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Investigation of Long Waves in the Tsunami Frequency Band on the Southwestern Shelf of Kamchatka

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Abstract. Two inexpensive cable bottom pressure stations were installed on the southwestern shelf of Kamchatka (Okhotsk Sea) in 1987 and two more in 1988 to provide longwave measurements in the tsunami frequency band, to investigate the generating mechanism of these waves, and to test the instrumentation. Microfluctuations of atmospheric pressure were recorded simultaneously. Two cable lines were torn off by ship anchors in March 1989 but others are still working in spite of highly dynamic activity on beaches and in hard ice regimes. Careful data analysis of two months of observations (September–October, 1987) showed that: (1) the atmospheric spectra were very stable and monotonic in the period range 2–50 min and corresponded to a power law of $\omega^{-2.3}$, (2) the direct generation of long waves by atmospheric pressure fluctuations was negligible, (3) there was high correlation between background longwave oscillations and sea state, (4) the structure of the offshore longwave field was in good agreement with theoretical estimates of standing waves for a linear slope.

Key words. Tsunami measurements, bottom cable stations, infragravity waves, atmospheric fluctuations.

1. Introduction

The west coasts of Kamchatka are regions which are strongly exposed to the effects of marine natural disasters. Although the Kuril Islands protect the Okhotsk Sea from the direct threat of tsunami waves, some strong tsunamis (e.g. the Kamchatka Tsunami on 5 November 1952 and the Chile Tsunami on 23 May 1960) have penetrated into the region and caused substantial damage. But the most dangerous and ruinous hazards for these coasts are storm surges and storm-generated wind waves. Six to seven strong surges are observed here each year, the most destructive in recent years occurred in November 1980, January 1982, November 1986, and October 1988. During surges, long surf waves run over sandy tongues of land, upon which the majority of villages and industrial activities are located, and destroy many structures (Figure 1). For research to provide trustworthy forecasts of marine hazards for this region, it is necessary to continuously monitor sea-level variations and longwave processes. Unfortunately, the high dynamic activity of beaches makes it difficult to maintain stationary tide gauges on the west coast of Kamchatka and, thus, no systematic sea-level observations are made here. For this reason, the Kamchatka Administration of the Hydrometeorological Service appealed to the

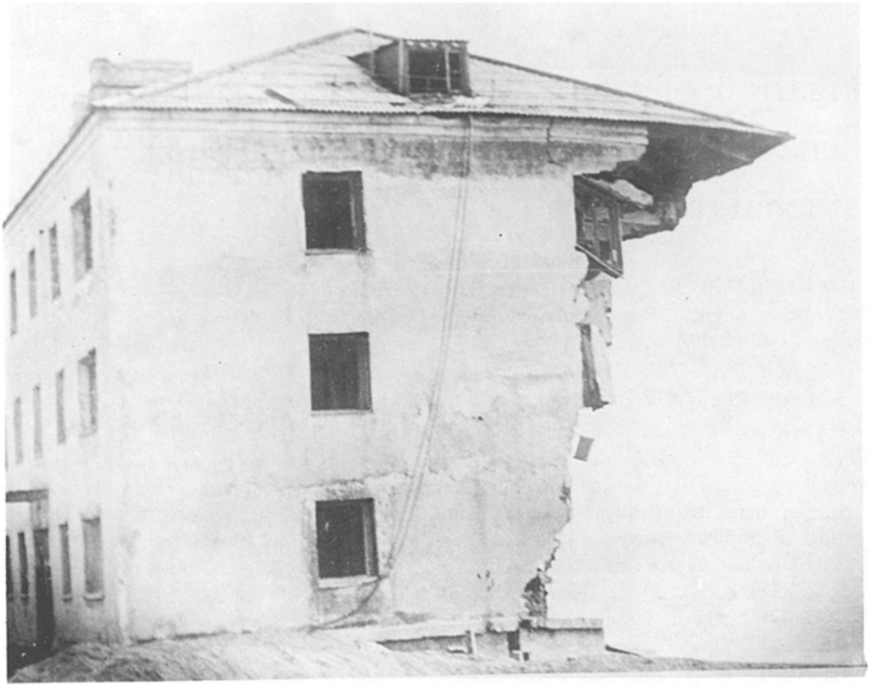

Fig. 1. An example of the destructive effects of sea waves on a nearshore building on the southwestern coast of Kamchatka.

Institute of Marine Geology and Geophysics (IMGG) to make measurements based on bottom cable stations. This capability has been developed at IMGG for the remote sensing of tsunamis and other long waves in a broad frequency band.

The Kamchatka shelf of the Okhotsk Sea is a complex and interesting area that has been poorly investigated. The relatively long and homogeneous shelf, and a remarkably straight and plane coastline are conducive to the formation of boundary long waves associated with both atmospheric activity and the nonlinear interactions of wind waves.

During the IMGG expeditions in 1987–1989, several experiments were conducted on the southwestern shelf of Kamchatka and routine sea level recording was established. The main scientific purposes of these experiments were

(a) instrument testing, and a study fo the feasibility and efficiency of establishing inexpensive, long-term bottom cable stations in regions characterized by high beach instability and severe ice conditions;
(b) the investigation of long-wave background spectra, with special attention to generating mechanisms and correlations with possible external sources;
(c) studies of tide and storm surges in this area and the development of adequate forecast models.

Item (c) is beyond the scope of this paper. Our attention will focus on long waves in the tsunami frequency band, i.e. on waves with periods of 2–120 min. The nature of these waves on the shelf was of great interest in the 1950s and 1960s (Munk *et al.*, 1956, Donn *et al.*, 1956; Takahasi and Aida, 1962; Snodgrass *et al.*, 1962; Munk, 1962; Munk *et al.*, 1964). It was shown that background spectra are dominated by two types of boundary waves: edge waves, in which energy is trapped on the shelf and decays asymptotically seaward, and leaky waves which radiate energy into the open sea. In the absence of tsunamis, the primary forcing mechanism for these waves was assumed to be atmospheric fluctuations. Since the nature and pecularities of background oscillations in the tsunami frequency band have been considered to be fairly well-established, only a few studies related to this frequency band have been published recently (Bernard and Milburn, 1985; Thompson and Van Dorn, 1985; Hashimoto *et al.*, 1986; Van Dorn, 1987).

On the other hand, a great many papers (Huntley *et al.*, 1981; Holman, 1981; Middleton *et al.*, 1987; and others) have been devoted to ‘infragravity waves’ with periods 30–300 sec, associated with the nonlinear interaction of wind waves and swell in coastal waters. The importance of these waves is due to their role in beach transformation and destruction (Bowen and Huntley, 1984; Holman and Sallenger, 1986).

This report presents the principal results of our recent investigation on the shelf of Kamchatka, during which we have found that these two frequency bands are correlated. In particular, we show that wind waves and swell are an important source of background wave energy in the tsunami frequency band.

2. Instruments

The development of instruments for tsunami wave recording at the shelf zone was begun at IMGG (formerly the Sakhalin Complex Scientific Research Institute) on the initiative of S. L. Soloviev toward the end of the 1960s (Jacque and Soloviev, 1971; Jacque *et al.*, 1972). Bottom cable stations with Vibrotron sensors and coastal analog recorders were used initially. Improved sensors, recorders and cable lines made it possible to obtain one of the first records of tsunami waves in the open ocean on 23 February 1980 (Dykhan *et al.*, 1983).

Third-generation instruments, designed at IMGG, were used on the Kamchatka shelf. These instruments allowed the collection of real-time oceanographic data over a broad frequency band, including tides, surges, tsunamis, seiches, and surf beats. Two key features of the marine data system were the Digiquartz pressure sensors used in the bottom stations and the special electronic functional modules in the shore data recorders. The recorders had 4–8 channels which could be used in any combination to provide an optimal observational system; the system at Ozernovsk, e.g. consisted of three bottom pressure gages and a coastal microbarograph. Some additional details on the instrumentation may be found in Kovalev *et al.* (1989). A full description of the bottom pressure stations and other instrumentation will also be published by IMGG in 1991 as part of a special collection of technical papers.

Two types of bottom pressure sensors were used on the southwestern shelf of Kamchatka. The first was a standard Vibrotron sensor PDV-10, a similar but improved version of that used for tsunami observations near Shikotan Island (Dykhan *et al.*, 1983). The second was a quartz crystal transducer with a range of 0–3 MPa, hysteresis of 0.05%, and a typical accuracy under harsh environmental conditions of 0.25%. Some quartz crystals were also used as temperature gages. In addition, a precision shore microbarograph, designed at the Moscow Institute of Physical Engineering, provided simultaneous measurements of atmospheric fluctuations. The microbarograph also employed a quartz crystal sensor, with a range of 500–1100 hPa and a typical accuracy of 0.03%. Bottom sensor signals were transmitted via armored one-wire cables, and microbarograph signals via ordinary line, to a shore-based recorder and transformed there by an electronic analog filter-amplifier and amplitude selector. The transformed signal from each sensor (channel) was then integrated over a set time interval (0.25–8 min) and written on magnetic tape (compact-cassette) as sequential 15-bit words. The continuous simultaneous recording of ocean and atmospheric waves was intended to clarify the origin of long ocean waves in the tsunami frequency band. The instrument system also included a frequency/analog converter to provide direct visualization of sea-level oscillations as an aid to decisions involving marine hazard warnings.

3. Field Observations

Long-wave field measurements on the shelf of Kamchatka were carried out in September 1987 near Ozernovsk Village in southwest Kamchatka (Experiment KAMSHEL-87). The first cable station (V1) with a Vibrotron bottom pressure sensor was installed on 10 September at a depth of 9.5 m, about 800 m offshore; the second station (Q2) with a quartz sensor at a depth of 17 m, 1.4 km offshore, was installed the next day (Figure 2). The cables were connected to a multichannel recorder deployed in the winter dispatcher building of the collective fish farm, only 30 m from the waterline. No special effort was made to protect the cables in the surf zone, but the placement of the cables and their route through the surf zone and out of the water was carefully chosen. The precision microbarograph was installed in the same building on 1 September. The sampling interval (integration time) for all parameters was chosen to be 1 min.

The microbarograph worked until 7 October 1987. Water wave measurements continued with minor interruptions until 1 April 1988. Periodic changes of magnetic tape cassettes and routine recorder maintenance were performed by fish-farm workers. The measurements were terminated with the seasonal closing of the dispatcher building.

In September 1988, investigations on the Kamchatka shelf were resumed (Experiment KAMSHEL-88) and water wave recording stations V1 and Q2 were reacti-

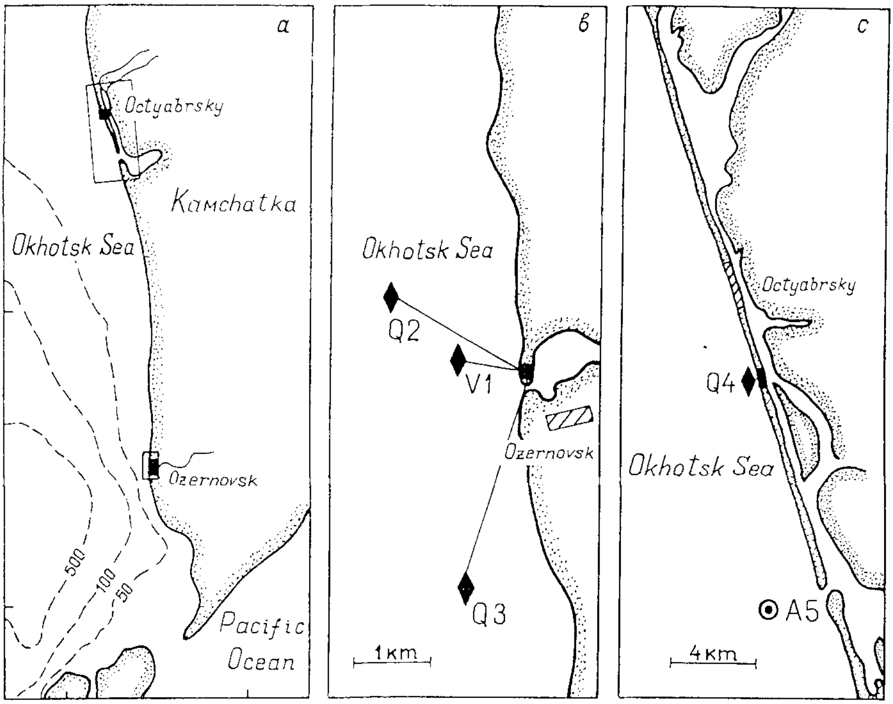

Fig. 2. Location of bottom cable stations on the southwestern shelf of Kamchatka.

vated. Data quality did not deteriorate, despite the one-year submergence of cables and sensors in the sea. In addition, station Q3 with quartz bottom pressure and water temperature sensors was deployed two miles south of station V1 at a depth of 10.5 m (Figure 2b). The corresponding cable was connected to the recorder and data from all stations were written on the same magnetic tape. Unfortunately, one of the farm-workers inadvertently disabled the tape recording at the end of September 1988, and the reason for the failure was not determined until the next IMGG expedition in May 1989. At that time it was also discovered that the cables to stations Q2 and Q3 were ruptured about 1.2 km from the shore. This apparently occurred in March 1989, when ships anchored nearby for shelter from the storm. As an unfortunte consequence, only a few days of simultaneous recordings at all three stations were obtained.

An inspection showed that cable conditions in the surf zone were quite satisfactory. The cables had been covered with sand, which protected them from damage. We also note that there was an early attempt in 1986 to install a cable bottom station with an analog recorder at Ozernovsk to provide tide and storm-surge observations for the Hydrometeorological Service. This attempt failed due to an unfortunate placement of the cable, as the line was destroyed in the surf zone within three weeks. The microbarograph was deployed again in May 1989, and at present

(February 1990) both station V1 and the microbarograph are successfully collecting data with few interruptions.

Additional instruments were also installed near the Octyabrsky Village in September 1988 as part of the KAMSHEL-88 experiment. At station Q4, a quartz sensor was deployed at a depth of 5.5 m about 600 m offshore (Figure 2c). In this region, big blocks of ice heap one upon another in the wintertime. To protect the cable, it was buried in sand to a depth of 2–3 m. As at Ozernovsk, a recorder and microbarograph were located in the dispatcher building. In addition, a self-contained unit with a vibrotron sensor was deployed at station A5 at a bottom depth of 20 m, about 20 km south of Q4. This station worked for three weeks. The sensitivity of the sensor was low and the data was subsequently used only for tide analysis.

Cassette exchanges in Octyabrsky were also performed by the local fishermen. Parallel analog recorder output provided them with tide level and marine-wave activity estimates. Unfortunately, power supply problems and a lack of continuous maintenance caused several data interruptions. At the end of October 1989, the recording of long water waves at station Q4 was temporarily stopped: we plan to resume observations at this station in 1990.

In spite of some misfortune, the results of the experiments on the southwestern shelf of Kamchatka are very encouraging. Relatively cheap cable stations, which were installed in a very complicated region characterized by a hard ice regime and high dynamic beach activity, have been working quite successfully for more than two years. Valuable scientific data have been obtained and are still being recorded. Some results of the data processing are presented below.

4. Data Description and Preliminary Analysis

All information from the cable stations and microbarograph were recorded on magnetic tape, read into a computer, and carefully verified. Each tape stored about 6–7 days of observations. This paper is devoted mainly to the analysis of data collected during the period September–October 1987 (the first 8 tapes obtained in Ozernovsk). In the Kamchatka region, these months are characterized by high activity and strong storms, but coastal waters are not yet ice-bound. Recorder maintenance procedures caused some loss of data between tapes, with the largest interruption of about 25 h occurring between tape numbers 4 and 5. Additional omissions occurred in the records of atmospheric fluctuations because of microbarograph power failure.

Atmospheric pressure and wind data from the Hydrometeorological Station at Ozernovsk were also used in the analysis. The standard time step of these data was 3 h, but station personnel made a special effort to measure these parameters every hour during intense storms, as a much-appreciated favor to the project. The least-square method was used to estimate tidal constituent for the records of stations V1 and Q2, then the predicted tides were subtracted from the initial records. High-pass Kaiser-Bessel filters (Harris, 1978) were then applied to the residual sea-level time series and the atmospheric pressure fluctuation records to isolate the high frequency components. These series were then used in the subsequent analysis.

5. Atmospheric Processes and Their Correlation with Background Longwave Oscillations in the Sea

The Okhotsk Sea is a zone of active cyclonegenesis, and the central part of the Okhotsk is characterized by the maximum number of cyclones occurring in the North Pacific (The Pacific Ocean, 1966). Some storms are very intense here, e.g. a cyclone in March 1988 had a central pressure of 942 mbar and was followed by devastating winds. Most approach Kamchatka from the southwest (i.e., from the Kuril Islands) or the west (from the Okhotsk Sea) (The Pacific Ocean, 1966; Likacheva *et al.*, 1985).

In the original atmospheric pressure records, typical amplitudes of the microfluctuations in calm, high pressure weather were 0.10–0.15 mbar; these amplitudes would increase to 0.3–0.5 mbar during periods of low pressure, with individual wave amplitudes exceeding 1 mbar. We subjected both microbarograph and ocean bottom pressure records to a high-pass Kaiser-Bessel filter with 2.5 h cutoff period. We then computed the rms atmospheric fluctuations, σ_p, and the rms longwave oscillations, σ_ζ, over 3 h segments of the records. These are presented in Figure 3, along with the simultaneous series of 3 hourly atmospheric pressure and wind speed observations.

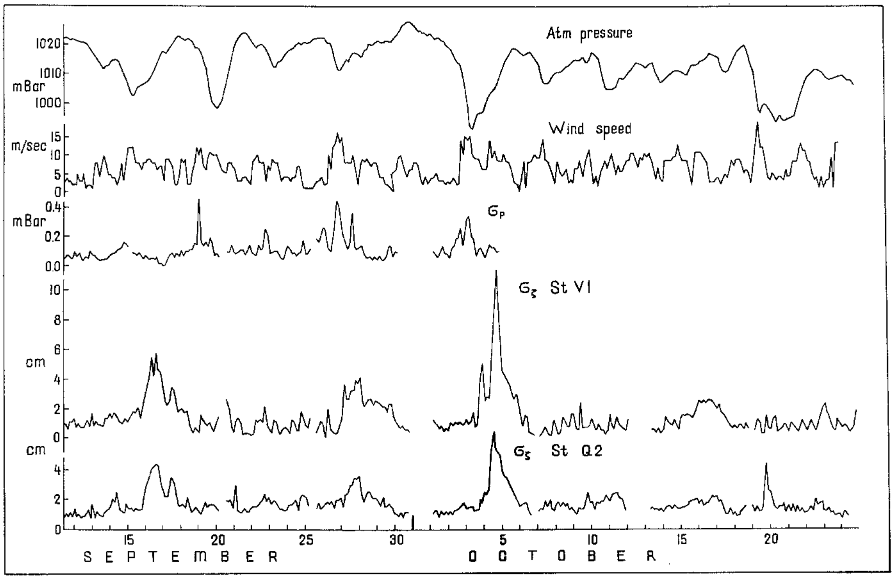

Fig. 3. Time series of atmospheric pressure, wind speed at the Ozernovsk Village, root mean square (rms) variation of atmospheric fluctuations (σ_p) and rms variation of long waves at stations V1 and Q2 (σ_ζ).

During the period under study, there were 5 weak and 4 strong cyclones in the Ozernovsk region. The strongest storms occurred during the periods 14–16 September, 18–21 September (typhoon Freda), 2–6 October, and 19–22 October, i.e. one cyclone every 5–6 days (Figure 3). This cyclone recurrence period is quite typical for the Okhotsk Sea region (Likhacheva and Rabinovich, 1985). Cyclone passage was accompanied by intensification of atmospheric fluctuations, and maximum fluctuations usually occurred at the front of a storm, 12–18 h before the minimum pressure was registered (Figure 3). There is a clear correlation between wind speed and the intensity of high-frequency atmospheric pressure oscillations, strengthening of the wind was usually accompanied by a growth in pressure fluctuations. But there are exceptions. For example, strong winds on 15 and 19 September did not cause noticeable pressure fluctuations; on the other hand, strong atmospheric waves were observed on 22 September, when the wind was relatively weak (Figure 3).

Spectral analyses of all data were then performed, using time series which had first been subjected to a Kaiser-Bessel high-pass filter with a 4 h cutoff period, then tapered with a Kaiser-Bessel window to improve the spectral estimates (Harris, 1978). The results of the atmospheric wave spectral analysis were unexpected. During the observational period (10 September–7 October) the spectra were smoothly monotonic in character and were extremely stable, although total energy varied by 1–1.5 orders, depending on atmospheric activity, the spectral shapes were practically the same in each case, and were best fit by an $\omega^{-2.3}$ power law (Figure 4). This is steeper than observed by other scientists; according to Gossard (1960), Golitsyn (1964), Herron *et al.* (1969), and Kimball and Lemon (1970), atmospheric pressure spectra in the frequency range 10^{-4}–10^{0} Hz decrease according to an $\omega^{-2.0}$ law. This difference is probably due to the influence of the sea.

Although an investigation of atmospheric waves was not the primary objective of this study, their observation was necessary to estimate the efficiency of direct forcing of long ocean waves by atmospheric disturbances. A traditional point of view considers atmospheric fluctuations to be the main source of background longwave sea-level oscillations in the tsunami frequency band (Munk, 1962; Munk *et al.*, 1964), and there is indeed convincing evidence of longwave generation by atmospheric waves (Munk *et al.*, 1956.; Donn *et al.*, 1956). Furthermore, Bondarenko and Bychkov (1983) describe an interesting example of long waves in the Caspian Sea which were apparently generated by a train of atmospheric internal gravity waves; the coherence between the atmospheric and marine waves was about 0.6, and both had periods of 23 min. But these cases are the exception, not the rule; much more frequently, researchers find an absence of any correlation between high-frequency oscillations in the sea and atmosphere (Munk, 1962; Takahasi and Aida, 1962).

The water-wave records at station V1 and Q2, together with the simultaneous measurement of atmospheric fluctuations at a nearby station, provide a good opportunity to examine this question more closely. Cross-spectral analyses were made using record segments of 3–6 days. A fast Fourier transform technique was

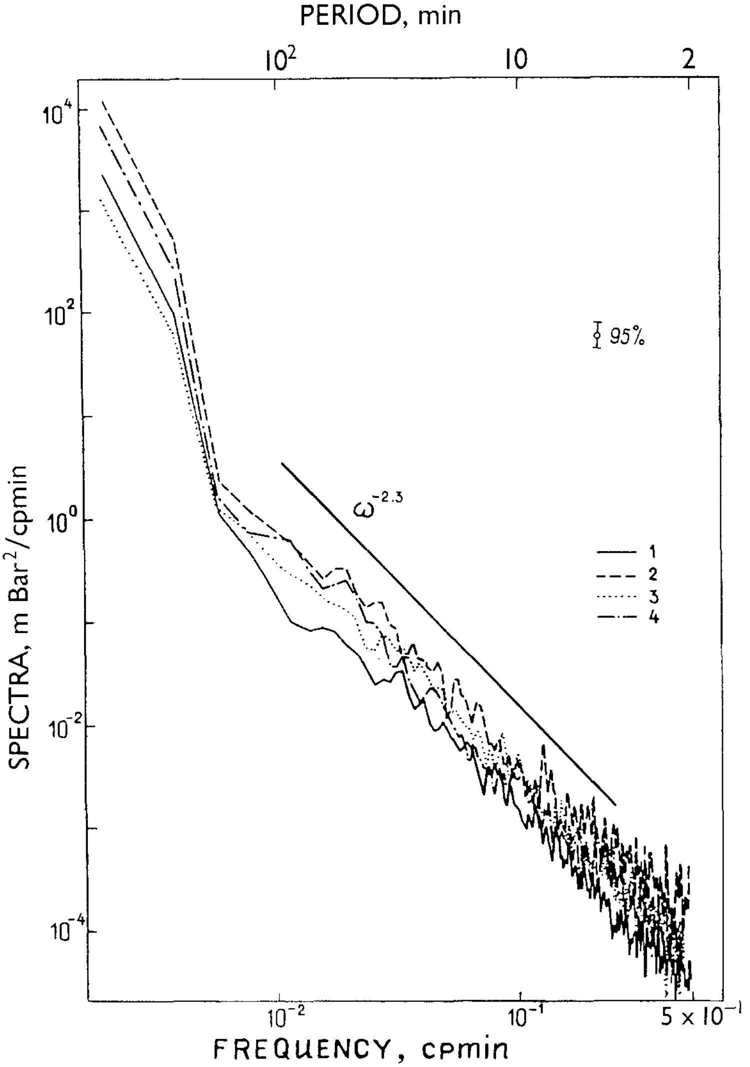

Fig. 4. Spectra of atmospheric pressure fluctuations for 4 different 5-day intervals in September–October, 1987.

used to obtain coherence and phase lag estimates; typically, the number of degrees of freedom was 100–200. For practically all of the period under study, the coherence between sea-level and atmospheric oscillations was less than 0.1, i.e. well below a significant confidence level. Figure 5a presents a very typical example. The single exception was the period 26 September–1 October when the coherence exceeded the confidence level and reached a value of 0.13 in the frequency range 0.02–0.09 cpmin (Figure 5b).

This behavior of the coherence between atmospheric and marine disturbances suggest that direct forcing of the sea surface by atmospheric pressure does not

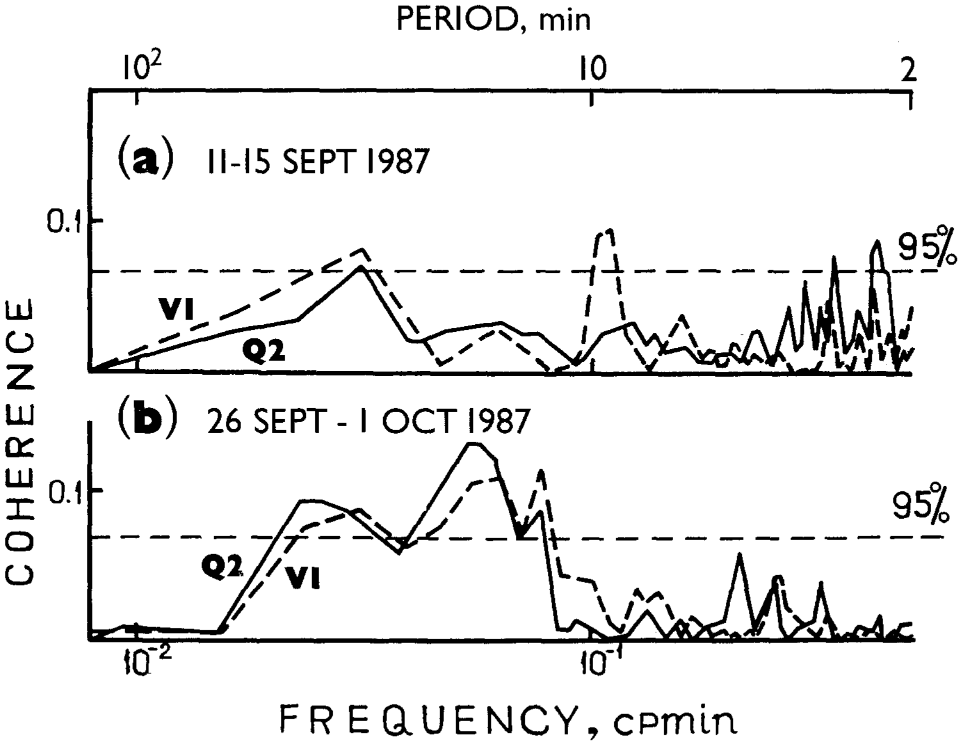

Fig. 5. Coherence between atmospheric fluctuations and long waves at stations Q2 (curve 1) and V1 (curve 2) for the periods (a) 11–15 September 1987 and (b) 26 September–1 October 1987.

normally play an important role in the generation of background long waves. It appears that strong longwave oscillations which are correlated with atmosphere fluctuations, such as observed by Munk *et al.* (1956), Donn *et al.* (1956), and Bondarenko and Bychkov (1983), are resonant in nature. But resonance conditions are rarely realized, so that these resonantly generated waves ('meteotsunami'), like actual tsunami waves, are of minor importance in the background spectra.

This being the case, what causes the background longwave oscillations with tsunami periods? There is a definite correlation between time variations of atmospheric pressure and longwave intensity (Figure 3). Typical longwave amplitudes were 1–3 cm during calm weather and from 5–15 cm during cyclone passages. Evidently, the atmosphere is the main source of excitation for these waves, but the energy transfer mechanism is far from trivial. Two mechanisms for indirect longwave generation are possible:

(1) scattering of 'meteotide' (surge sea-level displacement) by bottom and coastline irregularities;

(2) nonlinear interaction of water gravity waves (swell, wind waves).

The first mechanism is well known for internal waves, and irregularities of relief are the main generating source (LeBlond and Mysak, 1977). Kulikov and Shevchenko (1985) showed that surface long waves may also be generated by a similar process. The second mechanism plays an important role in forming surf beats – longwave motions in a coastal zone with time scales of about 30–300 sec (Munk, 1949). Longuet-Higgins and Stewart (1962) described theoretically the origin of a forced wave component of surf beats, connected tightly with the group structure of surface gravity waves; Gallagher (1971) and Bowen and Guza (1978) have demonstrated the possibility of free edge waves generated by wind waves and swell.

Both mechanisms are characterized by a two-cycle energy transfer from the atmosphere to long waves. Which process is more important for waves in the tsunami frequency band is the subject of this special study.

6. The Correlation of Longwave Spectra with Sea State

On 2–6 October 1987 a strong cyclone passed by Ozernovsk. The cyclone was accompanied by significant longwave oscillations; σ_ζ exceeded 7 cm at station Q2 and 11.5 cm at station V1 (Figure 3). This case provided us with an excellent opportunity to investigate the origin of long waves.

A moving cyclone is associated with a sea-level displacement that represents a forced departure from static level appropriate to the 'inverted barometer law'. If such a displacement was the source of long waves through the process of diffraction and scattering, then waves with maximum amplitude should be observed at or before the moment of minimum pressure (maximum surge), since the longwave velocity is much higher than the cyclone speed. But in fact, the maximum waves clearly lagged the cyclone center by several hours (Figure 6). The correlation between pressure and long wave intensity (σ_ζ) indicates an average time lag of about 33 hours.

The reason for this time lag, and the origin of the observed long waves, may be clarified by comparison with the wind and wind-wave variability. Easterly (offshore) winds prevailed at the front of the cyclone (Figure 6), and only small wind-waves (less than 1 m) were observed. After the cyclone center crossed the region of Ozernovsk, the wind became westerly (onshore) and wind-waves then began to grow rapidly. The time of maximum long waves corresponds exactly to the time of maximum wind waves (visually estimated to be higher than 3.5 m).

Spectral analyses of long waves for different sea surface conditions show that longwave energy increased considerably during the storm in the high-frequency band (up to periods of 35–40 min) but was practically unchanged at low frequencies (Figure 7). Similar results have been obtained in the coastal zones of Japan and the Kuril Islands, where strong correlations have been noted between sea-state and background longwave oscillations. Storm-generated waves were found to accompany significant long waves with periods 1–18 min (Takahasi and Aida, 1962),

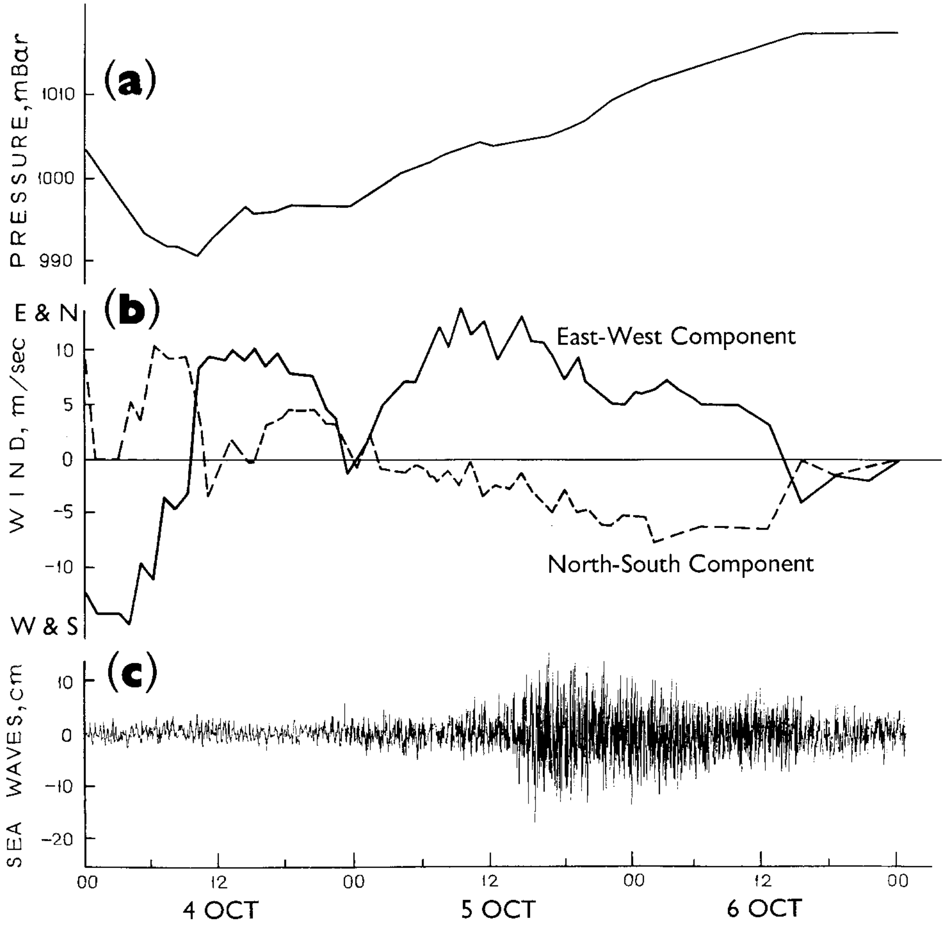

Fig. 6. Variations during cyclone passage on 3–6 October 1987 (a) atmospheric pressure, (b) east-west and north-south wind component at the Ozernovsk Village, and (c) background longwave oscillations at station Q2.

2–25 min (Aida *et al.*, 1970), 1.5–15 min (Bychkov *et al.*, 1972), and 1–25 min (Hashimoto *et al.*, 1986); corresponding spectral bands were 2 orders higher in rough weather than in calm weather.

Such spectral behavior proves that storm passage can cause a phenomenon analogous to 'negative viscosity', a well-known process in turbulence theory (Monin and Ozmidov, 1981), in which motions with high frequencies and small scales transfer energy to large-scale, low frequency movements. Negative viscosity may develop only in the presence of an intensive external source, and energetic storm waves are just such a source. Hasselmann (1971) presented a theoretical mechanism whereby energy could be transferred from short gravity waves to larger-scale motion, and suggested that this may be an important process in the generation of long ocean waves.

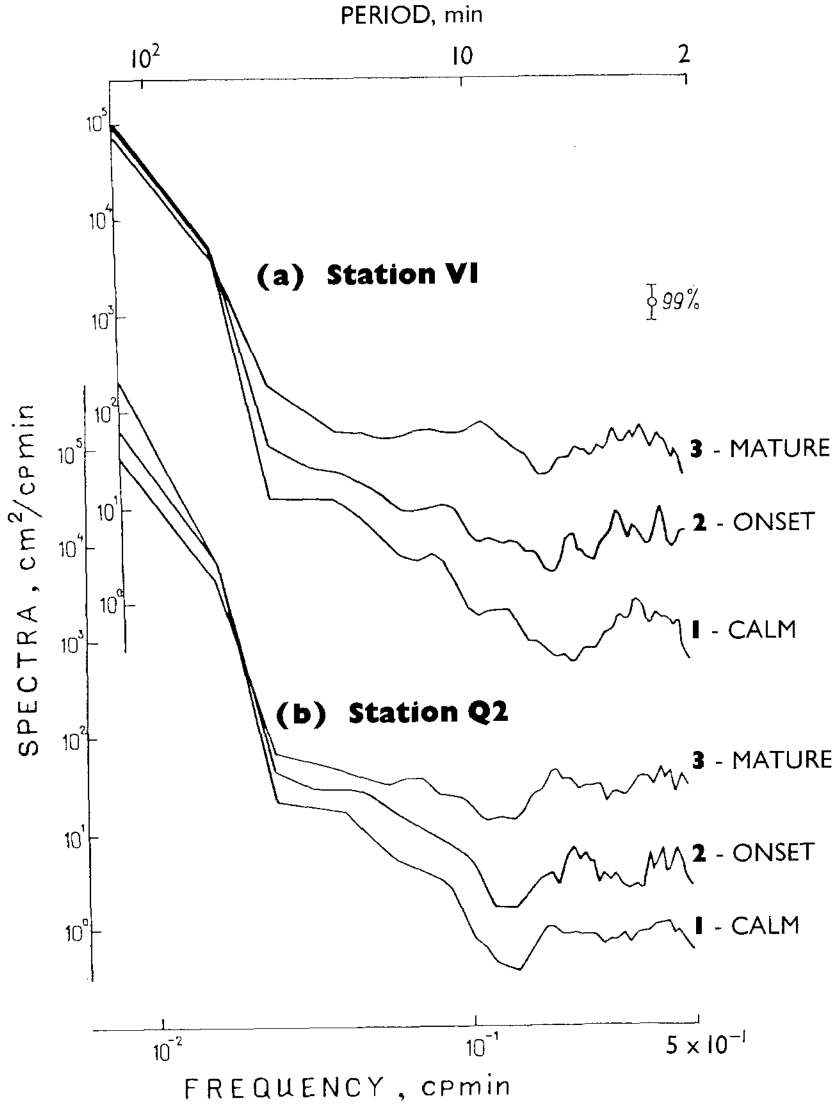

Fig. 7. Longwave spectra observed during the period 3–6 October 1987 at (a) station V1 and (b) station Q2 during three stages of the storm: (1) the calm period before storm arrival, (2) at the onset of the storm, and (3) during the mature phase of the storm.

Unfortunately, the sampling integration period of 1 min precluded quantitative estimates of this process, because of aliasing effects. Specifically, a rectangular filter with a 1 min window does reduce the amplitude of oscillations with a 6–7 sec period by a factor of 30, but that may still be insufficient to remove aliasing effects entirely. Thus, while storm-wave intensification activates nonlinear processes which increase energy transfer to low frequencies, the effects of aliasing also increase simultaneously.

Nevertheless, the reality and importance of this longwave generation mechanism is confirmed by data collected during the Second Soviet-American Tsunami Expedition (Kulikov *et al.*, 1983). Bottom pressure measurements at station P2, installed at a depth of 1000 m, showed a significant increase in longwave spectral energy in the 2–15 min period band, connected with the passage of typhoon Irma (16–18 September 1978). Here, the effect of wind wave aliasing was negligible because of hydrodynamic filtering due to the large depth of the sensor.

Background long waves in the tsunami frequency band (especially at the higher frequencies) can be generated in both coastal and open-ocean regions by storm-generated waves. The model of Longuet-Higgins and Stewart (1962) quite suitably describes the process. In contrast to marine baric waves, which are forced directly by atmospheric waves (Bondarenko and Bychkov, 1983), waves related to nonlinear wind wave interactions may be called 'infragravity waves'. This term is also used for motions with shorter periods (30–300 sec) (Holman, 1981; Middleton *et al.*, 1987).

7. Offshore Structure of Longwave Field

The longwave spectra at stations V1 and Q2 were relatively complicated (in contrast to the atmospheric spectra) and had well-pronounced minima and maxima at periods less than 10 min. The positions of these extremes were different for different stations but very stable and did not depend significantly on the synoptic situation. The spectrum for station Q2 has minima at periods of 8.1 and 3.4 min, and maxima at periods of 4.8 and 2.6 min; the corresponding periods for station V1 were 5.1 and approximately 2.2–2.3 min (minima) and 2.9 min (maximum) (Figure 8).

It is interesting that an abrupt decrease in coherence between the oscillations at stations V1 and Q2 coincided exactly with the first spectral minimum of station Q2; an abrupt change of phase from 0 to 180° also occurs at the same frequency (Figure 8). Wavelengths corresponding to this frequency were about 4–5 km, much longer than the distance between stations (about 1 km).

These features of the longwave spectra suggest that the observed spectral structure is determined not by pecularities of the external energy sources or by the mechanism of generation, but by the coastal zone topography and its corresponding system of eigen-oscillations.

Bathymetric relief in the Ozernovsk region is relatively plane and a linear slope model $h(x) = \alpha x$, where h is the water depth and x is the offshore coordinate, may be used to describe the longwave field in the coastal area. Normally reflected leaky waves are described by the expression (Lamb, 1932):

$$\zeta(\omega; x) = aJ_0(\chi), \tag{1}$$

where

$$\chi = (4\omega^2 x / g\alpha)^{1/2} \tag{2}$$

and where ζ is the sea surface elevation, a is the coastline amplitude, ω is the radial

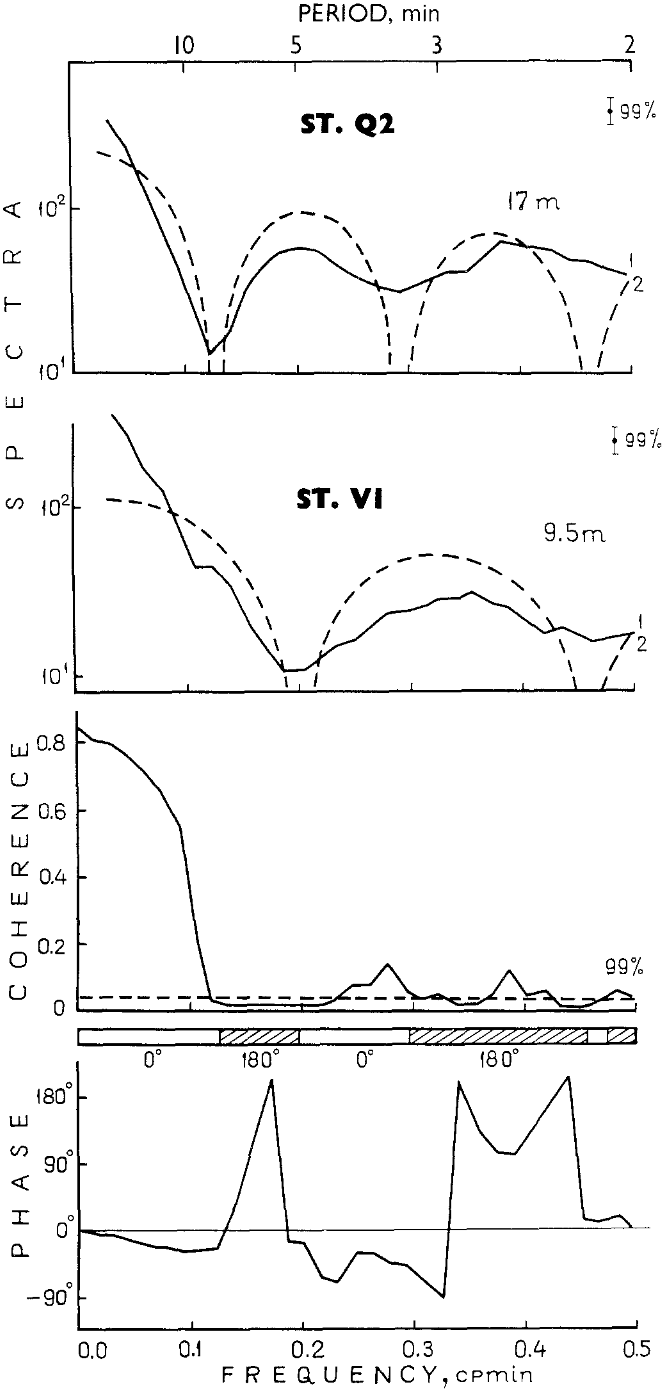

Fig. 8. Longwave spectra at stations Q2 and V1, and the coherence and phase differences between long waves at these stations. Dashed lines are the theoretical spectra for standing long waves; and the theoretical phase is also indicated just below the coherence plot.

frequency ($=2\pi/T$, where T is the wave period), J_0 is the 0th order Bessel function and g is the gravitational acceleration. The function J_0 has zeros when $\chi = \chi_k = 2.405, 5.520, 8.654$, etc. Apparently, for any distance offshore $x = x_i$ there are frequencies

$$\omega_{ki} = \chi_k(g\alpha/4x_i)^{1/2} \tag{3}$$

for which $J_0 = 0$, representing the nodal lines of standing waves parallel to the coastline (Suhayda, 1974; Holman, 1981). At the frequencies ω_{mi}, corresponding to the values $\chi = \chi_m = 3.832, 7.016, 10.174\ldots$, the function J_0 has extrema that are the antinodes of the standing waves.The theoretical spectral energy of standing waves predicted by this linear slope model are proportional to J_0^2 and have minima (maxima) at the frequencies $\omega_{ki}(\omega_{mi})$. Phase lags between waves at different stations will be 0 or 180°, depending on the frequency.

Calculations of relative spectral and phase differences were made using the expressions (1) and (2); values x_i were picked to provide the best correspondence between theoretical calculations and observational data. The best results were achieved with $x_i = 630$ m and $x_2 = 1250$ m (Figure 8). This means that incident waves were reflected primarily from the breaking line rather than the coast, and that this line was at a distance of about 150–170 m from the shore. Spectral maxima and minima, phase differences, and coherence between the data recorded at stations V1 and Q2 are in good agreement with theory.

The structure of longwave spectra becomes simpler on approaching the shore. The first spectral minimum is displaced to higher frequencies. This effect is clearly seen in the wave spectrum of station Q4 (Octyabrsky region), located closer to the shore than the other stations (Figure 9). In contrast, the most remote offshore station, Q2, has the most complicated spectral structure (Figure 8). We note here that our spectral estimates for periods of 2–3 min are qualitative, rather than quantitative, and a proper investigation of this portion of the spectrum would require denser sampling in both space and time.

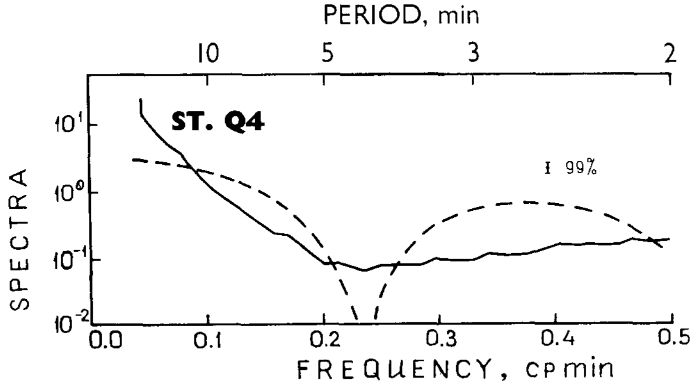

Fig. 9. Observational and theoretical spectra of long waves at station Q4 near Octyabrsky Village.

Similar offshore structure was observed by Suhayda (1974), who investigated wave motions with periods of 1–30 sec. And although he dealt with very different temporal and spatial scales, he too found good agreement with linear shallow water theory for standing leaky waves on a plane beach. These results do not exclude the possibility that edge waves are also present as a component of the wave field. But the profile of a standing edge wave normal to the coast is very similar to that of a normally incident leaky wave of the same frequency, and the separation of these two types of motions would also require a denser instrumental array (Guza and Inman, 1975).

8. Discussion and Conclusions

Measurements of long waves by bottom cable stations on the southwestern shelf of Kamchatka have demonstrated the feasibility of establishing inexpensive, long-term tsunami observation stations in a region with complicated ice, beach and hydrodynamical regimes. Perhaps the most surprising result is that, in spite of widespread opinion that atmospheric waves are the main source of background sea-level oscillations in the tsunami frequency band, these oscillations were found to be weakly correlated with atmospheric fluctuations, but strongly correlated with sea-surface activity. The process of longwave generation is similar to the effect of 'negative viscosity', i.e. energy transfer from small- to large-scale motions, but a thorough investigation of this phenomenon will require continuous measurements of sea waves with a sampling interval of 1–2 sec.

Our results do not eliminate as a source mechanism the resonant generation of long waves by atmospheric disturbance. A search for these apparently infrequent events in existing data sets, and their subsequent analysis, is our next task. Long-term, high quality, simultaneous time series of atmospheric fluctuations and long waves at station V1 were obtained in 1989; these will provide an opportunity for such a study. It will also be interesting to examine the stability of atmospheric spectra and the power law $\omega^{-2.3}$ as a function of different seasons.

A theoretical linear bottom slope model for standing leaky waves was found to be in good agreement with observational data at stations V1 and Q2. Initially, this result may appear to be in contradiction with the results of Munk *et al.* (1964) and Huntley *et al.* (1981), who showed that the background longwave field is composed primarily of trapped edge waves. In fact, however, offshore profiles for standing leaky waves and higher edge wave modes are very similar (Holman, 1981). To separate edge waves and leaky wave modes, and to estimate their relative contribution, it will be necessary to have additional offshore and longshore stations; i.e., a much larger orthogonal array.

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