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Long Wave Investigation at the Shelf and in the Bays of South Kuril Islands
南部 Kuril 列島의 陸棚과 灣에서의 長波分析

V. A. Djumagaliev* and A. B. Rabinovich*
브이에이 쥬마가리에브* · 알렉산더 라비노비치*

Abstract□A series of long wave measurements was made in the region of Shikotan Island (the South Kuril Islands) during 1990-1992: 7 bottom pressure stations were installed in 5 bays and inlets of Shikotan and 3 precise microbarographs were situated at the shore. The observations were taken in order to monitor tsunami waves, estimate resonance features of coastal topography, and investigate seiche generation mechanism. It was found that forced long waves dominate in the motions with periods exceeding 2 hours, freely propagating long waves prevail at periods of 30-120 min and eigen-oscillations of bays (seiches) are the predominant type of long waves at periods less than 30 min. The Helmholtz mode with period 30 min in Krabovaya Bay and 18.5 min in Malokurilskaya Bay is the most important type of wave motion in the inner Shikotan basins. There is a good correlation between passages of atmospheric disturbances and generation of seiches near the coast of Shikotan Island. In particular, jumps in atmospheric pressure excite seiches in different bays simultaneously, in each one with the corresponding dominant period. The atmospheric spectra were remarkably smooth and stable, and could be described by a $\omega^{-2.26}$ power law.

要 旨: Kuril 열도의 남부에 위치한 Shikotan 섬 지역에 대하여 1990-1992년간에 걸쳐 일련의 장파관측이 수행되었다. 5개 만과 Shikotan 유입부 등의 7개소에 저면 압력 측정장치를 설치하였으며, 해안에 3개의 정밀압력계가 위치하도록 하였다. 관측의 목적은 지진파랑의 관측, 히안지형의 공진특성 평가 및 부진동 생성 메카니즘의 조사에 두었다. 2시간 이상의 주기를 갖는 파동에 있어서는 의력에 의한 장파가, 30-120분 주기에서는 자유장파가 지배적이었으며, 30분 이하의 주기에서는 만의 부진동이 가장 지배적인 장파형태로 나타났다. Krabovaya만의 30분 주기 Helmholtz 모드와 Malokurilskaya만의 18.5분 주기모드가 Shikotan 내역에서 가장 중요한 파동형태이다. 대기 교란경로와 Shikotan섬 연해의 부진동 생성간에 상당한 상관관계가 있으며, 특히 대기압의 급상승은 각각 다른 부진동 주기를 갖는 여러만에 동시에 부진동을 일으킨다. 대기 스펙트럼은 매우 안정적인 것으로 나타났으며, $\omega^{-2.26}$ 지수식으로 나타낼 수 있는 것으로 사료된다.

1. INTRODUCTION

The region of the South Kuril Islands is an area of high seismic and atmospheric activity. The Pacific coast of the Kuril Islands is strongly exposed to the threat of tsunami waves. Catastrophic disasters may result of tsunami waves coming from the open ocean are amplified due to resonance on the shelf or in bays and in inlets. However, large long wave oscillations, so called 'meteorologic tsunamis' (Defant, 1961) generated by atmospheric disturbances, e.g. typhoons or passing fronts, may also be dangerous for coastal areas. Finally, a serious problem for fishing and merchant fleet is the 'range action' (Wilson, 1972; Botes *et al.*, 1982) related to eigenoscillations in harbours, forced by nonlinear interaction of storm waves.

The development of instruments for long wave recording and providing corresponding measurements in the shelf zone is a traditional direction of

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*러시아 科學아카데미, 遠東 海洋地質地球物理研究所 (Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences, Yuzhno-Sakhalinsk, 693002 Russia) scientific activity at the Institute of Marine Geology and Geophysics (IMGG), mainly because of the tsunami problem. A number of instruments were installed in the region of the South Kurils in 1960's and 1970's for the purpose of recording tsunami waves in the open ocean (Dykhan *et al.*, 1983).

Improved sensors, digital recorders and cable lines in recent years made it possible to undertake long-term array experiments. During the IMGG expeditions in 1987-1989, several hydrophysical experiments on the Okhotsk Sea shelf of Kamchatka (KAMSHEL-87, 88, 89) were conducted (Kovalev *et al.*, 1989; 1991). One of the surprising results of these experiments was that, in spite of wide spread opinion that the atmospheric waves are the main source of background sea level oscillations in the tsunami frequency band (0.1-0.01 cpm), these oscillations were found to be weakly correlated with atmospheric fluctuations, but strongly correlated with sea-surface activity (i.e. with wind waves). These observations were obtained in a region with a relatively long and homogeneous shelf and a remarkably straight, plane coastline, conductive to the formation of long boundary waves with relatively wide continuous spectra. It is interesting to compare long wave generation in this region and in the region of the South Kurils, where the shelf and coastline are strongly inhomogeneous and complex; many narrow- and wide-mouthed bays and inlets provide favorable conditions for generation of eigenoscillations (seiches) and a corresponding narrow discrete spectrum.

The investigation of long wave generation in general, and especially of seiche generation, was the main purpose of the IMGG experiments of 1990-1992 near the coast of Shikotan Island (South Kurils). Another important aim of these experiments was an examination of resonance properties of the bays in this region, including determination of associated eigenfrequencies and amplification factors. Beginning with the classical paper by Honda *et al.* (1908), this is a traditional problem for coastal areas, particularly for regions of high tsunami risk (Nakano and Unoki, 1962; Olsen and Hwang, 1971; Wilson, 1972). Several instruments were installed in bays and inlets of Shikotan Island to record tsunamis and background long waves; measurements of atmospheric pressure fluctuations were carried out simultaneously.[1]

Examination of long-term observations of atmospheric fluctuations is a subject of independent interest. In particular, the unexpected result obtained from experiment KAMSHEL-87 was the stable smooth monotonic character of atmospheric pressure spectra during the whole period investigated (10 September-7 October, 1987). The power law of the spectra, $\omega^{-2.3}$, was steeper than that observed earlier by other scientists (Herron *et al.*, 1969; Kimball and Lemon, 1970; Gossard and Hooke, 1975). They asserted that atmospheric pressure spectra in the frequency range 10^{4}-10^{0} Hz decrease according to an $\omega^{-2.0}$ law. Consequently, it was interesting to use the data from the Shikotan experiments to inspect the stability and power law of atmospheric spectra and to examine their seasonal variability.

Here we present some preliminary results of the investigations of long ocean waves and atmospheric fluctuations in the region of Shikotan Island.

2. OBSERVATIONS

A series of long wave field measurements were made near Shikotan Island during 1990-1992. As part of this widespread long wave study, 7 bottom pressure stations were installed and data sets from 5 Shikotan bays and inlets were collected during the appropriate experiments (Fig. 1). The bottom pressure gauges were of two types:

1) stationary long-term cable stations;
2) temporary autonomous stations.

The sampling interval (integrating time) for both cable and autonomous stations was chosen to be 1 min yielding a Nyquist frequency of 0.5 cpm.

The stations of the first type were installed inside Malokurilskaya Bay (P1), near the entrance of this

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[1] Very similar experiments are provided by S. Monserrat and his colleagues from the Universitat de les Isles Baleares, Spain in the region of the Balearic Islands (Mediterranean Sea) where extremely strong seiches ('rissaga phenomenon') are observed occasionally (Monserrat *et al.*, 1991; Monserrat and Thorpe, 1992; Gomis *et al.*, 1993).

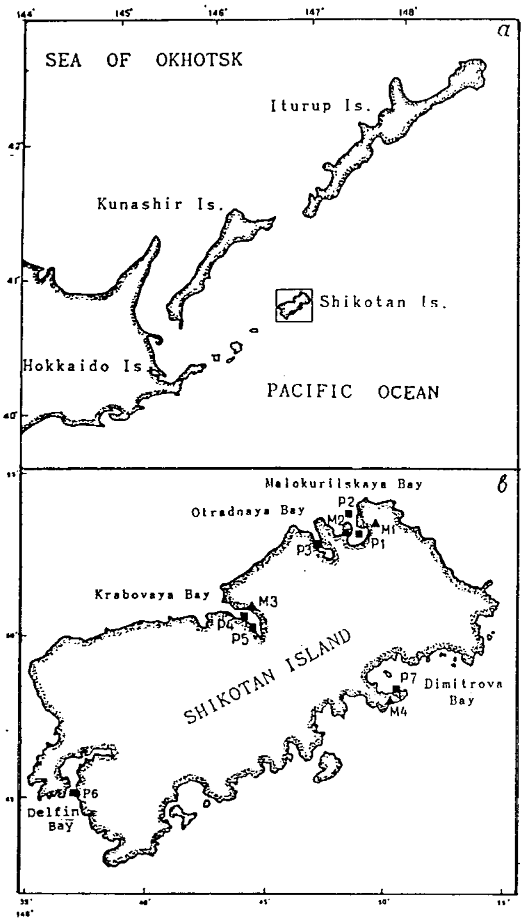

Fig. 1. Location of bottom pressure stations P1-P7 and microbarograph stations M1-M4 in the region of Shikotan Island.

bay (P2) and also in Krabovaya Bay (P4). The cables from these stations were connected to multichannel recorders deployed at the villages of Malokurilsk and Krabozavodsk. These stations were used for monitoring tsunamis and long-term sea-level observations. Some interruptions in wave recording were caused by problems with cable lines and shore recorders; in spite of this, several months of quality long wave observations were obtained at these stations and, in fact, a two weak tsunamis were recorded (Djumagaliev *et al.*, 1993a; Rabinovich *et al.*, 1993). The total amount of data consisted of more than 215,000 sampling counts for the stations P1, P2 and more than 410,000 counts for the station P4. Periods of the normal behaviour at these stations are shown in Fig. 2.

The temporary autonomous stations were installed for research purposes, and were placed in Otradnaya Bay (P3), Krabovaya Bay (P5), Delfin Bay (P6) and Dimitrova Bay (P7). The lengths of corresponding observational series were from 6 days (P6) to 21 days (P3).

Two types of sensors were used in bottom pressure gauges: (a) vibrotron pressure transducers; (b) quartz crystals. The same sensors were employed in the Kamchatka experiments (Kovalev *et al.*, 1989; 1991) and in previous experiments near Shikotan Island (Djumagaliev *et al.*, 1989). The references just quoted give some additional details on sensors and recorders.

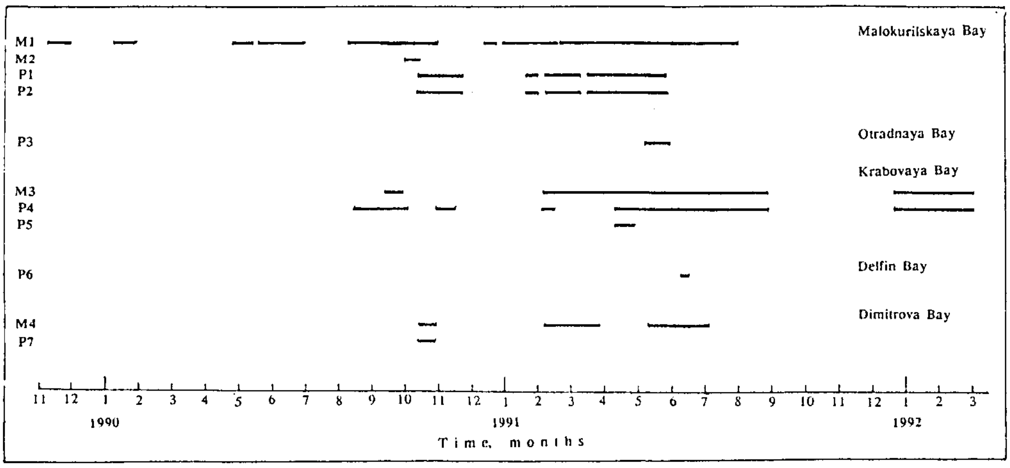

Fig. 2. Bar chart of qualitative record lengths from the Shikotan experiments.

Long-term observations at the cable stations, together with the records from the temporary autonomous stations, afforded an opportunity to investigate resonance and amplification properties of different bays inlets of Shikotan Island.

In addition, precision shore microbarographs with quartz sensors were used to measure atmospheric pressure fluctuations in the region of the South Kuril Islands. A microbarograph (M1) was installed at the Hydrophysical Observatory 'Shikotan' (Malokurilsk Village) in autumn of 1989. Two others were placed in 1990 in Krabozavodsk (M3) and near Dimitrova Bay (M4) (Fig. 1). Ten day measurements of atomspheric fluctuations were also taken in September-October, 1990 at the Hydrometeorological Station Malokurilsk (M2) in about 1.6 km from the Hydrophysical Observatory 'Shikotan'. The main purposes of atmospheric measurements were: investigation of the pressure-induced long ocean waves and examination of the atmospheric gravity wave field in the surface layer itself. The sampling (integrating) interval for atmospheric waves was also chosen to be 1 min. The same microbarographs were used earlier in KAMSHEL experiments (Kovalev *et al.*, 1989; 1991).

3. LONG WAVE ANALYSIS IN VARIOUS BAYS

All information from the bottom pressure stations and mirobarographs was recorded on magnetic tapes, read into computer, and carefully verified. The least squares method was used to estimate tidal constituents in the sea level records, and then the computed tides were subtracted from the records. The residual time series were then analysed. As an example, simultaneous segments of such residual series for the stations P1 and P2 are presented in Fig. 3. Long wave oscillations with a period of about 18.5 min are clearly seen in these records.

Spectral analysis of the data was performed; a Kaiser-Bessel window (Harris, 1978) was used to improve spectral estimates. Synchronous pieces of sea-level records from different stations were employed for cross-spectra analysis. Some results are presented in Fig. 4 and Fig. 5 and will now be discussed.

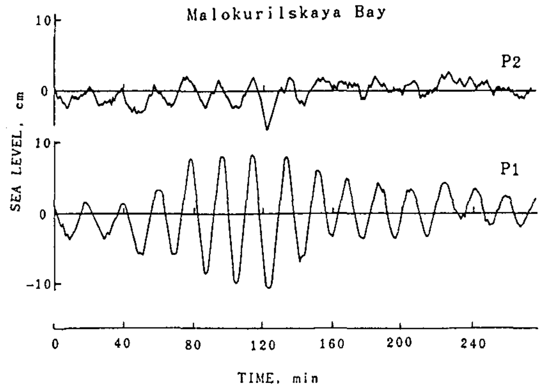

Fig. 3. Typical segments of residual time series of bottom pressure stations P1 and P2 in the region of Malokurilskaya Bay.

We will consider here some features of long wave fields in various bays and inlets of the Shikotan Island in turn.

3.1 Malokurilskaya Bay

Malokurilskaya Bay is a bottle-like bay with a narrow mouth and wide elliptic inner basin. Seiche oscillations in Malokurilskaya Bay have been a subject of intensive study in recent years. Djumagaliev and Fine made bottom measurements of long waves inside and outside the bay in the autumn of 1986 and showed that the predominant oscillations in this bay, with a period of about 18.5 min, are related to the Helmholtz (fundamental bay) mode (Djumagaliev *et al.*, 1989). Rabinovich and Levyant (1990) computed eigenfrequencies and eigenvectors of the bay; evaluating eigenvalues by the Ritz method, they found that the gravest modes in Malokurilskaya Bay have the following periods: 18.9, 6.5, 3.8, 3.4, 2.6, 2.3 min. Rabinovich and Levyant (1992) reexamined bottom pressure measurements of 1986 and also processed two-month records from the Malokurilsk coastal tide-gauge; the observed periods of eigenoscillations in Malokurilskaya Bay agreed well with computed ones.

Bottom pressure measurements in 1990-1991 in the region of Malokurilskaya Bay made it possible to verify results mentioned above and to estimate the amplification factor of the bay. Detailed treat-

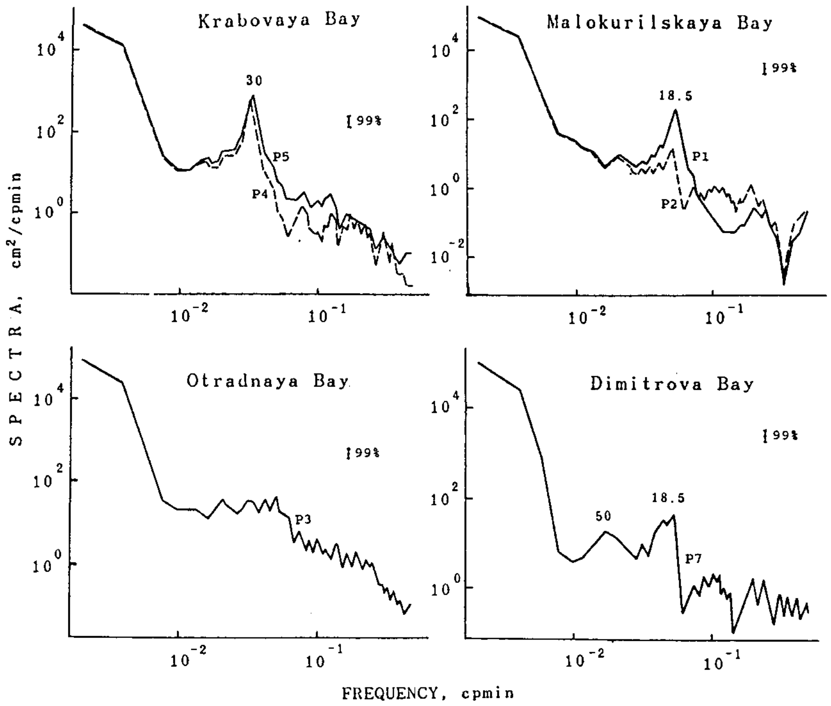

Fig. 4. Spectra of bottom pressure stations near Shikotan Island; periods of some prominent spectral peaks (in min) are marked.

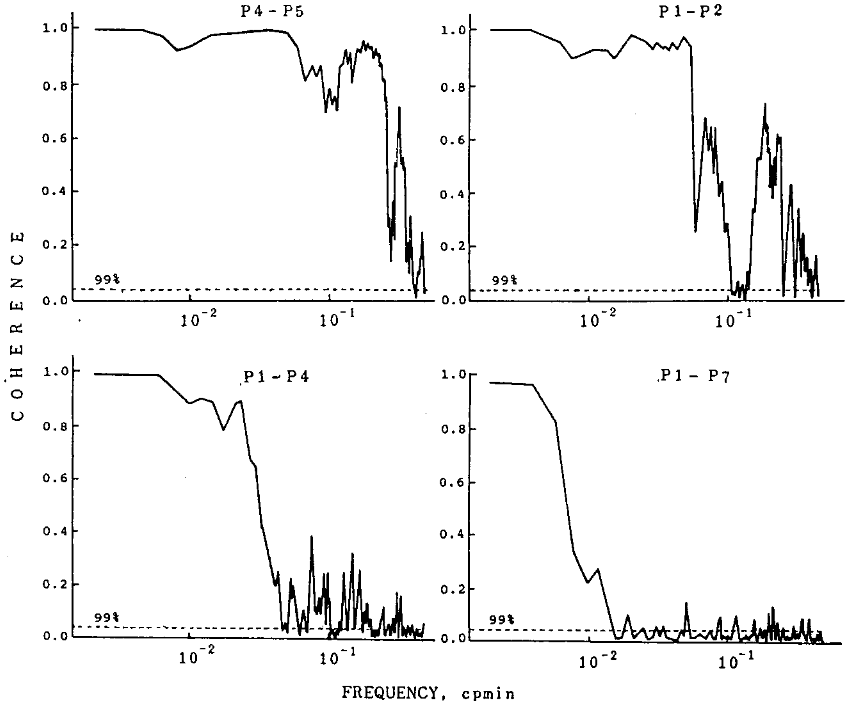

Fig. 5. Coherence between some pairs of bottom pressure stations installed near Shikotan Island.

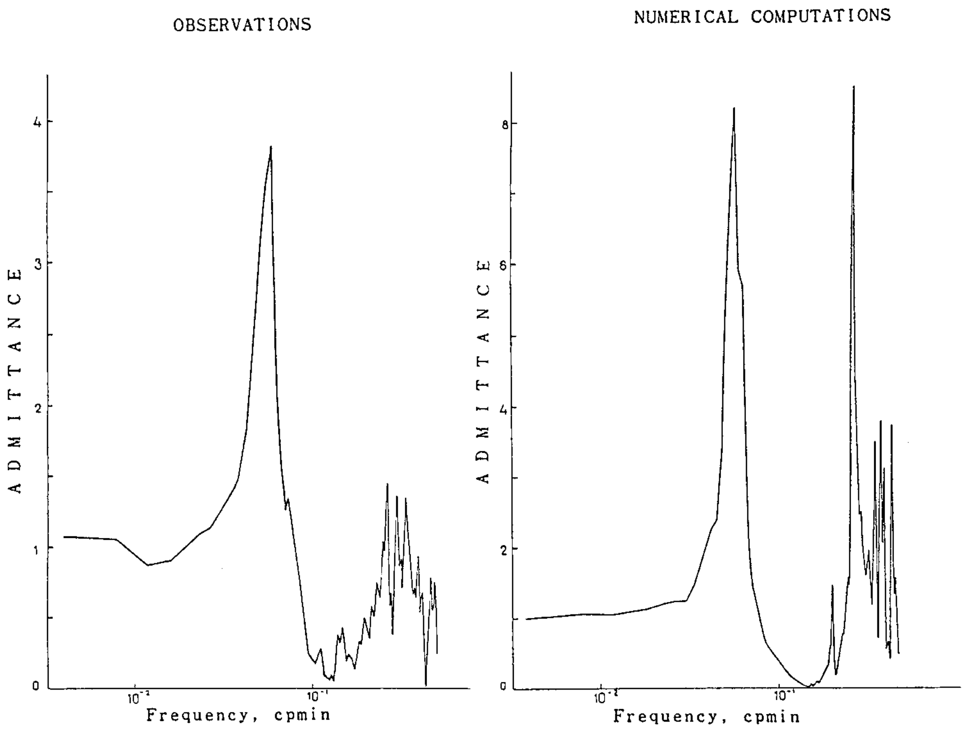

Fig. 6. Observed (left) and computed (right) admittance functions between station P2 (at the entrance of Malokurilskaya Bay) and station P1 (inside the bay).

ment of this problem is the subject of a separate paper (Djumagaliev *et al.*, 1993b); here we will quote only some important results.

The P1 station data showed that fundamental seiche oscillations with period of about 18.5 min are very stable and strongly dominate within Malokurilskaya Bay (Fig. 3, 4). Their typical heights were 8-10 cm, and maximal heights during the observational period were about 30 cm. Some higher order modes are also manifested in the records; the observed periods 3.9, 3.3, 2.8 min are in good agreement with the periods computed by Rabinovich and Levyant (1990) for the 2nd, 3rd and 4th eigenmodes. Absence of the 1st mode maximum in the P1 spectrum is apparently related to the closeness of the P1 position to the corresponding nodal line.

The fundamental mode showed up also in the P2 data at the entrance to the bay (Figs. 3, 4) but it was much weaker there. Between P2 and P1 stations, this mode shows amplification by a factor 3.8 (Fig. 6, left).

The Hansen hydrodynamical numerical (HN) method was used to estimate amplification of incoming waves. Nondissipative linear long-wave equations were solved numerically by a finite-difference technique; a random signal described by an autoregression model of the first order was used as an input function. Computed and observed resonance periods agreed remarkably well, but computed amplification of the Helmholtz (fundamental) mode was twice as big as the observed one (Fig. 6). This difference is apparently related to the influence of friction and non-linear factors.

Both computation and results of direct observations show that Malokurilskaya Bay has well defined resonance properties: Q is about 12-15 for the fundamental mode, and strong amplification of tsunami waves inside the bay is quite possible in principle.

On February 16, 1991 a weak tsunami caused by an earthquake of magnitude Ms=5.9 (mb=6.1-6.3) with an epicenter located near to Shiashkotan

Island (North Kurils), was recorded by bottom pressure stations P1 and P2 and by the Malokurilsk tide gauge (Djumagaliev *et al.*, 1993a). Inside Malokurilskaya Bay, this tsunami manifested itself as a 'seiche storm' with duration of about 5-6 hours. No noticeable oscillations were recorded during this time on other Kuril tide gauges (Yuzhno-Kurilsk, Kurilsk) situated in locations with less prominent resonance properties.

The other tsunami on December 22, 1991, caused by the Urup earthquake of magnitude $Ms=7.4$, occurred at a moment when, unfortunately, both stations P1 and P2 were out of operation. This tsunami was recorded on several Russian and Japanese tide gausges (Rabinovich *et al.*, 1993; Hatori, 1993). Records from the Malokurilsk tide gauge showed that oscillations there were stronger than elsewhere, with the exception of Kragovaya Bay (see below).

3.2 Krabovaya Bay

Krabovaya Bay is in fact a long and narrow inlet. Krbozavodsk Village, situated in this inlet, is an important Kuril fishery port, open for foreign vessels. Absence of continuous tide gauge measurements in the inlet was one of the reason for installing long-term cable station (P4) there and for mounting a special experiment to investigate resonance oscillations in this inlet and estimate possible tsunami risk.

Direct statistical analysis of bottom pressure records of the P4 and P5 stations and their spectral analysis demonstrated that prominent oscillations with period of about 30 min are typical features of Krabovaya Bay. Seiches with period of 13 min are also observed in this inlet from time to time (the corresponding spectral maximum in Fig. 4 is better seen for the P4 record). These two periods, as was demonstrated by Fine (1991), are related to the fundamental and 1st eigenmodes of the inlet. Fine used the HN-method to compute long waves inside the inlet by the same method as was used for Malokurilskaya Bay (Djumagaliev *et al.*, 1993b), and showed that Krabovaya Bay has even more marked resonance properties (i.e. higher Q and stronger amplification) than the latter. Field measurements at stations P4, P5 confirm this conclusion; typical seiche heights in this inlet were 10-12 cm; maximal seiches were up to 50 cm, which is much more than in Malokurilskaya Bay. This is in good agreement with observations by Honda *et al.* (1908) and Nakano and Unoki (1962); they found that strong seiches near the coasts of Japan are usually observed just in long and narrow inlets. Seiche oscillations in other regions are of similar character, particularly in the bays and inlets of the Balearic Islands, Spain. Gomis *et al.* (1993) explained this peculiarity of seiche generation using a simple theoretical model of a rectangular flat-bottomed inlet. The amplification factor (F) for this model may be written as

$$F=\frac{A_{in}}{A_{out}}=\left(\frac{4\pi L}{d}\right)\left(\frac{H_{out}}{H_{in}}\right),$$

where A_{in} and A_{out} are the wave amplitudes inside and outside the inlet, H_{in}, and H_{out} are the corresponding depths, L is the inlet length and d is its width. This expression shows that increasing the inlet length, or reducing its width or depth, amplify the oscillations inside the inlet.[2]

In the spectra from stations P4, P5 in Krabovaya Bay, a weak maximum with a period of 47 min can be seen (Fig. 4); this is apparently related rather to resonance properties of the shelf than to eigenoscillations of the inlet.

3.3 Otradnaya Bay

The form of Otradnaya Bay is very similar to Krabovaya Bay, but the oscillations in this inlet are quite different. No prominent seiches were recorded at the station P3 during the observation period. Strong thunderstorm and atmospheric pressure jumps on May 8, 1991, which generated noticeable seiches in Kragovaya Bay and other bays and inlets of Shikotan Island, excited only slight long wave oscillations with unstable periods in Otradnaya Bay (Fig. 8). The reason for such difference is obscure, possibly it can be explained by the very shallow swampy character of Otradnaya Bay. Nonlinear effects and

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[2] Certainly true up to a certain limit; then friction and non-linearity will begin to weaken incoming waves. Apparently in Otradnaya Bay we have just this situation.

strong dissipation may prevent significant oscillations within this domain.

There are only some weak maxima with periods 47, 33, 24 and 19 min in the P3 spectrum. It is interesting to note that weak oscillations with period 47 min are observed also in the region of Malokurilskaya and Krabovaya Bays (Fig. 4), this confirms the hypothesis of their relation to the outer shelf.

3.4 Delfin Bay

The spectrum of the bottom pressure at station P6 installed in Delfin Bay was relatively smooth and had no noticeable peaks. This bay is elongated and shallow; in accordance with results of Nakano and Unoki (1962) and Gomis *et al.* (1992) it should have pronounced resonance properties and significant seiche oscillations. Consequently, the results obtained were unexpected. One possible reason was that the station was placed too near the mouth, i.e. at the probable position of a nodal line of the fundamental bay mode. Other reasons were insufficiently long observation period and absence of significant atmospheric disturbances capable of generating seiches during this period. Additional measurements are desirable to investigate the seiche oscillations and estimate resonance periods of this inlet.

3.5 Dimitrova Bay

Dimitrova Bay is a widemouthed bay of irregular form (Fig. 1) open to the incident ocean waves. There are two prominent maxima in the P7 spectrum, with periods 50 and 18-20 minutes; some smaller spectra peaks have periods 6.6, 4.5 and 2.8 min.

No numerical computations have been made yet for this bay, which is why the nature of observed oscillations is unclear, although it may be supposed that, with the exception of the 50 min waves, they are related to eigenoscillations of the bay.

4. LONG WAVE STRUCTURE

It may be assumed that long wave field in the investigated region is formed by (1) forced motions, (2) free long waves propagating along the shelf, and (3) eigenoscillations of individual bays and inlets. Using results of cross-spectral analysis of various pairs of bottom pressure stations, it is possible to examine wave structure of sea level oscillations in the region of Shikotan Island. The diagrams presented in Fig. 5 correspond to four different situations:

(1) two stations inside the same bay (P4-P5);

(2) one station inside the bay, the other one near the entrance to the bay (P1-P2);

(3) two stations inside two different bays at the same side of the island (P1-P4);

(4) two stations inside two different bays on opposite sides of the island (P1-P7).

It is clear from the figures that coherence functions for all pairs of stations have similar shapes at low frequencies but are quite different at high frequencies.

The first pair (P4-P5) has a very high coherence (more than 0.8-0.9) down to periods of a few minutes; then there is a deep trough at the period 3.6 min and a sharp coherence peak (about 0.75) at the period 3.2 min.

The second pair (P1-P2) has coherence more than 0.9 down to periods of about 18 min (i.e. to the period of the fundamental bay mode); at smaller periods there are some peaks and valleys in the coherence function which, as was demonstrated by Djumagaliev *et al.* (1993b), correspond very well to the modal structure of eigen (seiche) oscillations in Malokurilskava Bay.

The coherence between variations at stations P1 and P4 located in two different bays of the northern coast of Shikotan Island is high down to periods of about 30 min (the fundamental period for Krabovaya Bay). An interesting maximum of coherence function (>0.92) corresponds to the period 47 min; the same maximum is also present in the P1-P3 coherence (not presented here). As was mentioned above, there is slight peak with exactly this period in spectra of stations P1, P2, P3, P4, and P5, which were all on the northern side of Shikotan Island. The corresponding oscillations are probably caused by edge waves propagating over the northern Shikotan shelf. A more likely possibility is that they are related to resonance amplification at the shelf of leaky waves incoming from the open ocean: as was shown by Rabinovich and Levyant (1992), shelf resonance of leaky waves in the region of South Kurils has a period very close to this value.

There are also small peaks exceeding the confidence level in the P1-P4 coherence, which means that there is a small amount of coherent energy at high frequencies. Apparently these coherence peaks are related to free long waves propagating along shelf of Shikotan. Stations P1 and P7, located on opposite sides of Shikotan, are correlated only at periods more than 100-150 min.

These results prove that in the region of Shikotan Island forced waves dominate in low frequency motions (with periods exceeding 2 hours). Free propagating long waves prevail at periods of 30-120 min but are present also at shorter periods, and standing long waves (seiches) are the predominant type of long waves at periods less than 30 min.

5. ATMOSPHERIC PRESSURE FLUCTUATIONS AND THEIR CORRELATION WITH SEICHE OSCILLATIONS

The region investigated is a zone of a high atmospheric activity. Attention in this study was paid principally to atmospheric gravity waves with periods from 2 minutes to a few hours, corresponding to long ocean gravity waves, particularly seiche oscillations in bays and inlets.

Spectral analysis of the data was performed for different periods (months or even seasons). During practically the whole observational period, the spectra were smooth, monotonic and surprisingly stable (Fig. 7). Depending on atmospheric activity the total energy of atmospheric fluctuations varied by an order of magnitude, but there were no visible changes in the spectra shapes. There were no noticeable differences also between the spectra from various stations. The general character and shape of the spectra were very similar to those observed in the southwestern part of Kamchatka (Kovalev *et al.*, 1989; 1991).

The best fit of atmospheric spectra in Kamchatka during the period 10 September-7 October, 1987 was with an $\omega^{-2.3}$ power law, which is steeper than that observed by Herron *et al.* (1969), Kimball and Lemon (1970), Gossard and Hooke (1975) and others ($\omega^{-2.0}$). Special investigation of this question was made using the data set of atmospheric fluctuations in Malokurilsk. Relevant results are presented in Table 1. As it is seen in the table, the power over different periods varies between $\omega^{-2.06}$ and $\omega^{-2.40}$. There are no visible discernible form or regularity in these changes and seasonal deviations are very small (Fig. 7). The average value of power law (-2.26) is practically the same as was observed in Kamchatka region.

Table 1. Results of spectral analysis of atmospheric fluctuations at Hydrophysical Observatory 'Shikotan' in the frequency range 0.01-0.5 cpmin

Date	Observational period min	Observational period days	Power law
7 Nov 89	29 687	20.6	−2.25
9 Jan 90	22 291	15.5	−2.37
23 Apr 90	20 654	14.3	−2.24
16 May 90	30 000	20.8	−2.40
14 Aug 90	13 259	9.2	−2.22
25 Aug 90	21 857	15.2	−2.25
11 Sep 90	8 490	5.9	−2.12
28 Sep 90	10 155	7.1	−2.13
15 Oct 90	14 803	10.3	−2.35
28 Dec 90	23 676	16.4	−2.06
Summary	194 872	135.3	−2.26

Typical amplitudes of the atmospheric microfluctuations were 0.05-0.1 mbar; however, from time to there were trains of atmospheric waves with amplitudes 0.3-0.5 mbar and jumps of atmospheric pressure of 1-2 mbar height.

Examination of atmospheric waves was not the primary objective of this study, but was necessary to estimate the efficiency of direct forcing of seiche oscillations by atmospheric disturbances. The detailed investigation of this question is a subject of a further paper but some preliminary conclusions can be made:

(1) there is a noticeable correlation between passages of atmospheric disturbances and generation of seiches in bays and inlets of the Shikotan Island;

(2) when a train of atmospheric waves has a period close to an eigen (proper) period of an inner basin, strong resonance seiche oscillations are generated in the appropriate basin;

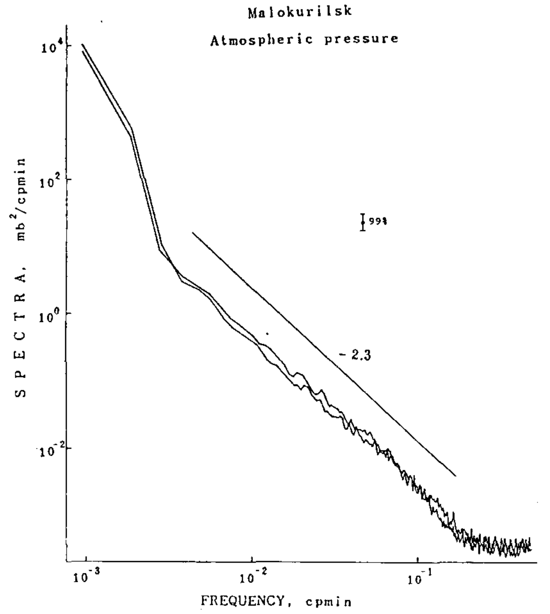

Fig. 7. Spectra of atmospheric pressure fluctuations in Malokurisk (Shikotan Island) in September 1989 and May 1990.

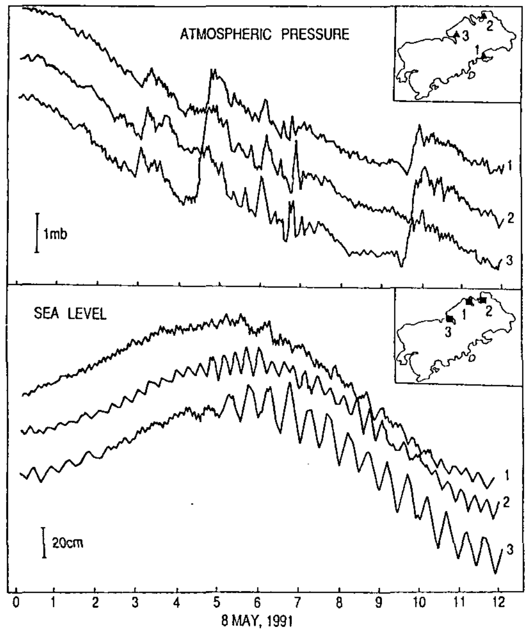

Fig. 8. Fluctuations of atmospheric pressure at stations M4 (1), M1 (2), M3 (3) and sea level oscillations at stations P3 (1), P1 (2), P4 (3) during the thunderstorm of 8 May, 1991.

(3) when the period of atmospheric waves is far from the resonance periods of the basin seiches are not generated, on the contrary, the existing seiches are frequently reduced;

(4) jumps of atmospheric pressure usually generate seiches in various basins simultaneously, in each one with the corresponding dominant period (a typical example of such seiche generation in three days of the Shikotan Island is presented in Fig. 8);

(5) the origin of seiche oscillations in the most cases was related to some kind of pressure disturbance, either pressure disturbances alone may be the main source of seiches, or the possible direct causes of seiche generation (wind gusts, gales, squalls etc.) are strongly correlated with these disturbances.

6. SUMMARY AND DISCUSSION

Seven bottom pressure stations were installed in 1990-1991 near Shikotan Island. These stations were used to examine seiche oscillations in bays and inlets of the island and also to analyse long wave structure in this region. It was found that in Malokurilskaya Bay the dominant type of oscillations has a period of 18.5 min and is related to the Helmholtz (fundamental bay) mode. The same mode with a period of about 30 min prevail in Krabovaya Bay. These seiche oscillations are quite stable, have typical heights of 8-12 cm and exteme heights of 30-50 cm. There are also long wave oscillations in these bays related to higher seiche modes but they are much weaker. Computed eigen periods of the bays are in good agreement with the observed ones.

The dominant waves in Dimitrova Bay have periods of 18-20 and 50 min. No noticeable spectral peaks are manifested in Otradnaya and Delfin Bays. Additional field investigations as well as numerical modelling are necessary to understand the nature of long waves in these bays.

Cross-spectral analysis of simultaneous bottom pressure records observed at different stations located in different bays proves that the long wave field in the region investigated is formed by three types of wave motions: (1) forced long waves (at the periods T<2 hours); (2) free long waves propagating over the shelf (T=30-120 min); (3) eigen oscillations of individual bays and inlets (T<30 min).

Long-term measurements of atmospheric pressure fluctuations made by precision microbarographs showed that atmospheric spectra in this region are remarkably smooth and stable, and described by an $\omega^{-2.26}$ power law. There is good correlation between passages of atmospheric disturbances and seiche generation near the coast of Shikotan Island. In particular, jumps in atmospheric pressure excite seiches in different inner basins simultaneously, in each one with the corresponding dominant period. Trains of atmospheric waves generate noticeable seiches when periods of these waves are close to the eigen periods of corresponding bays or inlets.

No attempt was made to find a possible correlation between seiches and wind or wind waves. Both field measurements near the coast of South Africa and numerical computations made by Botes *et al.* (1982) proved that this mechanism of seiche generation may be very important. We plan to undertake such investigations for the region of Shikotan Island in the near future.

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