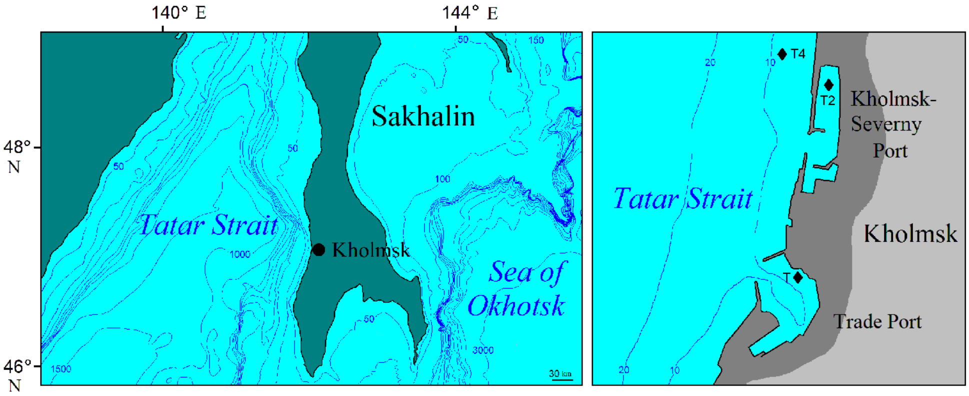
Introduction

Climate changes occurring in recent decades and accompanied by increased atmospheric disturbances and an increase in their duration require regular sea level observations in order to obtain an up-to-date understanding of the processes taking place in the coastal zone, especially in the areas where seaports are located.

Trade and Kholmsk-Severny ports are located in the bays of Kholmsk (Sakhalin Island); they are important not only for the city, but also for the entire island (Fig. 1). A connection with the mainland is held through Trade Port by the Vanino-Kholmsk ferry crossing by means of which a large volume of various cargoes is transported. The water areas of the bays adjacent to the ports are protected well from wind waves by hydraulic structures of various types [1]. However, for long-wave oscillations coming from the sea, such protection is ineffective. This type of oscillations, in particular, includes tidal ones, which have harmonics with periods from days to several hours [2]. The source of long-wave disturbances can be two fundamentally different types of processes leading to the formation of long waves – anemobaric (AB) and infragravity (IG) ones [3]. Anemobaric waves are generated due to the effect of atmospheric pressure and wind fluctuations on the sea surface, as well as level oscillations caused by the energy dissipation of large-scale long-wave formations such as meteorological tides or storm surges on heterogeneities of the relief and coastline. Infragravity waves arise from the nonlinear interaction of wind waves or large swells. Characteristic periods of AB waves lie in the range from several tens of seconds to several hours, and IG waves – in the range of 30–300 s. Penetrating onto the shelf and into the internal waters, these waves induce resonant seiche oscillations there.



F i g. 1. Maps of the region and the water area near Kholmsk showing locations of device installations marked with black diamonds

A peculiar feature of Kholmsk is presence of two closely spaced bays of comparable size (the distance between inlets is ~ 1 km) with a coupled system of oscillations (Fig. 1). Such an oscillatory system can be interpreted as two coupled oscillators. The paper [4] describes a study using a laboratory setup of water oscillations in two connected bays of equal sizes. It is demonstrated that due to the connection, the oscillations arising in one bay are transmitted to the neighboring one. In addition, the resonant periods of the bays vary due to the connection; the occurrence of both in-phase and anti-phase oscillations, as well as beats, is possible.

Seiches in adjacent real bays have recently aroused great interest among researchers, since this topic, in addition to scientific, has practical significance. Thus, the works [5–8] describe seiches in adjacent bays located in different regions of the World Ocean. However, these works consider bay systems that include a bay that is larger than the others. Kholmsk bays are almost equal in size; their interaction has not yet been studied.

The purpose of this paper is to study, based on theoretical concepts and data from field observations carried out recently, long-wave processes in the bays of Kholmsk and at the adjacent shelf, including the study of interaction of these bays.

Materials and methods

Object of study. The water areas of Kholmsk bays are demonstrated in Fig. 1. According to the website http://retromap.ru/1419537_z7_46.335550,142.22351&h=0, the parameters of the bays are as follows: Kholmsk-Severny Port – total length is 1008 m, length to the southern partition is 816 m, wide part length is 890 m, northern part length is 513 m, width at the inlet between the external piers is 221 m, width of the bay inlet is 139 m, average depth is 6.2 m; Trade Port – length to the ferry berth is 732 m, length from the bay inlet to the wall is 556 m, width is 422 m, narrow apex width is 109 m, its length is 350 m, bay inlet width is 174 m, average depth along the fairway is 6.5 m. The distance between the centers of the inlets to the bays is 1045 m.

The Tatar Strait near Kholmsk is generally characterized by a relatively weak manifestation of frequency-selective properties of the water area determined by topography: the shelf near Kholmsk is the narrowest and deepest off the western coast of Sakhalin, it expands both in the southern and in the northern directions. The shelf width in the Kholmsk area is ~ 40 km, the bottom slope is 0.0078.

Sea level observations. Sea level observations were carried out from September 2022 to May 2023 using three autonomous ARW-14 K wave meters: T meter (serial number 152), T2 meter (serial number 142) and T4 meter (serial number 149) (Fig. 1). The fourth device was also installed in the sea at an isobath of 4 m opposite the inlet of Kholmsk-Severny Bay, but it turned out to be faulty. Accuracy of bottom hydrostatic pressure measuring, which was subsequently converted into sea level oscillations taking into account the attenuation of short waves with depth, is 0.06% of the full scale of measurement and the pressure resolution is equal to ±0.0003% of the full scale of measurement. Discreteness of sea level and temperature measurements is 1 s.

Methods for processing data from field observations. Spectral analysis, filtering, tide subtraction and visualization of results and time series were performed using Kyma software, designed for complex processing and analysis of large-scale sea level data [1] [9]. The program enables to calculate the spectral density of oscillations for a selected time series using the usual windowed Fourier transform.

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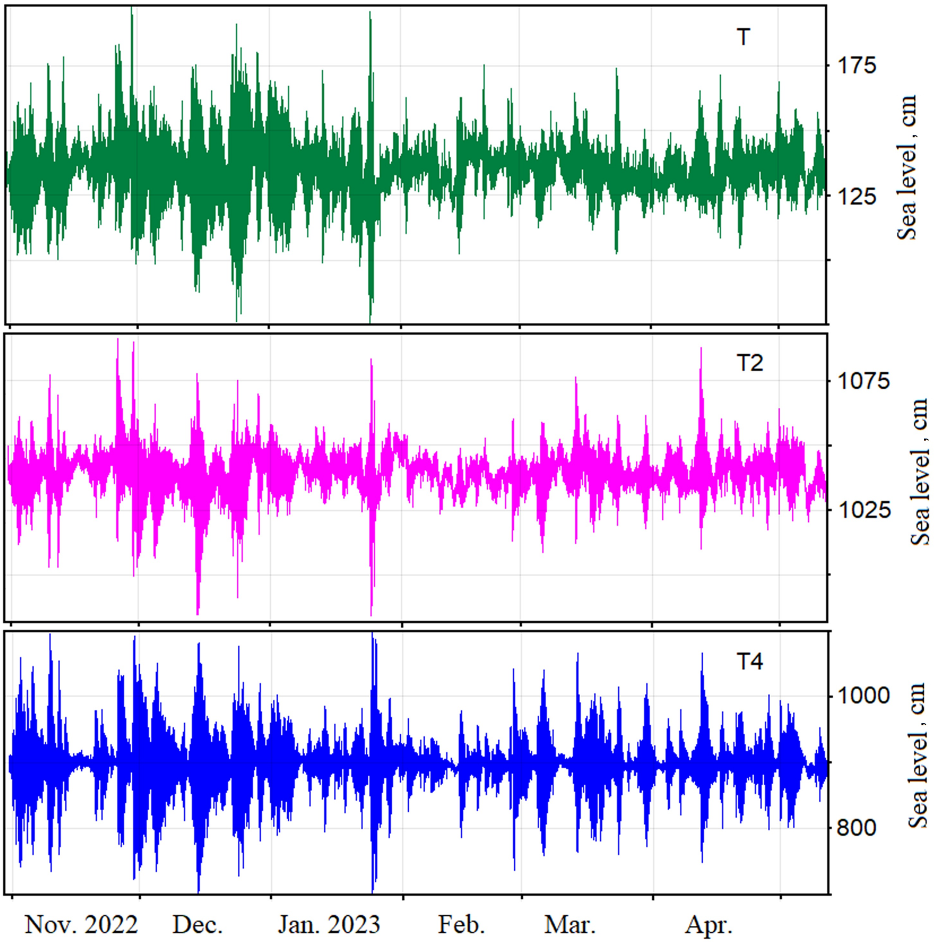
[1] Kovalev, D.P., 2018. *Kyma. PC Software.* Yuzhno-Sakhalinsk: IMGiG FEB RAS. State Registration No. RU2018618773 (in Russian).

The time series is divided into $(2n/w) - 1$ windows, where n is time series length, w is window size; the next segment of the time series is selected with a shift of half the length of the window. Filtration is carried out over each segment using the Kaiser–Bessel window (filtering can be disabled). For each window, the Fourier transform is then calculated for a predefined number of frequencies, starting at a given frequency. After calculating spectral parameters for each window, the average value between them is calculated.



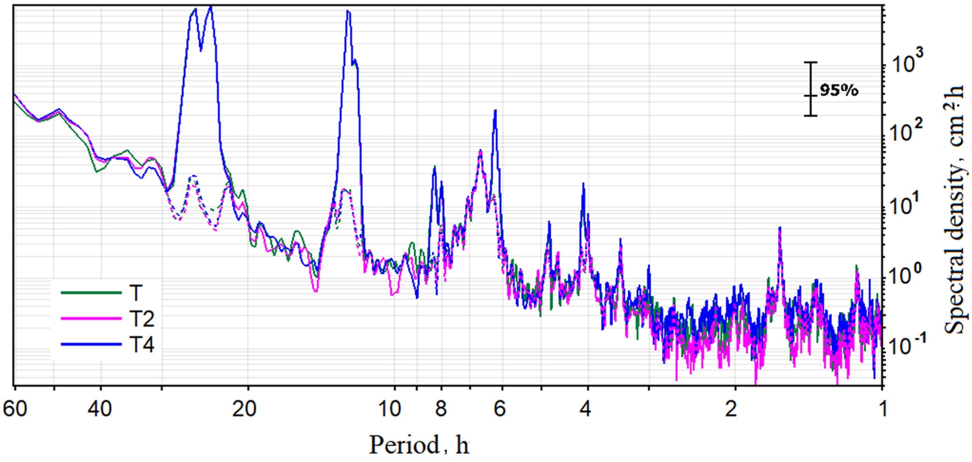
F i g. 2. Recorded time series of sea level oscillations from which the precalculated tide is subtracted. Here and in other figures, the device locations are shown: device T is installed in Trade Port Bay, T2 – in Kholmsk-Severny Bay, and T4 – in the Tatar Strait (on the shelf)

As a result of the observations, long-term time series of sea level variations were obtained. To analyze seiche oscillations, the precalculated astronomical tide was subtracted from the time series. Calculation of tidal harmonics and their subtraction from the original time series is performed with the help of 35 astronomical harmonics using LSMTM.exe application in the Kyma program. LSMTM.exe algorithm uses the least squares method, which was developed by A.B. Rabinovich and G.V. Shevchenko in the 70s of the 20th century. It has been tested several times and has shown good results in calculating tides. The time series with subtracted precalculated tide are given in Fig. 2.

Results and discussion

Using the time series obtained as a result of sea level observations and the Kyma program, spectral densities of level oscillations were calculated over the entire length of the time series. Since, as further studies showed, wave processes with periods of > 8 min were observed in the bays and they could not be seiches of the bays themselves; it is of interest to consider the range of wave processes for longer periods. In addition, it is necessary to separate tidal harmonics from seiches and other types of waves for the analysis.

Long-period tidal sea level oscillations. Spectral densities of sea level oscillations for time series with tide and series from which the precalculated tide is subtracted are shown in Fig. 3. This makes it possible to determine which peaks correspond to tidal harmonics and which – to other wave processes.



F i g. 3. Spectral densities of sea level oscillations for the time series with a tide (solid lines), and for the series from which the precalculated tide is subtracted (dashed lines)

The periods of maxima in the spectral densities of sea level oscillations are given in Table 1. This table also compares the values of the obtained periods and similar values of the periods of tidal harmonics according to the monograph [2]. Spectral peaks that do not have periods close to tidal harmonics can be attributed to wave processes of a different, non-tidal nature.

Table 1

Periods of wave peaks in spectral densities of sea level oscillations and corresponding tidal harmonics

Components of sea level oscillations	Period, h												
Inclusive of tide	24.7	23.8	12.4	12.0	8.12	8.00	–	6.22	–	4.1	4.0		
Not inclusive of tide	–	–	–	–	–	–	6.67	–	4.82	–	–	3.43	1.62
Tidal harmonic [2]	M_1	K_1	M_2	S_2	MK_3	SP_3	–	SO_4	–	$2MS_6$	M_6		

Long-wave processes of non-tidal nature. It can be seen from Table 1 that in the bays of Kholmsk and the adjacent area of the open sea the wave processes of a non-tidal nature with periods of > 1 h take place. The class of such waves includes Poincaré waves and shelf seiches.

Poincaré waves. Continuous spectra of the radiated waves (Poincaré waves) were studied because they could also be correlated with the recorded spectral peaks. With this phenomenon, similar to resonance in an organ pipe [10], a wave coming from the open ocean can be significantly amplified at selected "resonant" frequencies as a result of multiple reflections from the coast and shelf boundary.

Amplitude amplification γ (the ratio of the wave amplitude near the shore to the wave amplitude in the open ocean) is a characteristic that describes the continuous spectrum of Poincaré waves. Its value depends on the frequency of the wave and the alongshore wave number. If we assume that the shelf has a parabolic shape (along its entire length of 86 km), then generally the sea depth at the shelf is described by the equation $h = ax^2$ at $x_0 < x < L$. Then the Poincaré wave amplification factor $\gamma(\omega, 0)$ has the form according to the monograph [2]:

$$\gamma(\omega,0)=2\sqrt{\frac{L}{x_0}}\sigma\left(4\sigma^2+1-\cos(2\mu\sigma)+2\sigma\sin(2\mu\sigma)\right)^{-1/4} \tag{1}$$

at $\sigma^2 > 0$. Here $\mu=\ln\frac{L}{x_0}$; $\sigma^2=\frac{\left(\omega^2-f^2\right)}{gH}-\frac{1}{4}$, where f is Coriolis parameter, $\varphi = 47.06°$N for Trade Port Bay. The Coriolis parameter is determined by the well-known formula $f = 2\Omega \sin\varphi$, where φ is location latitude; $\Omega = 7.2921 \cdot 10^{-5}$ cycle·s^{-1} is circular frequency of the Earth's rotation. Function $\sin\varphi = 0.732$, taking this into account we obtain an inertial frequency of 0.384 cycles·h^{-1}, the period of inertial oscillations is 16.34 h.

The calculation of Poincaré waves amplification factor using equation (1) for the shelf under consideration in the Kholmsk region with the approximation $h(x) = 0.32x^2$ (x, km is the distance from the coast) revealed that they can include waves with a period of 3.56 h, which has a maximum with a value of 2.25. Note that in the energy spectrum there is a peak at 3.43 h period, which is close to the maximum

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[2] Efimov, V.V., Kulikov, E.A, Rabinovich, A.B. and Fine, I.V., 1985. [*Ocean Boundary Waves*]. Leningrad: Gidrometeoizdat, 280 p. (in Russian).

amplification; the second maximum with a value of 2.1 at a period of 1.63 hours is also close to the peak in spectral density at a period of 1.62 hours (Table 1).

Other causes for the occurrence of spectral peaks with periods of 3.43, 4.82, 6.67 h are possible, in particular, these could be seiche modes of the Tatar Strait.

Shelf seiches. These are standing sea level oscillations with periods corresponding to resonant frequencies depending on the seabed slope. In the Kholmsk area, shelf depth variations at a distance of up to 40 km can be approximated by a linear dependence $h(x) = \alpha x$, where α = 0.0078. The resonant periods of such a shelf are calculated using the equation from [3, p. 183]

$$T_n = 8\sqrt{L} \Big/ \left(n\sqrt{g\alpha}\right), \tag{2}$$

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

When calculating by equation (2), the period of the first mode is 1.61 h, the third is ~ 32 min, the fifth is ~ 19.3 min, the seventh is ~ 13.8 min, the ninth is ~ 10.7 min. We can assume that the period equal to 1.62 h (Table 1) belongs to the first mode of shelf seiches.

In addition to the first mode period, we obtained periods of the 3rd–9th modes, the values of which, lying in the range of 10.7–32 min, are close to the values of the observed peaks in the spectra. Therefore, it is obvious that waves coming to the shore from the open sea or passing atmospheric disturbances can induce shelf seiches in the resonant water area of the Tatar Strait near Kholmsk.

The carried out calculations and interpretation reveal that the peak periods identified by spectral densities can correspond to different wave processes – shelf seiches and Poincaré waves. It is difficult to determine specifically which of these processes was the cause of the observed peak; it is necessary to install several wave meters in the Tatar Strait waters near Kholmsk. The authors of this work also believe that Poincaré waves can contribute to the generation of seiche oscillations at periods close to them, but this problem is the theme of a separate study.

Seiches in the bays of Kholmsk. Seiches can be generated in bays under the effect of various factors. Many researchers have studied them in different water areas [11–14]. They revealed that the periods of seiche oscillations depend on the parameters of the water areas.

We are to consider waves with periods from 40 s to several tens of minutes, which include seiches in bays. For both bays we calculated the periods of eigen oscillations; this was carried out using the equation for a rectangular basin with an open inlet [15]:

$$\tau_{k,m} = \frac{4}{\sqrt{gh}} \frac{ab}{\sqrt{(1+2\mathrm{k})^2 b^2 + 4m^2 a^2}}, \tag{3}$$

where a, b, h are average length, width and depth of the bay, respectively; non-negative integers defining the mode number: k = 0, 1, 2, …, m = 0, 1, 2.

The periods of seiche oscillations calculated using equation (3) for basins having the characteristic dimensions of the bays under study are given in Table 2.

Table 2

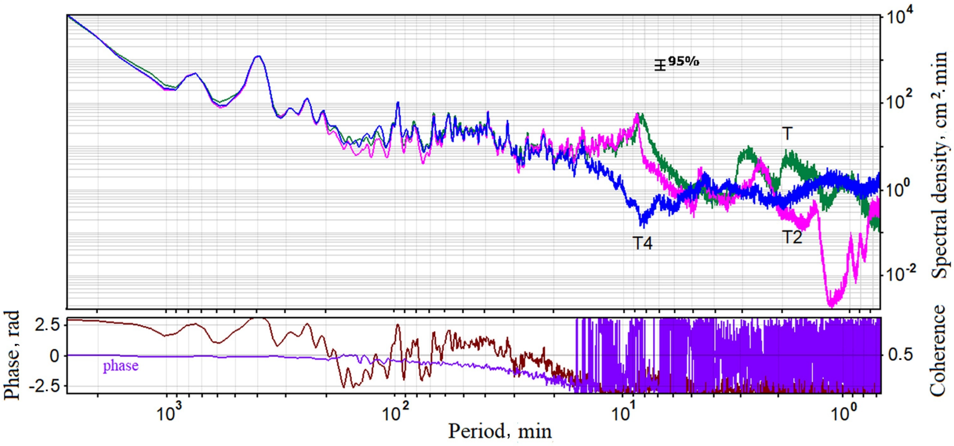
Calculated by equation (3) seiche periods in the model basins approximating the bays of Kholmsk

Mode number		Seiche periods $\tau_{k,\,m}$, min	
k	*m*	Trade Port	Kholmsk-Severny
0	0	4.7	8.6
1	0	1.6	2.9
2	0	0.9	1.7
3	0	0.7	1.2
0	1	2.7	0.9
1	1	2.0	0.9

Zero mode ($k = 0$, $m = 0$, the first largest value of the period for each water area) is the Helmholtz mode, which is similar to the fundamental tone of an acoustic resonator [16]. For the bays under consideration, the periods of this mode are 4.7 and 8.6 min.

In [17], the values of periods of Trade Port Bay longitudinal eigen modes were calculated under the assumption that the depth in its water area varies according to a parabolic law and at its inlet is 10 m. This calculation yielded the following values: 4.9; 2.0; 1.3; 0.9 min.

Figure 4 presents spectral densities for 40 s – 30 h periods of sea level oscillations. Note that the calculation was carried out for time series from which the precalculated tide was subtracted in order to exclude the impact of tidal harmonics of higher orders.



F i g. 4. Spectral densities of sea level oscillations, phase and coherence in the bays under study and in the Tatar Strait

In Fig. 4, the peaks of spectral densities in 1–10 min range of periods, the values of which exceed the confidence interval, are clearly visible. The periods of these peaks are given in Table 3, where the periods of shelf seiches with > 10 min values are also indicated. Previously performed studies of waves in Trade Port Bay revealed that wave processes with periods of ~ 1.83–8.17 min are seiches of this water area [18].

Table 3

Peak periods in spectral densities resulted from processing field observation data

Water area	Period, min							
Kholmsk-Severny	**1.32**	**2.40**	**8.65**	15.1	22.2	31.8	39.0	97.2
Trade Port	**1.83**	**2.83**	**8.17**	15.1	22.2	31.8	39.0	97.2
Tatar Strait	–	–	11.37	15.1	22.2	31.8	39.0	97.2

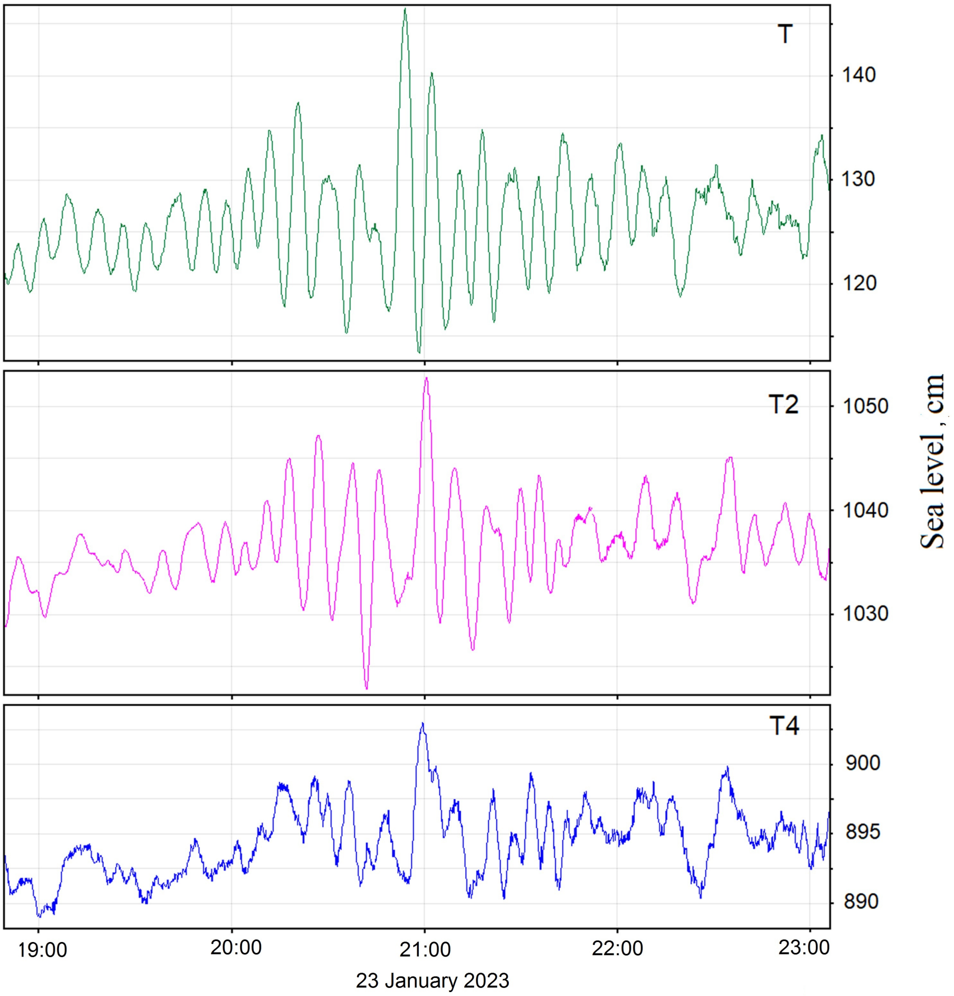
Note: Eigen periods of the bays are indicated in bold.

Note that wave processes with ~ 8 min periods are practically absent in the Tatar Strait open waters and in the area where T4 meter is installed (Fig. 4). This is due to a significantly pronounced minimum observed in the spectral density. At the same time, in [19] it is noted that the source of long-wave oscillations with the specified period recorded by the mareograph of Trade Port Bay are long-wave resonators that accumulate and amplify the energy of trapped waves in the area of Moneron Island and at the shelf near Chekhov. Numerical modeling of resonant oscillations in Trade Port Bay, according to this paper, did not demonstrate the presence of intense oscillations at ~ 8 min periods.

Comparison of the periods given in Table 2 and 3 shows that their values are close, except for the Helmholtz mode period of Trade Port Bay. Apparently, this is due to the fact that this bay has a large bayhead and equation (3) does not take into account the presence of such a water area feature. In [20], a study of the bay effect on seiches in a model rectangular basin with a bay was carried out and it was found that the presence of a bay leads to a change in the spatial structure of eigen oscillations and lengthens their periods, especially the one of the higher mode. Apparently, this circumstance contributes to the lengthening of the Helmholtz mode period in Trade Port Bay.

We note another unique property of the water area of Trade Port Bay water area – the presence of intense seiche oscillations over ~ 3 min period, which complicate the operation of the berth serving the ferry crossing [21]. This period corresponds to a single-node longitudinal seiche of the bay (Table 2), as well as the Helmholtz mode of its bayhead (~ 3 min). This further enhances the oscillations in the bayhead and western parts of the bay.

Interaction of bays. A number of papers [4, 5, 22] consider the manifestation of connections between the oscillations of two closely located bays and the possible presence of beats in them due to different periods of eigen oscillations. The authors of [5] believe that the interaction of connected bays will take place under condition $d/l_1 < 5.0$, where d is distance between the inlets of the bays; l_1 is length of one bay. For the bays of Kholmsk d/l_1 = 1045 m/1008 m = 1.04, therefore, interaction effects are possible.

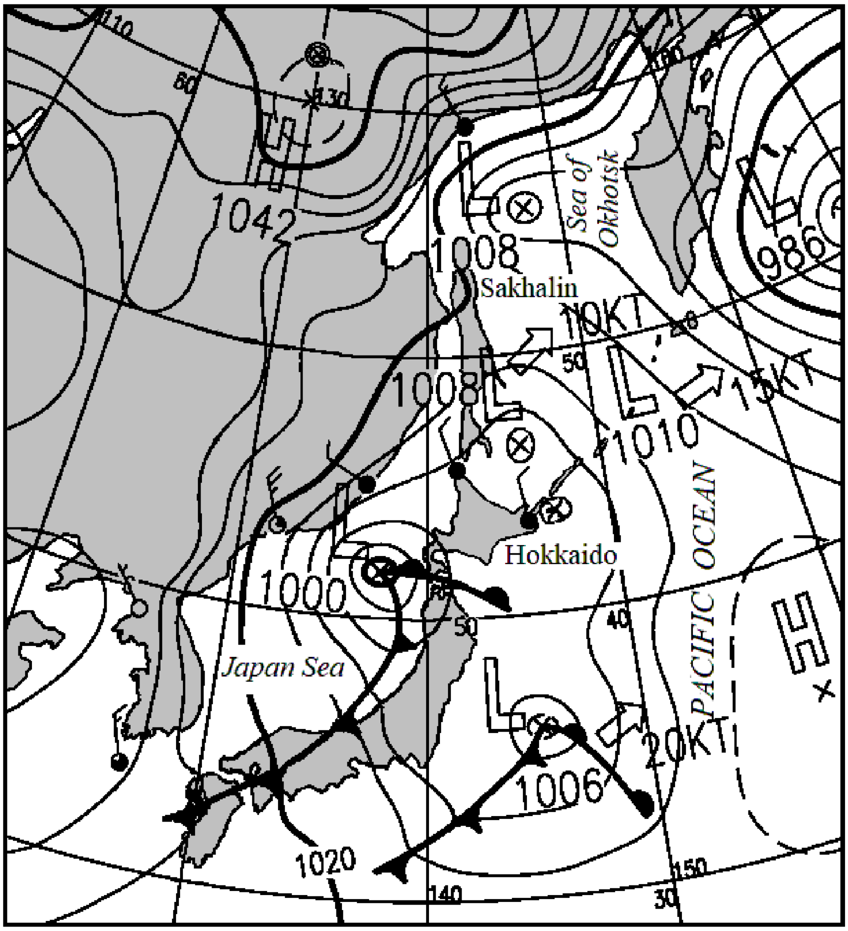


F i g. 5. Time variation of sea level oscillations using the time series with the subtracted precalculated tide in two bays of Kholmsk and in the open sea on January 23, 2023 starting from 19:00

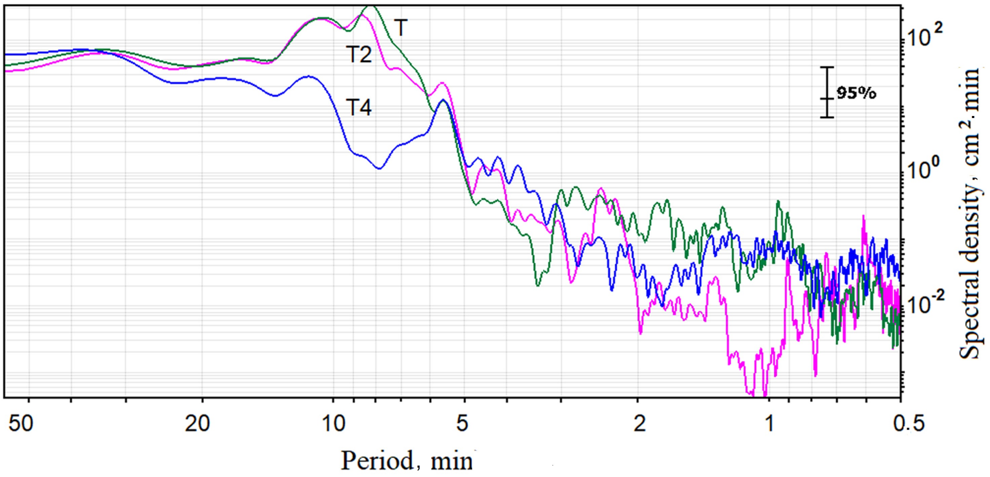
Time variation of sea level oscillations without taking into account the precalculated tide in two bays and in the open sea is represented in Fig. 5 for January 23, 2023. A significant increase in the amplitudes of sea level oscillations with close-by frequencies in the bays from 20:00 to 22:00 is clearly visible. For the open sea, the increase in oscillation amplitudes is 1.5–2 times smaller. At the same time, sea level oscillations at 21:00 in Kholmsk-Severny Bay (T2 meter) and in the open sea (T4 meter) almost coincide in phase, and in Trade Port Bay (T meter) are in an antiphase with them. Note that such synchronous increases in amplitudes are observed quite often and the cases when oscillations with maximum amplitudes in bays coincide in phase (for example, 11 March 2023) also take place.

We are to consider the conditions for generation of such oscillations. They can be different [14], but are usually associated with atmospheric disturbances. Figure 6 shows a fragment of a synoptic map from the weather site rp5.ru for 20 January 2023 at 06:00. It can be seen that at the time of formation of large-amplitude seiches in the bays, a cyclone moved over Sakhalin Island southernmost tip and it was accompanied by prolonged north-northeast winds of 7–19 m·s^{-1} speeds and gusts of up to 15 m·s^{-1}. It is obvious that the generation of seiches is caused by the impact of this cyclone. By the time of seiche generation, the background wave did not exceed 5 cm for the waves with periods of up to 10 min. Storm waves arrived at the observation points 12 hours after the occurrence of maximum-amplitude seiches and reached their maximum of 70 cm after 21 hours.

For the segments of time series under consideration (Fig. 5), the spectral densities of sea level oscillations (shown in Fig. 7) are calculated. These more detailed graphs indicate the presence of peaks at 5.62 min period for all meters, as well as at 8.17 and 10.5 min periods for T meter, at 8.65 and 10.92 min periods for T2 meter and 11.37 min period for T4 meter. For periods of ~ 8 minutes, a significant minimum is observed in the spectral density of sea level oscillations, calculated from the T4 meter data.

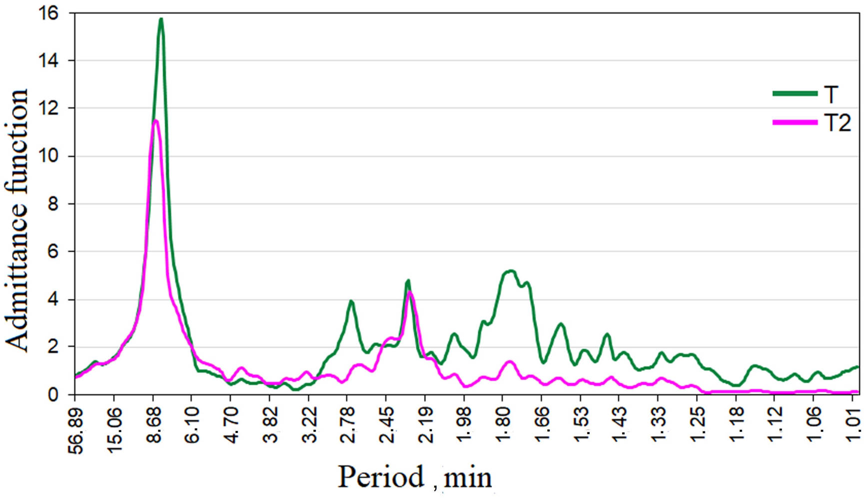


F i g. 6. Fragment of a synoptic map from the open weather site rp5.ru for January 20, 2023 at 6:00



F i g. 7. Spectral densities of sea level oscillations

Since resonant characteristics of the shelf affect the measurements of the instruments located in the bays, they can be removed from the spectra at the inlet sites by dividing the spectra by the spectrum of the instrument installed at the shelf, as proposed in [5]. The square root of this relationship can be considered as an estimate of the transmission function at the inlet, i.e., as the relative amplification of waves penetrating into the bay from the shelf. And since T4 meter was located at some distance from the bay inlets (Fig. 1), we can assume that it was weakly affected by the waves radiated from the bays at resonant frequencies.



F i g. 8. Admittance (amplification) functions at the inlets of the bays

Admittance functions calculated from the measured sea level oscillations in both bays are represented in Fig. 8. It can be seen that the resonant admittance peaks for both inlets look sharper than in the spectral densities (Fig. 7), and that the corresponding periods are slightly different: for Trade Port Bay the period is 8.0 min, for Kholmsk-Severny Bay – 8.53 min. According to the authors of [5], such small shifts are not surprising, since the spectrum at the shelf is not constant.

In addition to the main resonant peaks at the inlet to the bays, several secondary peaks are also visible in Fig. 7, 8. If for the Trade Port Bay a peak in the period of the first seiche mode of 2.7 min exists, then a peak in this period for the Kholmsk-Severny Bay is absent. Also, in both bays at 2.29 min period almost coinciding peaks that do not correspond to eigen oscillations of the bays (Table 3) take place. Apparently, manifestation of this period is due to the occurrence of coupled oscillations in the bays.

Such a system is characterized by a spectrum of normal frequencies [3], which can be reasonably compared with partial frequencies. A partial system is obtained from the original one by removing the connection. For example, one of the pendulums connected by a spring is fixed, or the inlet to one of the bays is closed. Partial frequencies always lie between normal frequencies [3]. In Table 3, partial periods are given, since their values were calculated with no regard to the presence of a neighboring bay.

In a system of coupled oscillators, two types of oscillations are possible: in-phase and anti-phase. For example, if the oscillators are pendulums connected by a spring, in-phase oscillations will occur if the spring is not working, and anti-phase oscillations will occur if the spring is working. For bays, this can be represented as follows: in-phase oscillations occur when current lines are directed from the bay towards the open sea, and anti-phase oscillations occur when they pass from one bay to another [4, p. 131]. The period of antiphase oscillations is less than that of in-phase ones [4, p. 130].

Interaction of Kholmsk bays is confirmed by graphs of spectrograms of sea level oscillations, correlations and differences in oscillation phases for these bays (Fig. 9). On the spectrograms of sea level oscillations for each bay (Fig. 9, *a*, *b*), horizontal stripes are clearly visible at periods of ~ 8 minutes. Moreover, these oscillations were intense throughout the entire observation interval. Due to the connection, the oscillations with the specified period is transmitted from Kholmsk-Severny Bay to Trade Port Bay and manifests itself there quite intensively.

Similar situation is observed, for example, in the system of Sevastopol bays [7, 8]. The Helmholtz mode of the Sevastopol Bay penetrates into the neighboring Karantinnaya, Kruglaya and other bays, and the Helmholtz mode of Karantinnaya Bay manifests itself with sufficient intensity in Sevastopol Bay.

Constant presence of ~ 8 min period in the spectrum of sea level oscillations in the bays under consideration can be explained by the fact that the Helmholtz mode is usually induced more easily than other modes of eigen oscillations [3]. In addition,

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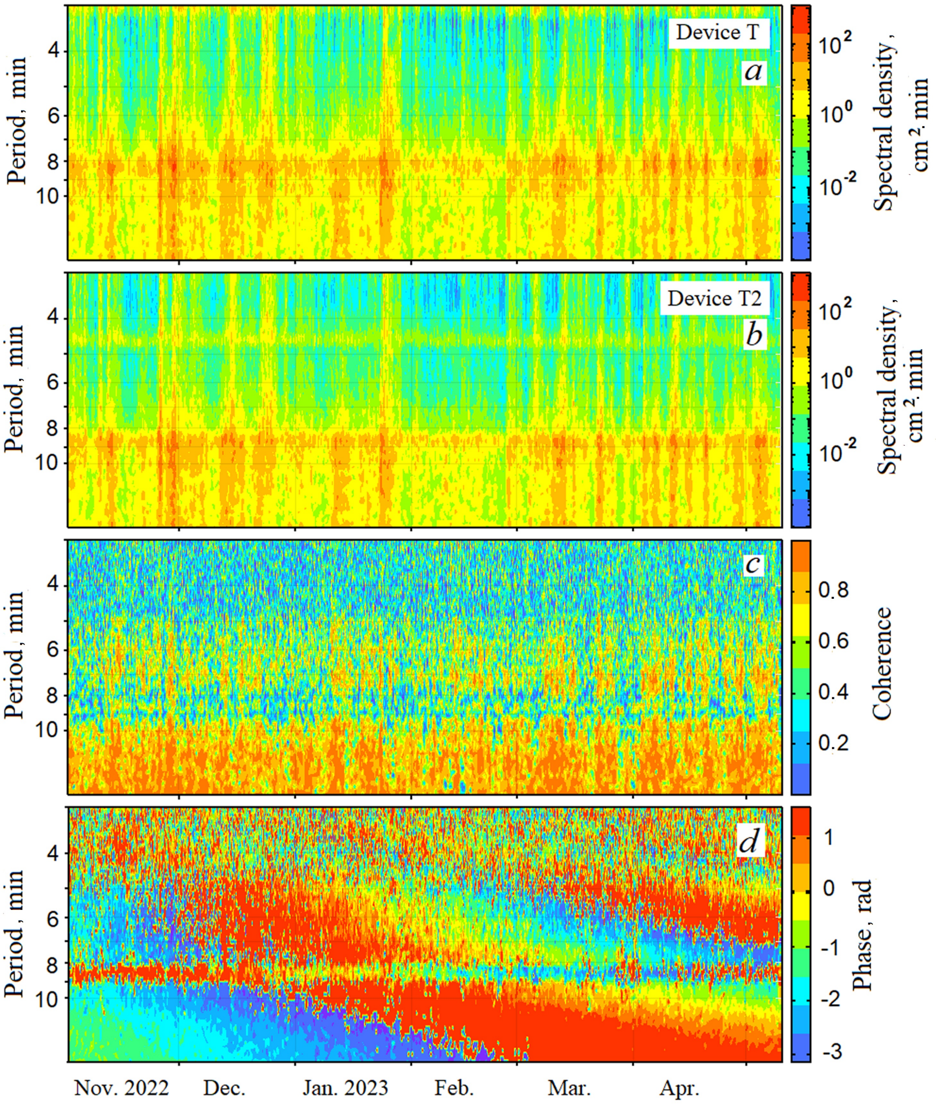
[3] Rabinovich, M.I. and Trubetskov, D.I., 1984. *Introduction to the Theory of Oscillations and Waves*. Moscow: Nauka, 432 p. (in Russian).

as mentioned above, the source of long-wave oscillations with the specified period registered by the mareograph in Kholmsk are long-wave resonators that accumulate and amplify the energy of trapped waves near Moneron Island and at the shelf near Chekhov [19, p. 44]. The coherence spectrogram (Fig. 9, *d*) at ~ 8 min oscillation periods also demonstrates a band with a coherence of 0.6–0.8 confirming the coupling of oscillations in these bays.



F i g. 9. Spectrograms of sea level oscillations in two bays (*a*, *b*), correlations (*c*) and phase differences (*d*)

Interaction of oscillations in neighboring bays is clearly demonstrated by the spectrogram of their phase difference (Fig. 9, *d*). There is (at 8–9 min periods) a stable horizontal band for the entire observation period, corresponding to the range of periods of eigen oscillations of the bays. Moreover, in January 2023 the oscillations were close to in-phase, and in March – April 2023 – to anti-phase. Besides, a rather slow cyclic phase change is observed in this band. We found this effect and then described it in [1]; it is explained by the synchronization of oscillations in the bay by waves arriving to the inlet [4].

On the eigen periods (less than 8 min) of the bays under consideration, no coupling of bays is observed despite the fact that peaks exist in the spectral densities of sea level oscillations at such periods. Apparently, this is due to the fact that the interaction of oscillators at periods of higher eigenmodes is difficult for some reason. This circumstance requires further research.

In [4], special cases of solving the Lagrange equation for an isolated system of two bays during their interaction are considered. Using the equation from this paper, we calculated the beat periods for the case when seiches initially exist only in one of the two bays:

$$T_b = \frac{2\pi}{(n_2 - n_1)/2}, \tag{5}$$

where n_1 and n_2 are frequencies of oscillations in bays. The calculation revealed that for peaks that stand out in the spectral density in two bays with 8.17 and 8.65 min periods, the beat period is 294.5 min (4.91 h). At the same time, in the spectral densities of sea level oscillations calculated from experimental data for three observation points, a peak (Table 1) with a period of 4.82 h (289.2 min) stands out; it differs from the calculated one by 1.8%, which is within the error limits of calculating the spectral density. This wave process is not caused by tidal harmonics or seiches and therefore is really a manifestation of beat caused by the connection between the bays.

Conclusion

Long-term (> 7 months) observations of sea level oscillations were carried out in the adjacent Trade Bay and Kholmsk-Severny Bay ports, located at 1008 m distance, as well as in the adjacent water area of the Tatar Strait. Discreteness of the performed measurements was one second.

Analysis of sea level oscillations for the range of 1–30 h wave periods, carried out using field data in order to exclude tidal harmonics, indicated the presence of four non-tidal wave processes with 1.6–6.7 h periods. The model calculations carried out revealed that wave processes with such periods can be attributed to shelf seiches, Poincaré waves and the Tatar Strait seiches.

Spectral analysis of 1–10 min period range showed the presence of seiches with 1.83–8.17 min periods in Trade Port Bay and with 1.32–8.65 min periods in Kholmsk-Severny Bay. In spectral densities of the Tatar Strait sea level oscillations, peaks at 5.62

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[4] Osipov, G.V. and Polovinkin, A.V., 2005. [*Synchronization with External Periodic Impact*]. Nizhniy Novgorod: NNGU, 78 p. (in Russian).

and 11.37 min periods stand out, and at ~ 8 min period, a well-defined minimum is observed.

It is indicated that during the generation of large-amplitude seiche oscillations, a cyclone was moving over the observation area, which was accompanied by prolonged north-northeast winds of 7–19 $m \cdot s^{-1}$ speeds and gusts of up to 15 $m \cdot s^{-1}$.

It is determined that throughout the entire time series of field observations in Kholmsk bays, coupled oscillations over ~ 8 min period took place; they corresponded to the Helmholtz mode period of Kholmsk-Severny Bay. These oscillations were induced in this bay and were transmitted to Trade Port Bay due to interaction. These oscillations at different times had both in-phase and anti-phase spatial structures. During periods of high eigen modes, no interaction between bays was detected.

The spectral analysis of the sea level oscillations under study made it possible to reveal the beats with a period of 4.82 h (289.2 min), resulting from the interaction of modes with close periods equal to 8.17 and 8.65 min.

The stated facts, as well as correspondence of the distance between the inlets of the bays to the proposed earlier interaction condition criterion enable us to assert that the coupled oscillations are present in two adjacent bays – Kholmsk-Severny and Trade Port.

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