

Article

Dynamics and Transformation of Internal Waves on a Shelf with Decreasing Depth

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Abstract: Based on the field data of laser interference devices obtained on the shelf of the Sea of Japan, the interaction of internal sea waves with the bottom and the transfer of energy from the sea wave to the seismic acoustic wave were studied. It has been established that when internal waves move from the depth dump to the surf zone, they transform, and their period decreases. When the energy of the internal wave is transformed into elastic bottom vibrations, the flow density is estimated to spread evenly over a shelf about 30 km wide. Taking into account the maximum amplitudes of elastic bottom vibrations caused by offshore internal waves, the density of the seismic energy flux will increase by 2–3 orders of magnitude and will be comparable to the density of the seismic energy flux caused by surface sea waves.

Keywords: internal waves; temperature sensor; laser meter of hydrosphere pressure variations; microseisms; maximum entropy method

1. Introduction

A large number of studies, mainly of theoretical model nature with the formulation and implementation of numerical experiments, are devoted to peculiarities of origin, development, and dynamics of internal sea waves in various conditions and their influence on the geophysical processes of their propagation environment, including the ambient biota. There have been considerably fewer field experimental studies due to the complexity of solving the set tasks, which take into account spatial and temporal scales required for conducting full-scale experiments.

Internal waves propagate in stratified ocean waters and are ubiquitous and well-studied features of continental shelves [1,2]. Large-amplitude internal waves interacting with the bathymetry can break down, forming wave packets, and travel up the shelf of decreasing depth to the surf zone [3–11]. Internal waves' dynamics is important for vertical mixing, cross-shelf transport, environmental variability, and the exchange of heat, nutrients, sediments, and pollutants in coastal ecosystems worldwide [12–21]. Currently, the most comprehensive picture of shelf internal waves' dynamics, including breaking, energy distribution and mixing, comes from laboratory and numerical studies [22–27].

Further, we would like to note interesting points described in other papers that are of some relevance to the main part of our work. For example, in [28], reflected internal waves associated with large-amplitude internal waves are observed in satellite data. In addition, the numerical modeling shows that rolling internal waves break down when they reach the sloping bottom. Horizontal energy distribution indicates that the maximum energy, about 2% of the incident radiation energy, is contained in one reflected wave. This may explain



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why reflected waves are rarely observed, since reflected waves must be large enough to be detected in satellite images. Although the energy of individual waves is small, up to 20% of an incident wave is reflected by wave groups.

In the work [29], the authors argue that part of the energy of an unreflected wave is lost due to irreversible turbulent mixing in the slope region during shallowing, and the propagating internal waves do not terminate abruptly but gradually decay.

In laboratory experiments to study the effect of shallow water on the attenuation of a single wave in a homogeneous layer, ref. [24] states that shoaling of a single wave leads to its destruction and formation of many turbulent splashes, or boluses, which propagate upslope, i.e., along a shelf of decreasing depth. Significant vertical mixing occurs everywhere from the shore to the rupture site. The kinematics of the rupture and the boluses run-up are described, and a rupture criterion is found. The energy of the rupture is investigated. In the considered range of parameters, 15% of the energy lost at the rupture point during the wave's movement toward the shore is spent on vertical mixing.

In the paper [4], the author discusses the behavior of internal waves in the presence of a seabed and argues that the kinetic energy of waves approximately twice exceeds the potential energy. The observed turbulence is not strong enough to dissipate the energy of the waves before they reach the shore. Because of high wave speeds on the seabed, the bottom stress is supposed to be an important source of wave energy loss, as opposed to solitary waves on the surface.

The work [30] showed that the solitons' energy dissipated sharply along the steep bottom slope, probably as a result of bottom friction and turbulent mixing. Internal solitons began to interact with the bottom and deformed when their amplitudes approached half the thickness of the near-bottom layer.

Back in 1997, ref. [31] showed that introducing bottom friction into numerical modeling allowed us to obtain results that were in good agreement with field observations of the dynamics of amplitudes and phases of internal waves propagating along the shelf from the initial observation point to distances of 13.5 and 26 km.

Thus, a quick review of some of the above studies leads to the conclusion that the bottom shape and friction against it play a great role in describing the observed internal waves of various shapes and configurations. When introducing friction coefficients of a specific value, the obtained results are in good agreement with the results of field observations. We can ask, if this is really so, does the bottom in these problems act as an absolutely reflective medium? And what does the friction coefficient have to do with it? If there is a friction coefficient, then there is also absorption of a part of the internal wave energy by the medium (bottom). Thus, the bottom should be considered as a medium that carries away a part of the energy of internal waves propagating along the bottom and interacting with it. Apparently, all this is quite ex-ante and only one question remains open: where are the field data confirming these conclusions? In order to confirm these conclusions, it is necessary to conduct fairly complex experiments involving equipment that measures the propagating elastic waves in the bottom, which result from the transformation of the energy of internal sea waves into the energy of elastic waves propagating at the bottom, at the corresponding periods. Considering that the periods of shelf internal waves are in the range from several minutes to several tens of minutes, and even hours, the equipment used must have a linear amplitude–frequency characteristic capable of covering the entire range of periods of interest without distortion, in order to avoid possible incorrect interpretation of the obtained results. In particular, it must have very high sensitivity for measuring elastic displacements of the bottom, since we do not know the values of possible displacements. At present, there is no installation in the world capable of performing such measurements at the bottom. Considering that elastic waves, generated as a result of transformation in the

seabed, propagate along the Earth's crust, the measuring equipment can be installed not at the point of their generation, but on land. However, this equipment must also have unique amplitude–frequency characteristics that allow recording any disturbances in the infrasonic and deep infrasonic ranges (with a linear characteristic) at the background level. At present, laser strainmeters that have the following main measuring characteristics satisfy these requirements to the greatest extent: operating frequency range from 0 (conventionally) to 100 Hz, displacement measurement accuracy based on the measuring arm of the laser strainmeter—0.03 nm [32,33]. The use of one of the described laser strainmeters located on land made it possible not only to record the transformed part of internal sea waves propagating along the shelf of decreasing depth, but also to trace the dynamics of internal waves' movement from the edge of the shelf to the surf zone.

2. Measuring Equipment

In the measurements, we used various equipment to measure temperature variations in a specific area of the sea, variations in hydrosphere pressure, and microdeformations of the Earth's crust.

Hydrosphere pressure variations were recorded using a laser hydrosphere pressure variations meter [34] or a modified laser hydrosphere pressure variations meter—a supersensitive detector of hydrosphere pressure variations [35]. The main technical characteristics of the latter hydrosphere pressure variations meter are as follows: operating range from 0 (conventionally) to 1000 Hz, accuracy of measuring hydrosphere pressure variations—0.2 MPa, operating depths—up to 50 m.

For temperature measurements, digital temperature sensors (DS18B20) installed inside thin-walled stainless steel housing were used. Contact with the housing surface is ensured by a thermally conductive layer. To improve the contact, the top part of the chip casing is ground before inserting the thermal sensor into the housing. The thermal sensors are capable of detecting a temperature change as small as 0.06 °C, with a response time of no more than 900 ms. Such sensors are installed on each of the above-described laser meters of hydrosphere pressure variation.

The variations in the Earth's crust deformation were recorded using a 52.5 m laser strainmeter, permanently installed on Schultz Cape [33]. Currently, it uses a frequency-stabilized laser as a radiation source, its long-term frequency stability is in the eleventh decimal place, and the short-term stability is 1–2 orders of magnitude better. The use of modern interferometry methods allowed us to achieve the following technical characteristics of the 52.5 m laser strainmeter: the accuracy of measuring crust displacement based on the laser strainmeter is 0.05 nm and the operating frequency range is from 0 (conventionally) to 100 Hz.

Data from all instruments are transmitted via cable lines and arrive at the onshore registration post in real time mode, where they undergo preliminary processing—filtering and decimation—using the hardware–software system and are entered into a database for further analysis and processing. The synchronization of data acquisition is provided by GPS receivers. Figure 1 shows a schematic map of the scientific equipment layout and measurement points.

These instruments were used for several years during the summer–autumn period for continuous monitoring of variations in temperature and pressure near the bottom, as well as microdeformations of the Earth's crust. In the section below, we have considered and analyzed the fragments of the record with registered internal waves for 2023 and 2024.

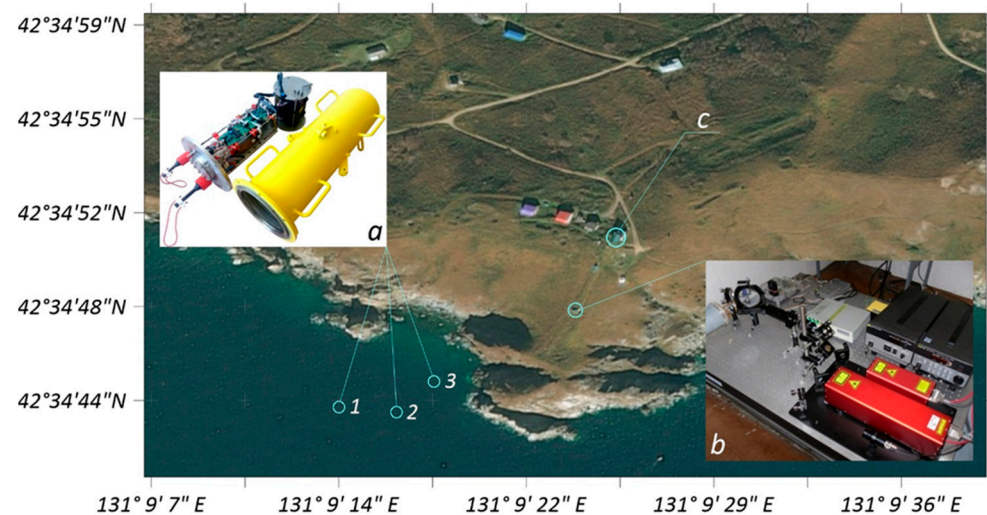


Figure 1. Schematic map of the equipment layout used in this study. Appearance and location of the laser meter of hydrosphere pressure variations (a), laser strainmeter (b), onshore registration point (c). Points 1, 2, and 3 indicate the deployment sites of the laser meters of hydrosphere pressure variations in 2023 and 2024, at depths of 32, 24, and 15 m, respectively.

3. Analysis of the Obtained Experimental Data

In the Sea of Japan, as in all seas of the Pacific Ocean, the main cause of internal waves generation is the barotropic tide. In the oceans, internal waves are mainly generated over the continental slope, the outer part of the shelf or other seabed relief forms, but the causes of their generation are not fully understood. As the results of observations and modeling show, internal waves in these zones are constantly generated by tidal movements and currents that have a component of movement in the direction of decreasing depths—across the shelf [36].

In 2023, the laser meter of hydrosphere pressure variations and temperature sensors installed on it recorded many physical phenomena associated with internal waves. The laser meter of hydrosphere pressure variations was installed on the shelf of the Sea of Japan at a depth of about 30 m (point №1 in Figure 1) to the south from Schultz Cape. When analyzing the obtained data, several characteristic types of internal waves were identified, shown in Figure 1.

The first type of internal waves (Figure 2a) mainly emerge during diurnal and semi-diurnal fluctuations of sea level (tides) and, as a rule, have a larger amplitude of temperature oscillations—up to 10 degrees and a longer period, ranging from 10 to 20 min. The second type (Figure 2b) is a wave packet consisting of several oscillations of small amplitude and periods from 3 to 10 min, relative to the types of internal waves considered below. The occurrence of these packets is not associated with fluctuations of sea level; they emerge on the shelf and propagate up to the measurement point, and then disintegrate in shallow water. The third type of internal waves regularly recorded in the autumn period is a solitary wave (soliton), and it is shown in Figure 2c.

Often, when wave packets enter shallow water or when the hydrological parameters of the environment change, they disintegrate, forming oscillations with a smaller period and amplitude. This phenomenon is shown in Figure 3.

As we can see in Figure 3, a large packet of internal waves with amplitude of 3 degrees and period of 10 min, after several hours of arrival at the measurement point, breaks up into a packet with period of 5 min and amplitude of 1–1.5 degrees, after which the oscillatory process disappears completely.

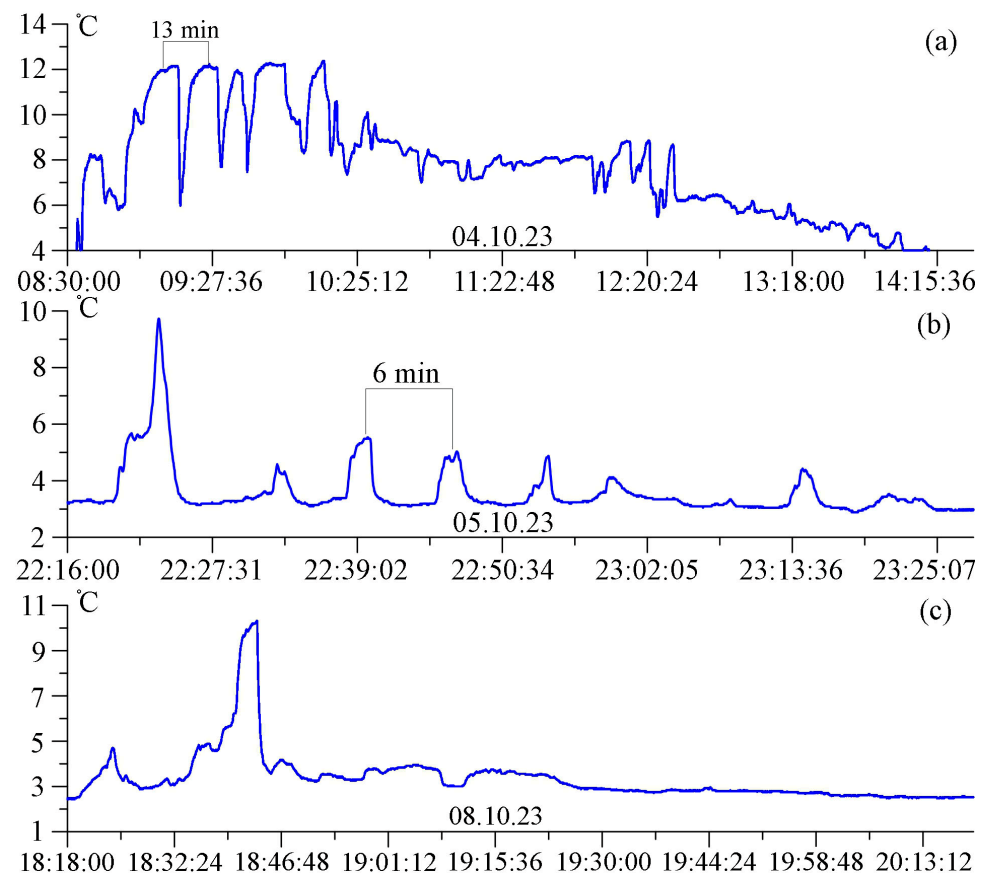


Figure 2. The main types of internal waves recorded using temperature sensors installed on the laser meter of hydrosphere pressure variations. (a) Temperature fluctuations against the background of tidal fluctuations, (b) wave packets, (c) solitary internal wave (soliton).

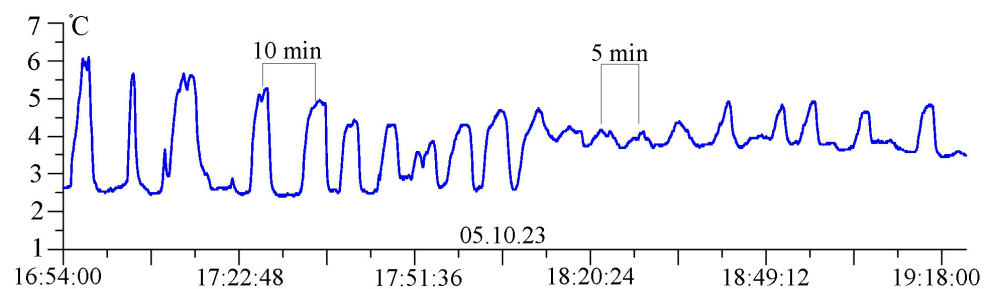


Figure 3. Disintegration of internal waves packet upon entering shallow waters.

Not only temperature sensors but also the laser meter of hydrosphere pressure variations can record internal waves. With its supersensitivity to even the smallest variations in hydrosphere pressure, it can easily record the smallest changes in bottom pressure caused by temperature fluctuations. Synchronous records of bottom pressure and temperature are shown in Figure 4.

As we can see from the graphs, variations in temperature near the bottom correspond to variations in bottom pressure of similar periods and almost similar behavior. It can be expected that variations in bottom pressure, acting on the bottom, cause corresponding variations in bottom deformations, which, propagating along the Earth's crust, can be recorded by the laser strainmeter (Figure 1b) installed on Shultz Cape.

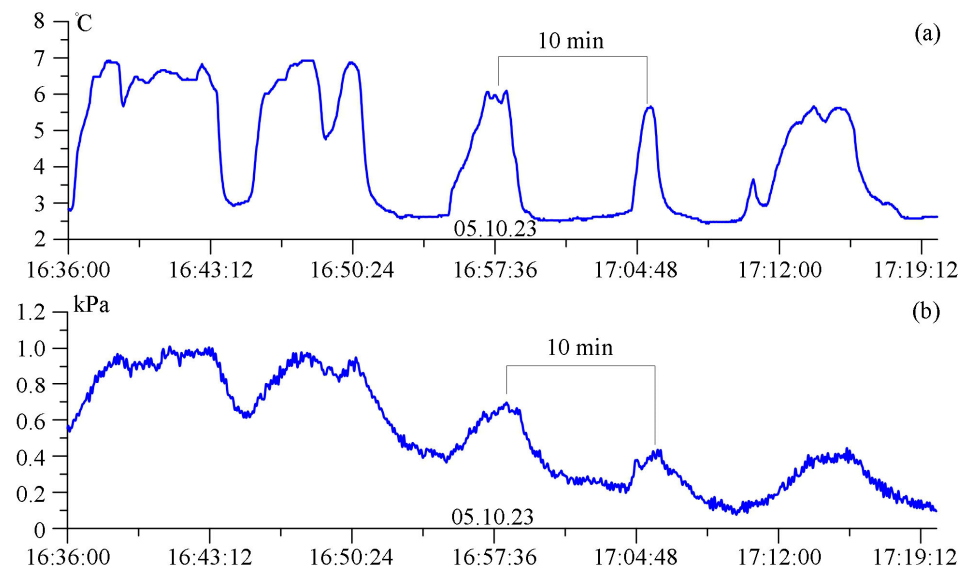


Figure 4. Synchronous records of temperature sensor (a) and laser meter of hydrosphere pressure variations (b).

4. Interrelation Between Thermocline Fluctuations and Microdeformations in the Upper Layer of the Earth's Crust

To investigate the relationship between vertical thermocline fluctuations in the coastal shelf zone and microdeformations of the Earth's crust, we used the experimental data obtained during the summer–autumn period of 2024. For this purpose, two spatially separated meters of hydrosphere pressure variations equipped with temperature sensors were deployed at depths of 24 m and 15 m at the marine experimental station “Shultz Cape” (points 2 and 3 in Figure 1), where temperature variations at the corresponding depths were recorded. Measurements of microdeformations of the Earth's crust were made using a 52.5 m laser strainmeter (Figure 1b). In addition to measurements of the above values, vertical temperature distribution over depth was also measured using a CTD profiler, which allowed monitoring changes in the thermocline depth. The measurements were made during summer and autumn periods at the depth of 35 m near point 1 shown in Figure 1. Figure 5 presents an example of synchronous records of two spatially separated temperature sensors and temperature distribution by depth.

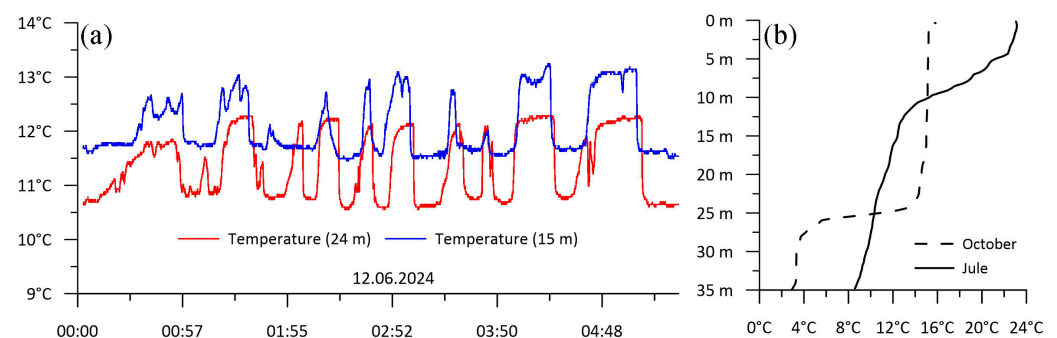


Figure 5. Example of a 5 h fragment of spatially separated temperature sensors synchronous record (a) and temperature–depth profiles based on CTD measurements (b) for July and October 2024.

The analysis of these figures shows that in the strainmeter record spectrum in the frequency range under consideration, clearly defined peaks with periods of 9.5 and 6.1 min with amplitudes of at least 25 dB above the background are distinguished. The magnitude of the shift in elastic oscillations with period of 9.5 min is about 0.4 μm . In the power spectrum of the DTS record, maxima with periods of 9.4 and 6.2 min with amplitudes of

at least 18 dB above the background are distinguished. The periods of the peaks obtained from the DTS and strainmeter records, within the measurement and calculation errors, coincide well with each other. In addition to the above spectral peaks, weaker maxima with periods of 12.4–12.5 and 7.3–7.4 min are present in the power spectra of the DTS and strainmeter records.

The plots of temperature variations from spatially separated sensors (Figure 5a) show oscillations with periods from 10 to 30 min. These fluctuations have a similar pattern on both sensors, with some differences. However, there are differences in the temperature values themselves, which is fully explained by the temperature–depth profile for July, shown in Figure 5b. Looking at the temperature–depth distribution for October (Figure 5b), we can see that the thermocline thickness increases from 10 to 26 m and thus both sensors will be located directly in the thermocline itself. Under these conditions, there will be no constant component in the temperature difference that is present in Figure 5a and, as a consequence, for further studies we can use the data obtained from all sensors located in the seasonal thermocline. These conditions were selected to enable a consistent comparison of the obtained results, thereby increasing the reliability of our conclusions.

Taking into account all of the above, for further analysis, we selected the synchronous fragment of the temperature sensor and laser strainmeter records obtained between 5:00 on 24 September 2024 and 21:30 on 26 September 2024 (UTC). The total duration of this fragment was 46.5 h (167,400 s). During this period, an increased intensity of internal wave packets appearance, associated with seasonal mixing of water in the surface layer, was observed. The data sampling frequencies for the laser strainmeter and temperature sensors were 10 Hz and 8 Hz, respectively. The difference in sampling frequencies is due to the fact that an analog signal from the laser strainmeter arrives at the registration point, and then it is digitized by the analog-to-digital converter. Temperature sensors transmit data in digital format, and their effective sampling frequency corresponds to the polling rate, which depends on the control microcontroller located inside the laser meter of hydrosphere pressure variations. The linear trend associated with a negative gradient of temperature change (approximately 1.5 °C) is then subtracted from the data from both temperature sensors. This operation was performed to ensure that the temperature gradient did not affect the low-frequency region during spectral analysis. Next, data were sampled with a time step $\Delta t = 150$ s for the laser strainmeter and $\Delta t = 120$ s for the temperature sensors to bring all data series to the same size.

Before spectral analysis, the experimental data were weighted in the time domain by a four-term Blackman–Harris window with side lobe level of –94 dB. To reduce the variance of the spectral estimation, averaging of the spectra obtained from the data segments overlapping by 50% was applied. In order to compare and validate the results obtained for the investigated data segments, spectra were also plotted using the maximum entropy method [37]. Since the results of spectral analysis for both temperature sensors are completely identical, Figure 6 shows the spectra of only one of the sensors installed at the depth of 24 m (point 2 of Figure 1). The results of spectral analysis of the laser strainmeter data are presented in Figure 7.

The analysis of these figures shows that in the strainmeter record spectrum in the frequency range under consideration, clearly defined peaks with periods of 9.5 and 6.1 min with amplitudes of at least 25 dB above the background are distinguished. The magnitude of the shift in elastic oscillations with a period of 9.5 min is about 0.4 μm . In the power spectrum of the DTS record, maxima with periods of 9.4 and 6.2 min with amplitudes of at least 18 dB above the background are distinguished. The periods of the peaks obtained from the DTS and strainmeter records, within the measurement and calculation errors, coincide well with each other. In addition to the above spectral peaks, weaker maxima

with periods of 12.4–12.5 and 7.3–7.4 min are present in the power spectra of the DTS and strainmeter records.

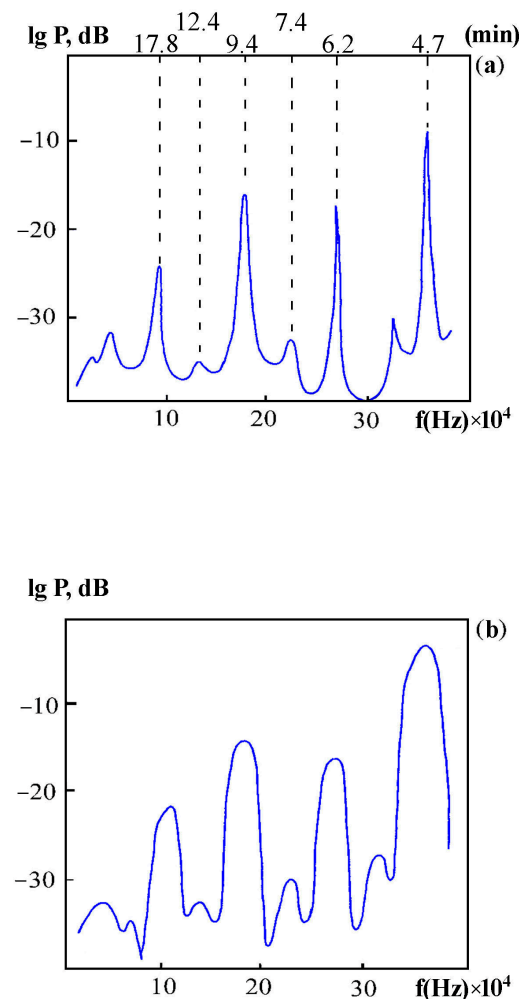


Figure 6. Power spectra based on data from the temperature sensor installed at the depth of 24 m, obtained using the maximum entropy method (a) and the fast Fourier transform (b).

The comparison of the spectra of the laser strainmeter and pressure sensor data shows that they have many coincidences. However, the presence of a large number of harmonics brings up a question of their physical nature. We compared the power spectra over a 46.5 h interval, which means that some harmonics may be a consequence of energy transfer from other harmonics in time, for example, a change in period due to the exit of an internal wave in shallow water.

In order to trace the dynamics of harmonic changes with time, long-term measurements (17.5 days) of background seismoacoustic oscillations in the range of internal waves were carried out using the laser strainmeter. After preliminary processing of the series, it was divided into smaller sections where oscillations in the range of internal wave periods (6–20 min) were clearly present. An example of such a section is shown in Figure 8. A consecutive series of spectra with 50% overlap was plotted for these sections. The duration of the plot for each spectrum construction was 8 h, with the overlap with the neighboring plot of 4 h. Figure 9 presents such a series of spectra constructed on the record fragment shown in Figure 8, with harmonics in the period range of interest.

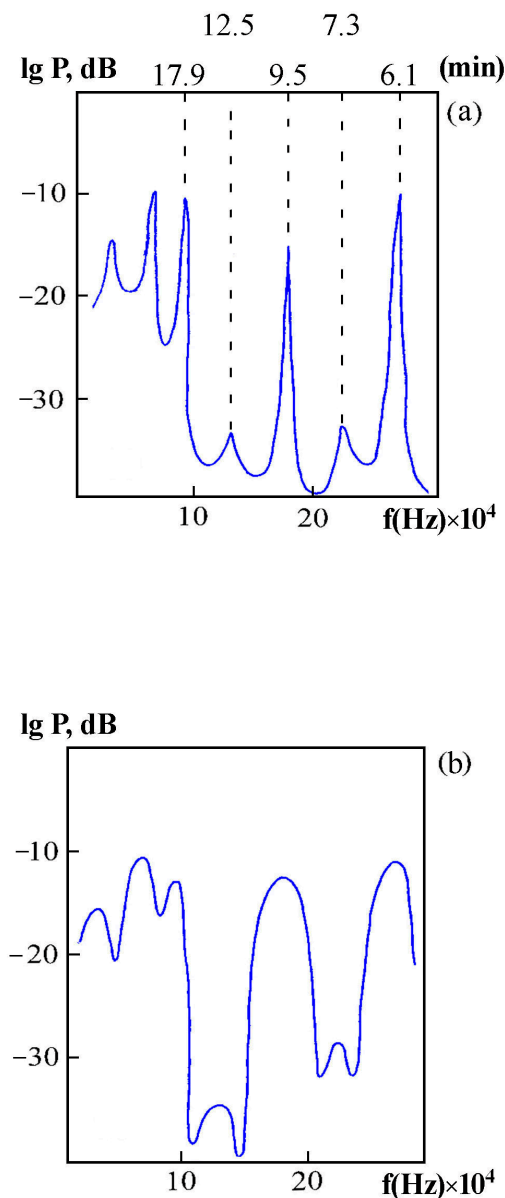


Figure 7. Power spectra based on data from the laser strainmeter, obtained using the maximum entropy method (a) and the fast Fourier transform (b).

Provided that the process of internal waves period decrease, shown in Figure 9, occurs over the entire width of the shelf (30 km), and knowing the duration of the transformation process (1536 min), we can find the average speed of internal wave propagation along the shelf. It is equal to 32 cm/s, which is in good agreement with the theoretical model calculations and experimental data obtained by other methods in this region. In addition, when analyzing the change in depth from the slope to the shore and considering the experimental data, it follows that the degree of change in the period of internal waves is directly proportional to the degree of change in the depth of the shelf zone area along which the internal gravity wave moves.

Figure 9 shows that the dominant peak in the first power spectrum plot has period of approximately 12.5 min. Subsequently, the energy from this peak “flows” successively to higher-frequency spectral components. Figure 9 clearly shows such behavior in the following sequence: 12.5 min–10.9 min–10.2 min–8.9 min–8.5, and 8.2 min. Below, we will try to explain the reasons for such behavior of harmonics in the spectrum.

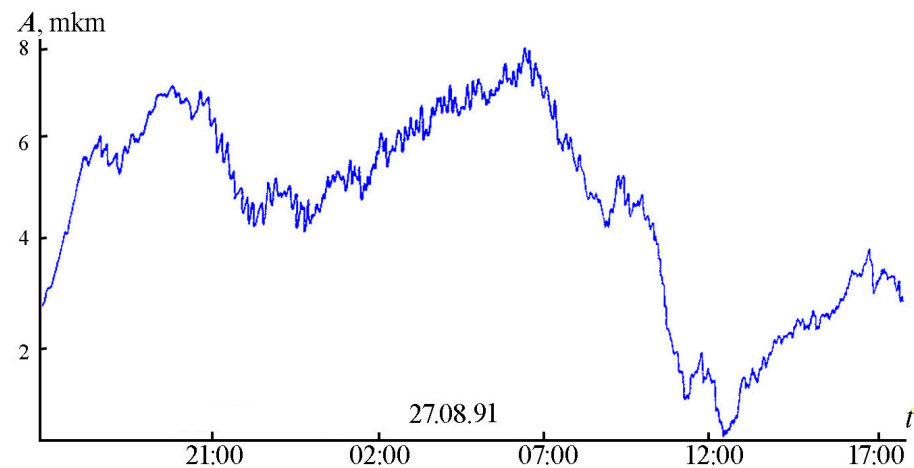


Figure 8. Fragment of the 52.5 m coastal laser strainmeter record. The ordinate axis shows the amplitude of the strainmeter abutment displacement (μm), and the abscissa axis shows Vladivostok time (UTC + 10 h).

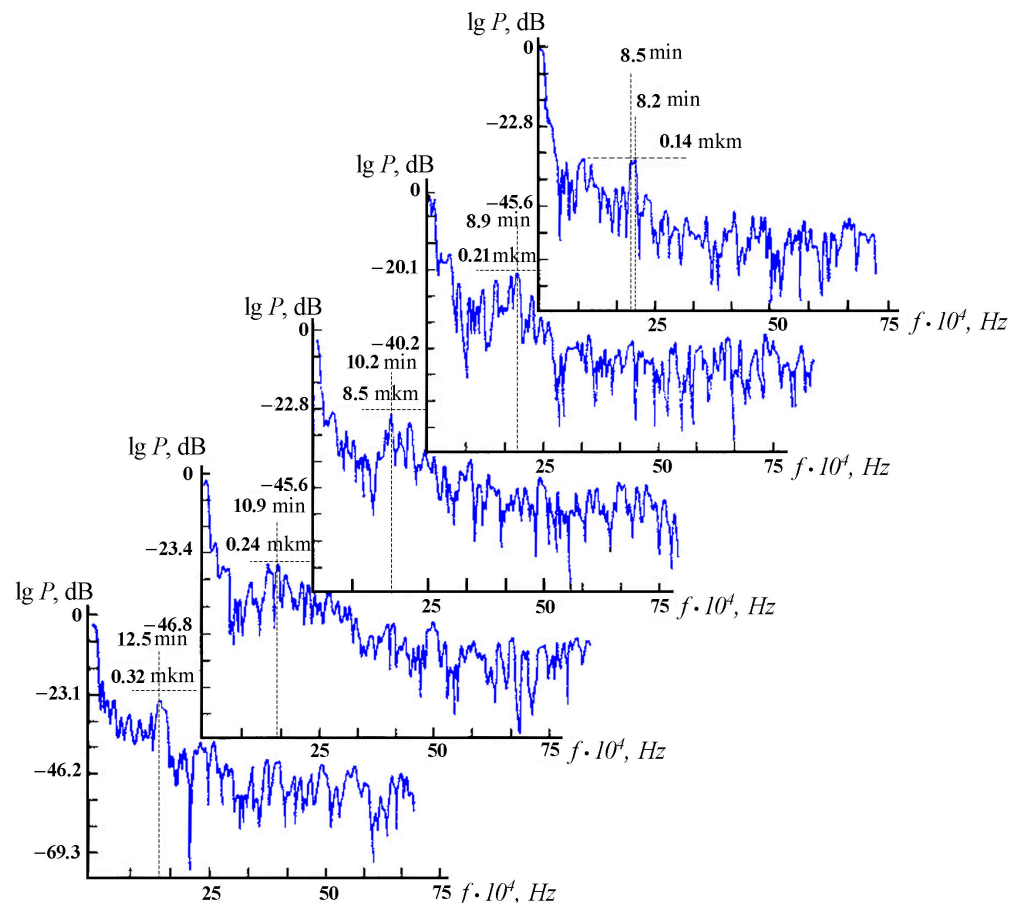


Figure 9. Successive series of power spectra with 50% overlap of adjacent fragments of the 52.5 m coastal laser strainmeter record.

5. Discussion of the Obtained Results

In the light of the above, several questions arise, the primary being whether internal waves can excite seismoacoustic oscillations in the lithosphere when moving along a flat or wedge-shaped shelf, and not only in the zones of abrupt depth changes (slope, shore). Based on the results of analyzing the spectra from the laser strainmeter and temperature sensors presented in Figures 6 and 7, we can give the answer: yes. However, the problem of analyzing the contribution of internal waves on the shelf in forming the

general seismoacoustic background is complicated by the fact that the shelf slope zone is not the only site of internal waves' generation. We know that internal waves can also be generated by barotropic tides interacting with specific seabed topographies. In [38,39], the mechanism of low-frequency microseisms generation by the interaction of internal waves with seabed topography irregularities was theoretically substantiated. Moreover, there are known cases of self-modulation and intensification of wave trains with short periods on the shallow shelf.

When considering the spectra presented in Figures 6 and 7, we can observe four distinct harmonics both in the spectrum plotted from the temperature sensors and from the laser strainmeter data. Hence, the second question arises, related to the physical processes contributing to the emergence of such a variety of internal wave periods on the shelf of decreasing depth.

In the spectrum of the temperature sensor record (Figure 6), a maximum with a period of 4.7 min can be distinguished, whose frequency is twice that of the main period of 9.4 min. The existence of this peak can be explained either by the presence of a standing wave due to reflection from the shore or by nonlinear generation of the second harmonic of the progressive internal wave with a period of 9.4 min. To confirm one or the other assumption, it is necessary to carry out additional experimental work associated with installation of additional temperature sensors directly near the shore. Another explanation may be the "flow" of energy from lower harmonics to higher harmonics; namely, an internal wave with period of about 12.5 min (one of those mentioned above) is initially generated. Due to significant nonlinearity and instability, the energy of the internal wave of a larger scale "flows" into the energy of the internal wave of a smaller scale. At the same time, this process is not discontinuous (given an almost flat sloping bottom), but consistent in the specified range. Such exact process can be observed in the consecutive series of spectra presented in Figure 9.

Provided that the process of internal waves period decrease, shown in Figure 9, occurs over the entire width of the shelf (30 km), and knowing the duration of the transformation process (1536 min), we can find the average speed of internal wave propagation along the shelf. It is equal to 32 cm/s [40], which is in good agreement with the theoretical model calculations and experimental data obtained by other methods in this region. In addition, when analyzing the change in depth from the slope to the shore and analyzing the experimental data, it follows that the degree of change in the period of internal waves is directly proportional to the degree of change in the depth of the shelf zone area along which the internal gravity wave moves.

6. Conclusions

The conducted experimental studies have shown that internal sea waves, when interacting with the bottom, excite seismoacoustic waves of corresponding periods in it. We have also established that when moving from the zone of generation (shelf break) to the surf zone, internal waves sequentially transform from internal waves of large periods to internal waves of smaller periods. We can assume that the degree of change in the periods of internal waves depends on the energy transferred by an internal sea wave to a seismoacoustic wave, which is also associated with the degree of change in the sea depth.

Let us estimate the seismic energy flux density that occurs as a result of propagation of a Rayleigh-type wave with periods of 8.2–12.5 min and amplitudes of 0.14–0.32 μm , which occurs when internal waves of the corresponding periods pass along the shelf and transform the energy of internal waves into the energy of elastic oscillations of the bottom. The seismic energy flux density in this case will be equal to $1.3 \times 10^{-10} \text{ J/s m}^2$. This flux density is distributed uniformly over a shelf about 30 km wide at any given time.

Taking into account only the maximum amplitudes of elastic bottom oscillations caused by the propagating shelf internal waves existing in the area of the instrument operation, the seismic energy flux density relative to a calm medium will increase by 2–3 orders of magnitude and be comparable to (or slightly less than) the seismic energy flux density caused by surface sea waves. It can have a significant impact on tectonic processes in the shelf area of the sea and adjacent regions.

Author Contributions: G.D.—problem statement, discussion, and writing of the article. S.B.—data processing, visualization. S.D.—data processing, discussion, and writing of the article. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Third party data. Restrictions apply to the availability of these data.

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