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Original article

Features of the Wave Processes in the South Kuril Strait Based on Observational Data

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Abstract
Purpose. The work is purposed at studying the waves in the South Kuril Strait within the period ranges from the wind waves to the tidal ones using the field observations data, and also at explaining the observed wave processes using the existing theories and models.
Methods and Results. The results of the analyzed long-term (up to 12 months) time series of observations of waves and water temperature performed with the 1 s discreteness by the bottom autonomous wave recorders ARW-K14 at three points in the South Kuril Strait coastal zone are considered. To detect wave processes, the spectral analysis was applied. It showed the presence of significant maxima in the spectral densities that resulted in revealing the diurnal and semidiurnal tidal waves, and the time series of seawater temperature fluctuations made it possible to find out the waves with a period of the tidal harmonic K_1. The seiche periods were calculated by the formula for a semi-open water area, and it showed the possibility of generating eigen oscillations of sea level in the South Kuril Strait with a period 5.0 hours, which was close to the period 4.8 hours derived from the observational data. It was revealed that the seiches amplitude are increased after the ebb reached its minimum level and further as the level grew. This effect (described by D. K. Chapman and G. S. Giese in their articles) is explained using the dynamic mechanism of generating the coastal seiches by deep-sea internal waves induced by a barotropic tide.
Conclusions. It is shown that both seiches and tidal harmonics can contribute energy to the wave process with a period 4.8 hours. The level fluctuations with the periods varying from 0.4 to 3 hours do not depend on tidal harmonics and, possibly, they are the seiches or the edge waves. The results of a spectral analysis of three time series permitted to find out that seiches in the South Kuril Strait were of low energy and there were no conditions for their significant resonant amplification. It was shown that a part of the energy of tidal waves was transferred to the seiche oscillations in the Krabovaya and Malokurilskaya bays. Having being analyzed, the sea level fluctuations in the range of infragravity waves showed the possibility of the South Kuril Bay fluctuations to transform to the chaotic ones, which had been confirmed by modeling the behavior of the dynamic system – the water mass of the bay excited by the incoming swell waves.

Keywords: seiches, swell, infragravity waves, tidal waves, chaotic vibrations, sea level oscillations, field observations, spectral analysis

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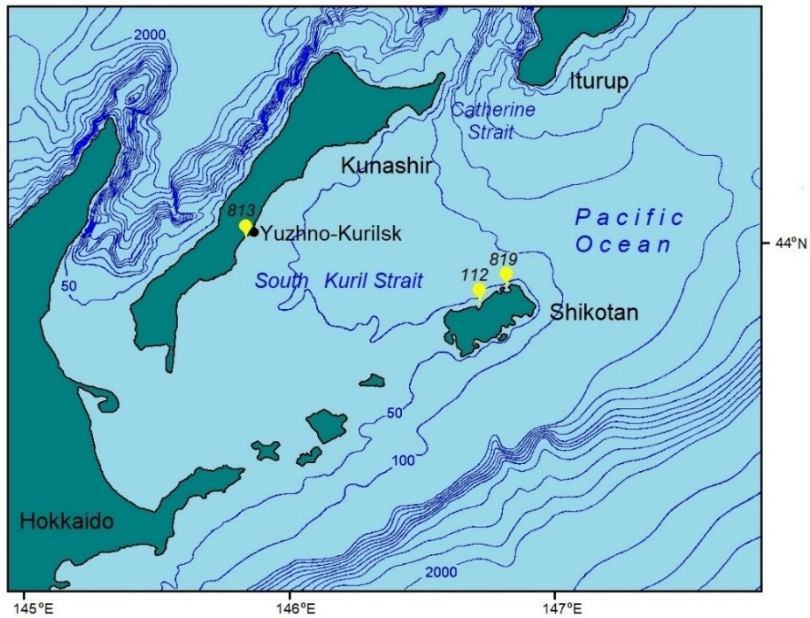
Introduction

The knowledge of wave regime characteristics for specific marine areas is of practical interest associated with shipping, fishing and coastal engineering. Since sea waves can intensify depending on weather conditions and bathymetric features of the coast, it is necessary to study wave accompanying factors. That is why the study of waves and wave generation conditions in specific water areas is relevant.

In the materials of the studies related to the considered water area, published earlier in [1, 2], the results of the study of waves in the South Kuril Bay – mainly in the range of wind wave and swell periods – using time series of observations with the help of instruments installed in the South Kuril Bay are presented. As for the study of waves in the strait itself, only small conclusions for the long wave range were made in these works.

Accordingly, for a detailed study of the wave field in the considered area, it was decided to carry out long-term measurements of waves in a wide range of periods of sea level oscillations at three points on the opposite sides of the South Kuril Strait. Taking into account the assumption that seiche activity is caused by high tides [3], it seems possible to verify this statement for the considered water area.

The main methods for the studies considered here were, first, long-term instrumental measurements of sea level and water temperature oscillations over a wide range of periods; secondly, spectral, cross-spectral and spectral-temporal analysis. This allows to detect wave processes that occur during the observed level and temperature oscillations from the energy maxima. The selected wave processes are simulated in accordance with the existing theories and formulas.



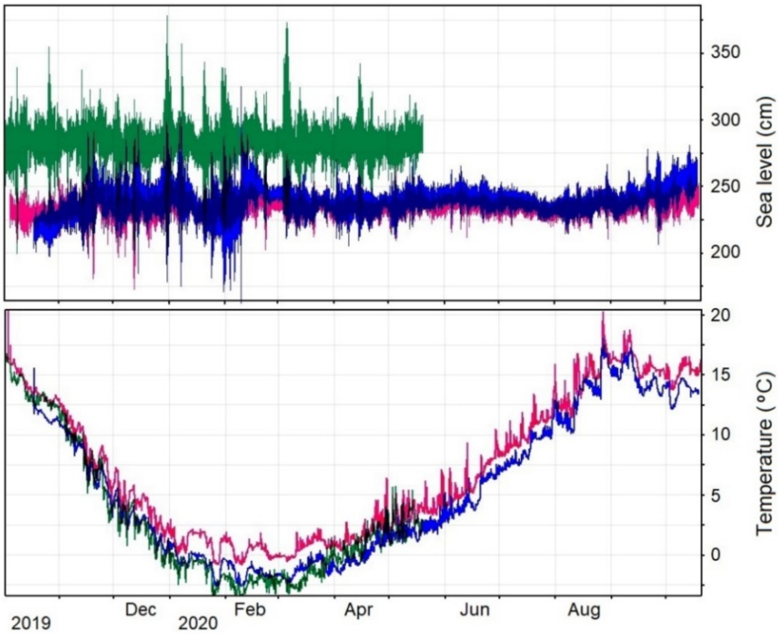
F i g. 1. Map of the South Kuril Strait and locations of the devices (yellow circles)

The aim of the research, the results of which are presented in this paper, is to study the waves in the range of periods from wind waves to tidal waves in the South Kuril Strait using field observation data. The obtained conclusions make it possible to take into account the manifestation of wave processes in the considered water area and to avoid the onset of negative consequences for navigation and fisheries, as well as during the construction of coastal engineering structures.

The present paper considers the results of a study obtained during an investigation of waves in the South Kuril Strait mainly from measurements taken by two devices: one in Shikotan Island and the Krabovaya Bay water area – No. *112*; another one – in the South Kuril Bay – No. *813* (Fig. 1). Simultaneously with these two devices, the measurements were taken by the third device No. *819*, installed in the Malokurilskaya Bay, Shikotan Island. However, the time series obtained with its help in the region of wave periods exceeding 1 h differed little from the time series of the device No. *813*.

Observations and the obtained data

The measurements were carried out by ARW-K14 wave recorders. Time series of sea level and temperature observations were obtained with one second discreteness and a duration of 8 months in the South Kuril Bay and about 12 months in Shikotan Island area in 2019–2020. Joint simultaneous registration was carried out for about 6.5 months from October 2019 to May 2020. The distance across the South Kuril Strait between Kunashir and Shikotan islands along the perpendicular to Kunashir Island measured on the 1985 v. 2 world map (Available at: http://retromap.ru/161985_47.058662,143.66374) is about 60.8 km. The distance from Hokkaido to Iturup Island is about 171.4 km, from Hokkaido Island to the Catherine Strait – 157.1 km, and Kunashir Island length is 107.9 km (Fig. 1). These parameters are necessary for calculating resonant properties of the South Kuril Strait water area.



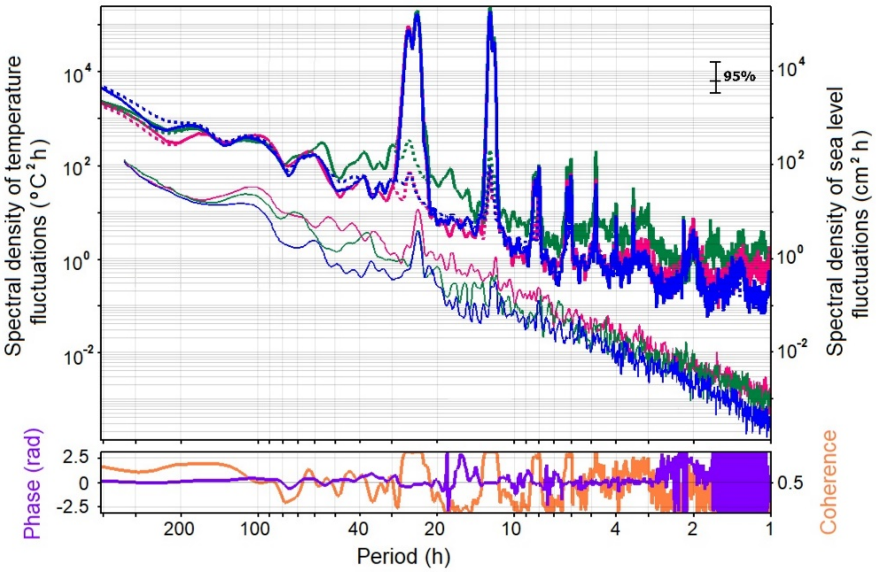
F i g. 2. Time series of the sea level and temperature oscillations. Red color – based on the device *112* data, blue color – *819*, green color – *813*. The pre-calculated tide is subtracted from the level time series

The time series of sea level and temperature oscillations obtained as a result of measurements are shown in Fig. 2. Since tidal oscillations significantly clutter up the figure, the precalculated tide was subtracted from the data series using the *Kyma* software [1] [4]. The spectral and cross-spectral analysis of time series, the results of which are considered here, were also carried out using this software.

Analysis of longwave sea level oscillations

In this section, long-wave sea level oscillations with a period over 1 h are considered. Fig. 3 shows the spectral densities of sea level oscillations calculated over the entire length of the measured time series, including time series, with the subtracted pre-calculated tide. From this figure, it can be seen whether certain peaks are tidal harmonics. The peaks in the range of diurnal and semidiurnal tidal harmonics stand out significantly. At the same time, their periods coincide for all three observation points and are close to O_1, K_1, SO_2 and S_2 (table) periods given in [5]. The tidal harmonics with shorter periods, as can be seen from Fig. 3 have lower energy, but also stand out well and exceed the confidence interval.

Note that the problem of a detailed tidal analysis was not posed in this paper. Here, it was necessary to show at which periods tidal harmonics can appear and at which periods – other types of waves, which is carried out by comparing the spectral densities for the original time series and the series with the subtracted pre-computed tide.



F i g. 3. Spectral densities of the sea level fluctuations (thick lines). Dashed lines are the spectral densities for the time series with the subtracted pre-calculated tide; thin lines are the spectral densities of temperature fluctuations. Green color denotes the spectrum for the South Kuril Bay (device *813*), blue color – for the Malokurilskaya Bay (device *819*) and pink color – for the Krabovaya Bay (device *112*). Coherence (orange line) and phase (purple line) are for the time series of the South Kuril and Krabovaya bays

[1] Kovalev, P.D., 2018. *Kyma*. [computer program] Yuzhno-Sakhalinsk: Institute of Marine Geology and Geophysics, registration no. RU2018618773 (in Russian).

Peak periods in the graphs of spectral density and correspondence to their tidal harmonics

Measured period, h	Period of a tidal harmonic, h	Tidal harmonic in [5]	Measured period, h	Period of a tidal harmonic, h	Tidal harmonic in [5]
29.93	29.07	α_1	8.00	8.00	SP_3*
25.85	25.85	O_1, MK_1*	6.20	6.21	M_4*
23.93	23.93	K_1, 24 S_1	4.80	4.86	S_4*
12.43	12.44	α_2, SO_2*	6.00	6.00	3KM_5
12.00	12.00	S_2	4.00	4.00	S_6*
8.42	8.49	NO_3*			

* For a shallow water tide.

The spectral densities of sea water temperature oscillations were also calculated. The graphs are quite smooth with a decay law of approximately −1/2. The peak exceeding the 95% confidence interval for all three time series has a period of 23.97 h and corresponds to the K_1 tidal harmonic (Fig. 3). The peaks at periods 12.00 and 12.43 h are somewhat smaller than the confidence interval, except for the graph related to the Malokurilskaya Bay, but even here the excess is insignificant. The periods of these peaks also correspond to tidal harmonics.

One more feature of the spectral density of water temperature should be noted. Even for wave processes with periods of 23.97 h, the spectral maximum energy exceeds the average level by about one order of magnitude, while for tidal level waves with the same period, the excess is more than four orders of magnitude.

Seiches

It is common knowledge that in harbors and bays, under the influence of various factors, eigen resonant oscillations of water areas – seiches – can be generated. Many papers are devoted to the results of their study in different areas of the World Ocean, for example, [6–9]. At the same time, the resonant properties of the water areas of specific coasts determine the parameters of eigen oscillations of these water areas, and the periods of shelf seiches depend on the bottom slope. At the same time, as the authors of [10] believe, coastal waters usually oscillate at resonant frequencies in the range from 0.5 to 5 cycles per hour, which is typical of a particular harbor, bay or shelf.

The energy to excite seiches can come from different sources. Thus, the papers [9, 11–13] give estimation of the energy of atmospheric disturbances transmitted in the open sea by meteorological tsunamis, and they, in turn, coming to the coastal zone or bay, excite seiches in them. Other researchers (for example, in [14]) consider standing waves in port basins arising from the energy supply from the open sea, where it can be generated by a wider range of mechanisms, such as tides, surf, tsunamis, internal waves and atmospheric disturbances [3, 6, 7, 15]. However, the dominant source may differ from harbor to harbor, depending on the presence of such mechanisms and the specific geographical situation of the harbor. Therefore, it is of interest both to consider the seiches themselves and to determine the source of their energy.

Since the depth along the South Kurile Strait varies significantly, and the formulas for calculating seiches for a variable sea depth are quite complex, a simple formula by the Dubois method [2] was used for the estimated calculation. It is applicable for calculating a single-node seiche of a water body with variable depth. In this method, the axial line of the water area is divided into *n* sections of Δx length and the period is calculated by the following formula

$$T = \left(\frac{4}{\sqrt{g}}\right) \sum_{i=0}^{i=h} \Delta x / (\sqrt{H_i} + \sqrt{H_{i+1}}\ ), \quad (1)$$

where H_i and H_{i+1} is the water depth at the points of intersection of the axial line with the listed sections, evenly distributed along the water area length.

The length of the South Kuril Strait from Hokkaido Island to the northern tip of Kunashir Island was divided into 15 segments 10.9 km long, and the depth determined from the bathymetric map was recorded at the boundaries of each segment. The calculation using formula (1) showed a period of 5.0 h. According to the observations, there is a peak in the spectral density with a period of 4.8 h, i.e., close enough to the calculated one.

Note that for the range of wave periods of 4.8–5 h, according to the data of [5], there are several tidal harmonics. It was not possible to separate which of them can transfer energy to seiches (possibly in a resonant way). A peak with a period of 4.8 h is present on the graphs of spectral densities for time series with a tide for all observation points, and for time series with a subtracted tide, the amplitude of the waves is 2.8 times less. Therefore, it can be assumed that the discovered wave process is a seiche, and the tidal harmonic transfers part of the energy to it.

Taking into account the parameters of the South Kurile Strait given above and the average depth of about 150 m, the periods of eigen resonance modes were determined using the formula for semi-open rectangular basins of length *L* and uniform depth *H* [9, p. 198]

$$T_n = \frac{4L}{(2n+1)\sqrt{gH}} \qquad \text{for the } n \text{ mode} = 0, 1, 2, 3, \dots, . \quad (2)$$

As a result of the calculation for the South Kuril Strait water area, possible periods of seiche oscillation modes from 0.4 to 2.9 h were obtained. Note that wave processes in the strait with a period of about 3 h are shown in the papers of other authors, for example, in [16, 17]. The authors of the cited papers believe that this maximum is associated with the Helmholtz mode for the South Kuril Strait as a whole.

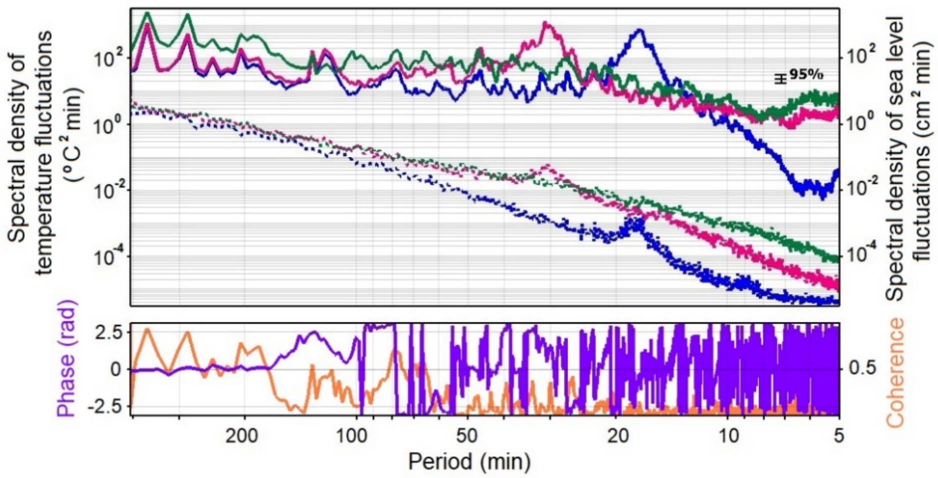
In [18], it was concluded that the seiche periods calculated using the above formulas (1), (2), as a rule, turn out to be very close to the measured values, which was also obtained in this work. Thus, the carried-out calculations show that seiches can be generated in the South Kuril Strait at the periods of the detected peaks in the spectral density of sea level oscillations. These periods are determined by the resonant properties of the strait water area.

Further, wave processes with periods of sea level and temperature oscillations in the range from 5 to 200 min are considered. Shorter periods of surface waves belong to the infragravity (IG) wave range and will be analyzed below. The calculated spectral densities for this range are shown in Fig. 4. On the graphs of spectral densities related to the Malokurilskaya and Krabovaya bays, broad

[2] Arsenyeva, N.M., Davydov, L.K., Dubrovina, L.N. and Konkina, N.G., 1963. [*Seiches on the Lakes of the USSR*]. Leningrad: Publishing House of Leningrad State University, 184 p. (in Russian).

peaks are clearly visible at periods of about 18 and 30 min, respectively. These peaks belong to the eigen oscillations of the bays, and since the devices were located in the bays, these peaks are well pronounced.

The graph of the spectral density of sea level oscillations (Fig. 4) for Yuzhno-Kurilsk also contains peaks exceeding the 95% confidence interval at periods from 20 to 100 min, but their excess over the background level is less than an order of magnitude, and this is due to the fact that that the South Kuril Bay is more open and its quality factor is lower. The coherence between the time series of Yuzhno-Kurilsk and the Krabovaya Bay for the considered periods does not exceed the confidence level, which is obvious due to the large distance between the points, and therefore the coherence plot is not shown in the figure.



F i g. 4. Spectral densities of sea level fluctuations (solid lines) and temperature (dotted lines) based on the data of devices *819* (blue color), *112* (red color) and *813* (green color); coherence (orange line) and phase (purple line) are between the time series of the Malokurilskaya (device *819*) and Krabovaya (device *112*) bays

Note that for the area under study, V.Ya. Maramzin [19] constructed a numerical model of seiche oscillations using the finite element method. In this case, the oscillations with periods shorter than two hours were calculated. One of the periods obtained in the calculation, corresponding to the eigen oscillations of the South Kuril Strait, is 43.8 min and is quite close to the 47 min recorded by us (difference of 7%). The slight difference is apparently related to the approximations used in constructing the numerical model.

According to the spectral analysis data given in [16], the maximum in the spectrum has the same period as according to our data. At the same time, since the coherence for this period between the time series of the South Kuril and Krabovaya bays does not exceed 0.05 and is significantly lower than the confidence level of 0.4, it can be concluded that the level oscillations with this period are due to the local topography of the South Kuril Bay and they are not seiches of the entire South Kurile Strait.

Consequently, the results of a spectral analysis of three time series show that seiches in the South Kuril Strait have low energy and are relatively weak compared to Malokurilskaya and Krabovaya bays. It means that there are no conditions for a significant resonant amplification of incoming waves. The authors of [20] M. Nakano and S. Unoki also refer the South Kuril Strait to water areas where strong seiches are rarely observed. Nevertheless, for sea level oscillations with periods from 0.42 to 2.9 h and for a period of 4.8 h, the coherence between the time series of sea level oscillations measured on different sides of the South Kuril Strait exceeds 0.5 (see Fig. 3). It can be concluded that they are seiches of the strait water area, and oscillations with a period of 4.8 h have the highest energy.

On the graphs of the spectral density of temperature (Fig. 4), only peaks corresponding to the eigen frequencies of the Malokurilskaya and Krabovaya bays are distinguished. At the same time, since the energy of sea level oscillations is much greater for surface waves, it is possible to transfer it to temperature oscillations – the internal waves.

Energy transfer to seiches from tidal waves

As noted above, scientists believe that the energy to excite seiches can come from tidal waves. Paper [3] can, apparently, be considered as one of the fundamental studies in this direction. Based on the analysis of 10-year time series, its authors showed that high tides are necessary to create high seiche activity. Let us consider this statement in relation to the South Kuril Strait bays.

Using the *Kyma* software option, significant wave heights with a period of 27–34 min, defined as average wave heights for the Krabovaya Bay and with a period of 16–19 min for the Malokurilskaya Bay, were calculated. The graphs for the Krabovaya Bay are shown in Fig. 5. They look similar for the Malokurilskaya Bay. In the South Kuril Bay, according to the results of the spectral-temporal analysis, wave processes with periods from 20 to 100 min are observed, but the excess of the height of these waves over the background level is small, no more than three times the amount. In addition, the energy of background oscillations, as can be seen from Fig. 4 is high, and for this reason it is not possible to determine whether the tidal energy is transmitted here to seiches or comes from other sources.

Fig. 5 *a*, *b* clearly shows that the seiche amplitude increases with the height of the tidal wave, which is also confirmed by the spectrogram (Fig. 5, *c*). In this case, the maximum amplitude of seiches corresponds to the minimum sea levels. Thus, during the maximum ebb on June 21, 24 and 25, the seiches with a period of about 30 min and a maximum amplitude are observed around 12 a.m. It can be concluded that a part of the tidal wave energy is transferred to seiches. At the same time, as shown in the same graphs, but for stormy weather, the amplitude of the seiches exceeds the values of the maxima excited by the tidal wave by more than 1.5–2 times. This means that most of the energy in the studied water area is transferred to seiche oscillations from other sources – the energy of atmospheric disturbances, which is first transferred to long waves in the open sea, and already they, coming to the coastal zone or bay, contribute to the generation of seiches.

To understand the possible mechanism of the tidal influence on seiches, the studies devoted to this theme should be analyzed. Thus, the paper [3] shows that the shallow water pycnocline (a thin mixed layer) development increases

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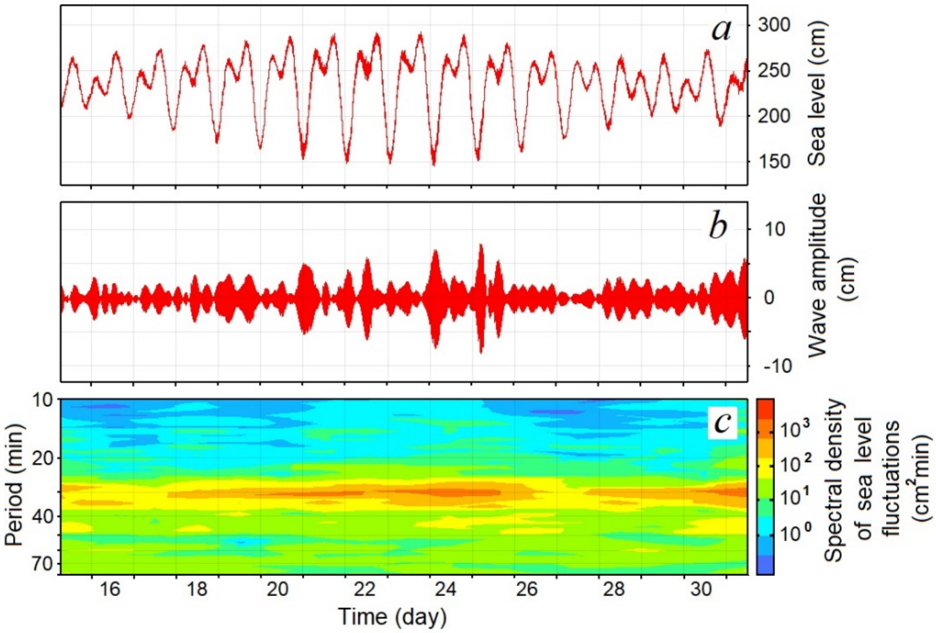
[3] Alfonso Sosa, E., Capella, J., Morell, J.M., López, J.M., Corredor, J.E., Dieppa, Á. and Teixeira, M., 2001. Coastal Seiches, Internal Tide Generation, and Diapycnal Mixing off Puerto Rico. In: E. Alfonso Sosa, 2001. *Variabilidad Temporal de la Producción Primaria Fitoplanctónica en la Estación CaTS (Caribbean Time-Series Station): Con Énfasis en el Impacto de la Marea Interna Semidiurna Sobre la Producción*. Ph.D. Thesis. Mayagüez, Puerto Rico: Department of Marine Sciences, University of Puerto Rico. Apéndice D., pp. 297-346.

the Brunt–Väisälä frequency and reduces the tidal flow slope. Under proper astronomical influence and vertical stratification conditions, the barotropic tide energy on or near the shelf is transferred to the shelf in the direction of generating internal tides and coastal flow into the platform waters, which leads to an increase in the coastal seiche activity.



F i g. 5. Sea level oscillations with a tide (*a*), amplitude of seiche oscillations with a period of about 30 min (*b*) and spectrogram (*c*) for the Krabovaya Bay (June, 2020)

At the same time, studies [21–23] and others describe the relationship between the bottom slope and the generation of internal tides by barotropic tides. This latitude-dependent process has been shown and is now widely accepted [3] to occur worldwide and at regional as well as at global levels.

Ultimately, a relation between the barotropic tide and coastal seiches is obtained. Such a hypothesis was proposed in [24] and confirmed by observations of barotropic tides in the southeastern part of the Caribbean Sea [3]. The theoretical support for this hypothesis is provided in [25], where a dynamic mechanism of coastal seiche generation by deep-sea internal waves is studied using a linear two-layer coastal model, in which internal waves coming from the deep ocean collide with the bottom topography of a stepped shelf.

Long before, some scientists, such as R.A. Harris [4] [3], believed that seiches are only meteorologically forced. However, in some cases, as studies have shown [3], there is an inverse relationship between wind speed and seiche activity;

[4] Harris, R.A., 1907. *Manual of Tides. Part V: Currents, Shallow-Water Tides, Meteorological Tides, and Miscellaneous Matters*. Washington: U.S. Government Printing Office. Chapter 9, pp. 472-482. Available at: https://archive.org/details/harris-1894-manual-of-tides-part-iv-b-and-v/page/n7/mode/2up [Accessed: 27 July 2023].

furthermore, the absence of high levels of seiche activity after low tides in the southeastern Caribbean during the 10-year observation period argues against meteorological forcing.

In the case of seiche generation considered here, their amplitude increases with the height of the tide and reaches a maximum in syzygy. This is consistent with the mechanism of seiche generation described above. Nevertheless, the authors suppose that with a significant decrease in the energy transmitted by the tide to seiches, they may be excited as a result of the storm waves or by mechanisms joint with the tide.

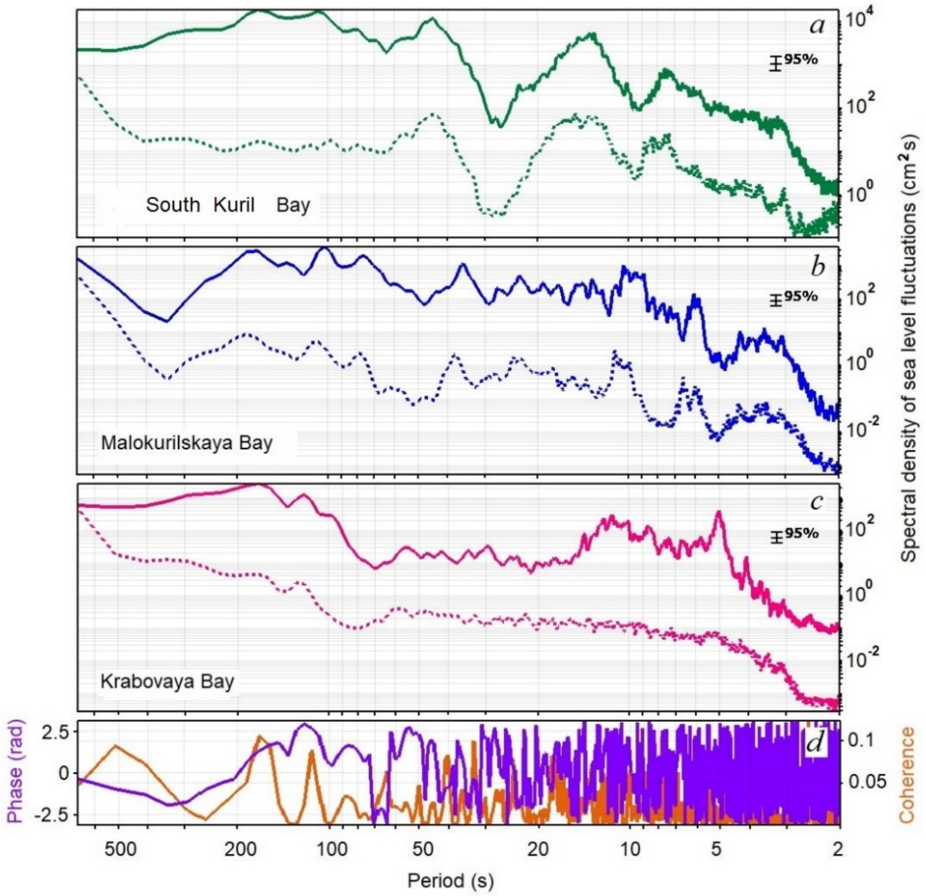
As for the intensification of seiches at low ebb levels, the authors suggest the presence of the mechanism described in [26]. It shows that the synchronism of the wave packet initiation and the K_1 wave is associated with the cyclic separation of the tidal stream of K_1 oscillations from the height located between the islands in the Urup Strait, with the accompanying creation of eddies, which subsequently generate wave packets.

In the case under consideration, a similar situation is possible with the tidal flow separation at the heights of the straits between the South Kuril Islands, connected with the South Kuril Strait. A similar effect was also described based on the study results of Palawan Island [27], where a strong tide over the Aves Ridge was suggested as a probable mechanism for the generation of solitons arriving on the southern coast of Puerto Rico. The papers [3, 24] describe additional studies confirming the relationship between the internal tide – soliton – coastal seiches in the northern part of the Caribbean.

Range of periods for wind waves, swell and infragravity waves

The study of this range of wave periods from about 5 s to 10 min is of interest, since, when coming in the coastal zone, these waves contribute to the formation of rhythmic landforms, bars and can be responsible for the coastline destruction and, as a result, damage to coastal engineering structures, especially taking into account the fact that part of Yuzhno-Kurilsk is located on a low coast near the sea. In contrast, Malokurilskoye and Krabozavodskoye are located on the shores of fairly well-closed bays, and the waves on the coast near these settlements are much less. This is also seen from the comparison of the spectral density graphs of sea level oscillations for three points (Fig. 6).

Since waves in the range of considered periods can pose the greatest danger to the Yuzhno-Kurilsk coast, a more detailed attention will be paid to these wave processes. According to Fig. 6, during a storm in the South Kuril Bay, the spectral density graph of sea level oscillations in the range of wind waves and swell is quite smooth. Two gentle peaks are distinguished at periods of about 7.5 and 14 s, corresponding to swell waves. The second period is close to the low-frequency boundary of these waves and is apparently determined by the swell coming from the Pacific Ocean.

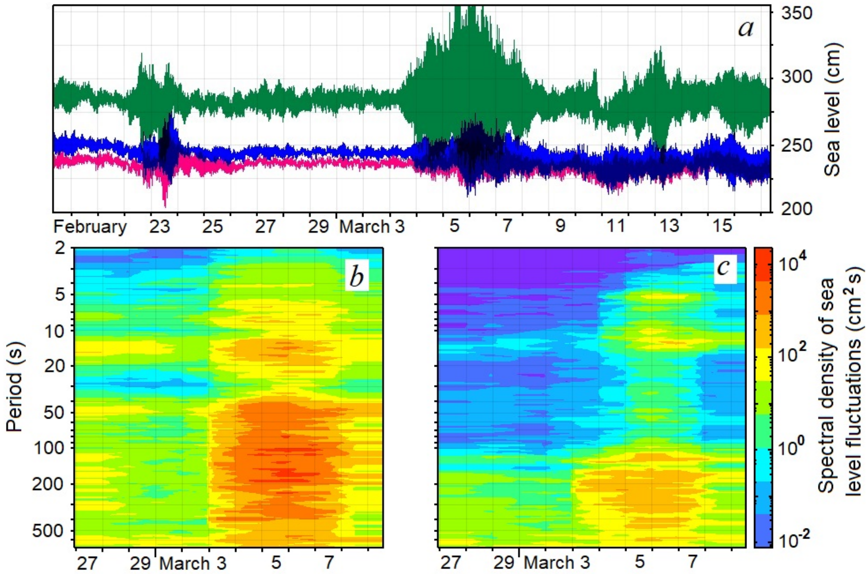


F i g. 6. Spectral densities of sea level oscillations (*a* – *c*) for the storm on March 3–8, 2020 (solid lines) and for calm weather in February 26–March 3, 2020 (dashed lines). Coherence (orange line) and phase (purple line) are between time series of the Malokurilskaya and Krabovaya bays (*d*)

On the spectrogram for the storm (Fig. 7, *b*), two peaks are also clearly distinguished. However, in the range of infragravity waves with periods over 30 s on March 3–7, the spectrum does not contain significantly pronounced peaks (Fig. 7, *b*). At the same time, for calm weather, a series of peaks (Fig. 6, *a*) on the periods of wind waves and swell from 3 to 15 s are clearly distinguished on the spectral density graph, and on the spectral density diagram (Fig. 7, *b*) for light waves on March, 27, the mode structure of infragravity waves is clearly manifested. This is especially noticeable in the spectral peaks at periods of about 50, 120 and 300 s.

The phenomenon of spectral peak attenuation during a storm was also noted in [28] for the bay of the port of Kholmsk. A significant attenuation of the peaks in the spectra in the present study is explained by the transition of a dynamic system (the water mass in the Kholmsk Bay, oscillating at resonant periods excited by an external influence – an incoming swell) to chaotic vibrations. This conclusion was made based on diagnostic tests proposed by F. Moon [29] and confirmed by modeling a dynamic system using the Duffing equation.

We believe that in this case, with the external excitation arrival (storm waves of large amplitude, reaching 85 cm during observations) in the South Kuril Bay, the spectrum of infragravity waves is wide and does not contain significantly pronounced periodic wave processes, i.e., can be attributed to the spectrum chaotic process. In addition, since the dynamic system converts the swell energy with periods of 10–15 s into periods of lower frequency infragravity oscillations, which is possible only in nonlinear systems, the considered dynamic system is also nonlinear.



F i g. 7. Time variation of sea level oscillations with the subtracted tide (*a*) (red color – based on the device *112* data, blue color – *819*, green color – *813*); spectrogram of the time series segment for the South Kuril Bay (*b*) and time series spectrogram for the Krabovaya Bay (*c*)

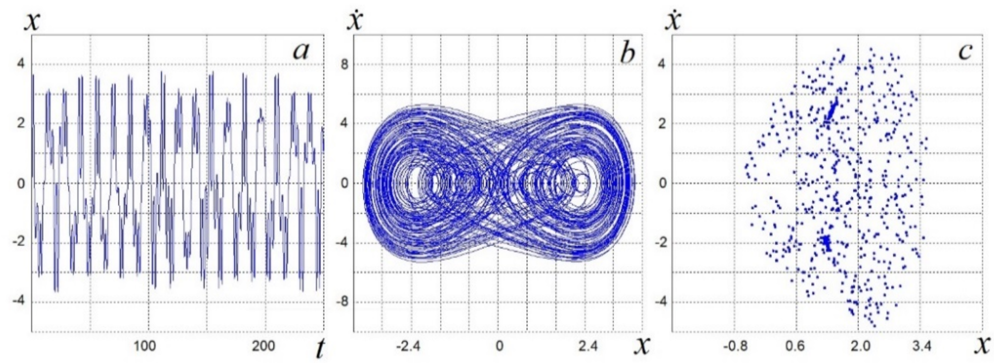
To test the possibility of chaotic waves in the South Kuril Bay, numerical simulation of oscillations was carried out using the Duffing oscillator. Its special feature is the possibility of obtaining chaotic dynamics [30]. At the same time, the nonlinear system considered here (the water mass in the South Kuril Bay) can be represented by the Duffing equation, which describes a 2nd order system with irregular oscillations and an external periodic effect – storm waves [5] [30]. The system model is described by an equation in the following form

$$\ddot{x} + k\dot{x} + \omega_0^2 x + \alpha x^3 = F\cos\omega t\,, \tag{3}$$

where the dot denotes differentiation by time t; F and ω is the amplitude and frequency of external periodic excitation (T period); ω_0 is the eigen frequency of the oscillator (T_0 period); k is the attenuation coefficient; α is the coefficient of non-linearity. This equation describes the motion of a classical particle in the double well potential.

[5] Hayashi, C., 1986. *Nonlinear Oscillations in Physical Systems*. Princeton, New Jersey: Princeton University Press, 410 p.

The results of numerical simulation of the dynamic system under consideration (3) – the interaction of infragravity waves in the water area with incoming swell waves, carried out using the software [6], showed that for the periods of infragravity waves detected in the bay and incoming swell waves with periods of 14 s, with an increase in the external F action amplitude and small value of the attenuation parameter k in a dynamic system, chaotic vibrations may occur. Fig. 8 shows the model time course of dynamical system fluctuations, its phase portrait and the Poincaré mapping. They show that for the values of the parameters indicated below the figures, chaotic vibrations will be observed in the dynamic system with weak attenuation near the second subharmonic [29]. The simulation shows that when F decreases to 0.1 and the nonlinearity coefficient α to 0.05, the oscillations in the system will be harmonic.



F i g. 8. Model time variation of the dynamic system fluctuations (*a*), its phase image (*b*) and the Poincaré mapping (*c*) for the model parameters: amplitude F = 6.5 and period of external forcing T = 14 s; period of eigen oscillations of the oscillator T_0 = 166 s; attenuation coefficient $k = 10^{-3}$; non-linearity coefficient α = 0.5

Note that the problem of the sea wave transition to the chaotic one is touched upon here because the study of the behavior of marine dynamical systems by chaotic motions is necessary for practical purposes and taking into account the consequences that the emergence of complex dynamics can lead to. At the same time, in chaotic environments, such as water, a huge wave with destructive power can appear from a combination of small magnitude waves. Therefore, consideration of the question of the possible system transition to chaotic vibrations is important.

Conclusion

Long-term (up to 12 months) observations of wave processes (sea level oscillations) and water temperature were carried out at three points in the coastal zone of the South Kuril Strait. As a result, high-quality time series with one second discreteness were obtained, which enabled to carry out a detailed study of wave processes in the strait and bays in a wide range of periods – from wind waves to tidal waves.

[6] Kovalev, P.D. and Ivolgin, V.I., 2018. *Puan* [computer program] Yuzhno-Sakhalinsk: Institute of Marine Geology and Geophysics, registration no. RU2018665955 (in Russian).

In the range of sea level oscillations with periods greater than 1 h, powerful peaks are distinguished on the spectral density plot at periods of diurnal, semidiurnal tidal harmonics. The energy of tidal harmonics of shorter periods is less by about two orders of magnitude. For all tidal harmonics, time series coherence of the South Kuril and Krabovaya bays exceeds the confidence level.

The calculated spectral densities of sea water temperature oscillations for periods longer than 1 h showed that their graphs are quite smooth with a decay law of about −1/2. The peak exceeding the 95% confidence interval for three time series has a period of 23.97 h and corresponds to the K_1 tidal harmonic. Peaks at periods of 12.0 and 12.43 h are somewhat smaller than the confidence interval, except for the Malokurilskaya Bay, but even here the excess is insignificant. The periods of these peaks also correspond to tidal harmonics.

For the estimated calculation of seiche periods, a formula according to the Dubois method was used, which is applicable to determine the single-node seiche period in a variable depth water area. At the same time, the length of the South Kuril Strait was divided into 15 segments, and the depth was recorded at each segment boundaries. The calculation showed 5.0 h period, which is close to the peak with 4.8 h period, determined from the spectral density of sea level oscillations. However, it is not possible to unambiguously determine whether these oscillations are seiches, since the $3KM_5$ tidal harmonic has a close period of 4.86 h.

The calculation of seiche periods using the formula for a semi-open rectangular basin showed possible periods of seiche oscillation modes from 0.42 to 2.9 h. It is shown that the magnitude of these peaks does not depend on the tide, which means that the corresponding wave processes of non-tidal origin are seiches or, possibly, edge waves. At the same time, the results of a spectral analysis of three time series show that seiches in the South Kuril Strait have low energy and are relatively weak, which means that there are no conditions for their significant resonant amplification, which is consistent with the conclusions of M. Nakano and S. Unoki.

The issue of tidal energy transfer to seiches, the possibility of which is suggested by G.S. Giese et al. is considered. It is shown that a part of the energy of tidal waves is transferred to seiche oscillations of the Krabovaya and Malokurilskaya bays, since an increase in seiche amplitudes with an increase in tide height is observed. A hypothesis to explain this effect was proposed by G.S. Giese, and theoretical support using the dynamic mechanism of coastal seiche generation by deep-water internal waves excited by barotropic tide was carried out by D.K. Chapman and G.S. Giese.

At the same time, most of the energy in the studied water areas is transferred to seiche oscillations from other sources, which was shown by the analysis of waves during the passage of atmospheric disturbances over the observation area. It was not possible to estimate the tidal energy transfer to seiches in the South Kuril Bay due to significant background oscillations in this area.

An analysis of level oscillations in the range of infragravity waves was carried out. Taking into account the nature of the spectral density change of level oscillations in the South Kuril Bay with the arrival of waves, as well as the theoretical prerequisites outlined by F. Moon, an assumption about the possibility of transition of oscillations in the bay to chaotic ones has been made.

The carried-out simulation of the dynamic system behavior – the water mass of the bay, excited by the incoming waves, showed that for the periods of infragravity waves and incoming swell waves with periods of 14 s detected in the bay, with an increase in the external influence amplitude, chaotic vibrations may occur in the dynamic system. This should be taken into account to ensure the safety of navigation, since in chaotic environments a destructive wave can arise from a combination of small waves.

REFERENCES

1. Kovalev, P.D., Shevchenko, G.V. and Kovalev, D.P., 2005. [Study of Long-Wave Motions in the Southern Part of the Kuril Chain]. In: V. N. Khramushin, ed., 2005. *Marine Researches and Technique of Ocean Studies*. Vladivostok: FEB RAS. Iss. 1, pp. 69-81 (in Russian).
2. Kovalev, P.D., Shevchenko, G.V. and Kovalev, D.P., 2005. Investigation of the Sea Level Fluctuations in the Yuzhno-Kurilskaya Bay in 2005. In: OSCORA, 2005. *Proceedings of the 21st International Symposium on Okhotsk Sea & Sea Ice: Mombetsu, Hokkaido, Japan, 19-24 February 2006*. Mombetsu, Hokkaido, Japan: OSCORA, pp. 225-231.
3. Giese, G.S., Chapman, D.C., Black, P.G. and Fornshell, J.A., 1990. Causation of Large-Amplitude Coastal Seiches on the Caribbean Coast of Puerto Rico. *Journal of Physical Oceanography*, 20(9), pp. 1449-1458. https://doi.org/10.1175/1520-0485(1990)020<1449:COLACS>2.0.CO;2
4. Plekhanov, Ph.A. and Kovalev, D.P., 2016. The Complex Program of Processing and Analysis of Time-Series Data of Sea Level on the Basis of Author’s Algorithms. *Geoinformatika*, (1), pp. 44-53 (in Russian).
5. Parker, B.B., 2007. *Tidal Analysis and Prediction*. NOAA Special Publication NOS CO-OPS 3. Silver Spring, Maryland: NOAA, 378 p.
6. Wilson, B.W., 1972. *Seiches*. Advances in Hydroscience, vol. 8. Elsevier, pp. 1-94. https://doi.org/10.1016/B978-0-12-021808-0.50006-1
7. Korgen, B.J., 1995. Seiches. *American Scientist*, 83(4), pp. 330-341.
8. De Jong, M., 2004. *Origin and Prediction of Seiches in Rotterdam Harbor Basins*. The Netherlands: Partners Ipskamp Beheer B.V., 119 p.
9. Rabinovich, A.B., 2009. Seiches and Harbor Oscillations. In: Y. C. Kim, ed., 2009. *Handbook of Coastal and Ocean Engineering*. Singapore: World Scientific Publishing Company, pp. 193-236. https://doi.org/10.1142/9789812819307_0009
10. Defant, A., 1960. *Physical Oceanography*. Oxford: Pergamon Press. Vol. 2, 598 p.
11. Rabinovich, A.B. and Monserrat, S., 1996. Meteorological Tsunamis near the Balearic and Kuril Islands: Descriptive and Statistical Analysis. *Natural Hazards*, 13(1), pp. 55-90. doi:10.1007/BF00156506
12. Monserrat, S., Vilibić, I. and Rabinovich, A.B., 2006. Meteotsunamis: Atmospherically Induced Destructive Ocean Waves in the Tsunami Frequency Band. *Natural Hazards and Earth System Sciences*, 6(6), pp. 1035-1051. doi:10.5194/nhess-6-1035-2006
13. Hibiya, T. and Kajiura, K., 1982. Origin of the Abiki Phenomenon (a Kind of Seiche) in Nagasaki Bay. *Journal of the Oceanographical Society of Japan*, 38(3), pp. 172-182. doi:10.1007/BF02110288
14. De Jong, M.P.C., Holthuijsen, L.H. and Battjes, J.A., 2003. Generation of Seiches by Cold Fronts over the Southern North Sea. *Journal of Geophysical Research: Oceans*, 108(C4), 3117. doi:10.1029/2002JC001422
15. Giese, G.S. and Chapman, D.C., 1993. Coastal seiches. *Oceanus*, 36(1), pp. 38-46.
16. Rabinovich, A.B., 1993. [*Long Gravity Waves in the Ocean: Trapping, Resonance, Radiation*]. Leningrad: Gidrometeoizdat, 324 p. (in Russian).
17. Rabinovich, A.B. and Levyant, A.S., 1992. *Influence of Seiche Oscillations on the Formation of the Long-Wave Spectrum near the Coast of the Southern Kuriles*. Oceanology, 32(1), pp. 17-23 (in Russian).

18. Sudolsky, A.S., 1991. [*Dynamic Phenomena in Reservoirs*]. Leningrad: Gidrometeoizdat, 262 p. (in Russian).
19. Maramzin, V.Ya., 1985. Calculations of Seiche Oscillations by the Method of Finite Elements in a Basin of Arbitrary Form. In: DVNTS Akad. Nauk SSSR, 1985. *Theoretical and Experimental Investigations of Long-Wave Processes*. Vladivostok: DVNTS Akad. Nauk SSSR, pp. 104-114 (in Russian).
20. Nakano, M. and Unoki, S., 1962. On the Seiches (the Secondary Undulations of Tides) along the Coast of Japan. *Records of Oceanographic Works in Japan*, (6), pp. 169-214.
21. Morozov, E.G., 1995. Semidiurnal Internal Wave Global Field. *Deep Sea Research Part I: Oceanographic Research Papers*, 42(1), pp. 135-148. doi:10.1016/0967-0637(95)92886-C
22. Müller, P. and Briscoe, M., 1999. Diapycnal Mixing and Internal Waves. In: University of Hawaii, 1999. *Proceedings Hawaiian Winter Workshop, University of Hawaii at Manoa, Jan 18-22, 1999*. Hawaii: University of Hawaii, pp. 289-295.
23. Müller, P. and Briscoe, M., 2000. Diapycnal Mixing and Internal Waves. *Oceanography*, 13(2), pp. 98-103. doi:10.5670/oceanog.2000.40
24. Giese, G.S., Hollander, R.B., Fancher, J.E. and Giese, B.S., 1982. Evidence of Coastal Seiche Excitation by Tide-Generated Internal Solitary Waves. *Geophysical Research Letters*, 9(12), pp. 1305-1308. doi:10.1029/GL009i012p01305
25. Chapman, D.C. and Giese, G.S., 1990. A Model for the Generation of Coastal Seiches by Deep-Sea Internal Waves. *Journal of Physical Oceanography*, 20(9), pp. 1459-1467. doi:10.1175/1520-0485(1990)020<1459:AMFTGO>2.0.CO;2
26. Squire, V.A., Kovalev, P.D. and Kovalev, D.P., 2021. Soliton-like Waves in the Vicinity of the Southern Kuril Islands. *Physical Oceanography*, 28(1), pp. 3-19. doi:10.22449/0233-7584-2021-1-3-19
27. Giese, G.S., 1983. The relationship between coastal seiches in Puerto Rico and tide generated internal solitary waves. In: E. H. Williams, ed., 1983. *Proceedings of the Association of Island Marine Laboratories of the Caribbean, 17th meeting, Miami, USA, 16–20 May 1983*. Miami, USA: University of Miami. Vol. 17, pp. 17. Available at: http://www.amlc-carib.org/meetings/procs/1983AMLC_Proceedings.pdf [Accessed: 27 July 2023].
28. Kovalev, P.D. and Kovalev, D.P., 2019. The Dependence of the Wave Mode from External Periodic Excitation in the Harbor of Port Kholmsk. *IOP Conference Series: Earth and Environmental Science*, 324, 012016. doi:10.1088/1755-1315/324/1/012016
29. Moon, F.C., 1987. *Chaotic Vibrations: An Introduction for Applied Scientists and Engineers*. Chichester: John Wiley & Sons, Ltd., 309 p.
30. Kovacic, I. and Brennan, M.J., eds., 2011. The *Duffing Equation: Nonlinear Oscillators and their Behaviour*. Chichester, West Sussex, U.K.: Wiley, 392 p. doi:10.1002/9780470977859

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