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THE TSUNAMIS OF JANUARY 3, 2009 IN INDONESIA AND OF JANUARY 15, 2009 IN SIMUSHIR AS RECORDED IN THE SOUTH KURIL ISLANDS

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ABSTRACT

Bottom pressure gauges installed by the Institute of Marine Geology & Geophysics RAS in Shikotan Island, Kitoviy Bay (Iturup Is.) and near Cape Van der Linde (Urup Is.), recorded two tsunamis during the month of January 2009. The first of the recorded tsunamis was generated by the January 3, 2009 earthquake in Indonesia and the second by the January 15, 2009 Simushir Island earthquake in the nearby seismic zone of the South Kuril Islands. The two tsunamis were additionally recorded by tide gauges at Hanasaki (Hokkaido Is.) and Malokurilskaya Bay (Shikotan Is.), but with considerable delay of the Indonesian tsunami from its estimated time of arrival. The tsunami travel time delay can be attributed to effects of energy trapping by Japan's continental shelf. The maximum height of the Simushir tsunami (97 cm in the Kitoviy Bay) was also observed much later than the arrival of the first wave. Totally, the oscillations lasted for about 32 hours, which is very long time period for the relatively weak tsunami. The present study investigates these apparent anomalies of the

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Keywords: *Tsunami, Earthquake, Indonesia, Kuril Islands, Urup, Iturup, Simushir, Shikotan, Hokkaido island, long wave spectral analysis, January 15, 2009 Simushir tsunami, January 3, 2009 Indonesia tsunami*

long wave oscillations and whether they were caused by reflected waves from the original earthquake or from a secondary tsunami generated by a weaker aftershock.

1. INTRODUCTION

In July 2008, the Marine Geology & Geophysics Institute of the Far East Branch of the Russian Academy of Sciences installed bottom pressure gauges in Shikotan Island, near Cape Lovtsov (on the north-eastern part of Kunashir Island), in Kitoviy Bay (of Iturup Island) and near Cape Van-der-Lind and Cape Kastrikum (Urup Island)(Fig. 1). The specific purpose for the installation was to record tsunamis originating close to the South Kuril Islands active seismic zone and to study long wave spectra variability depending on weather conditions.

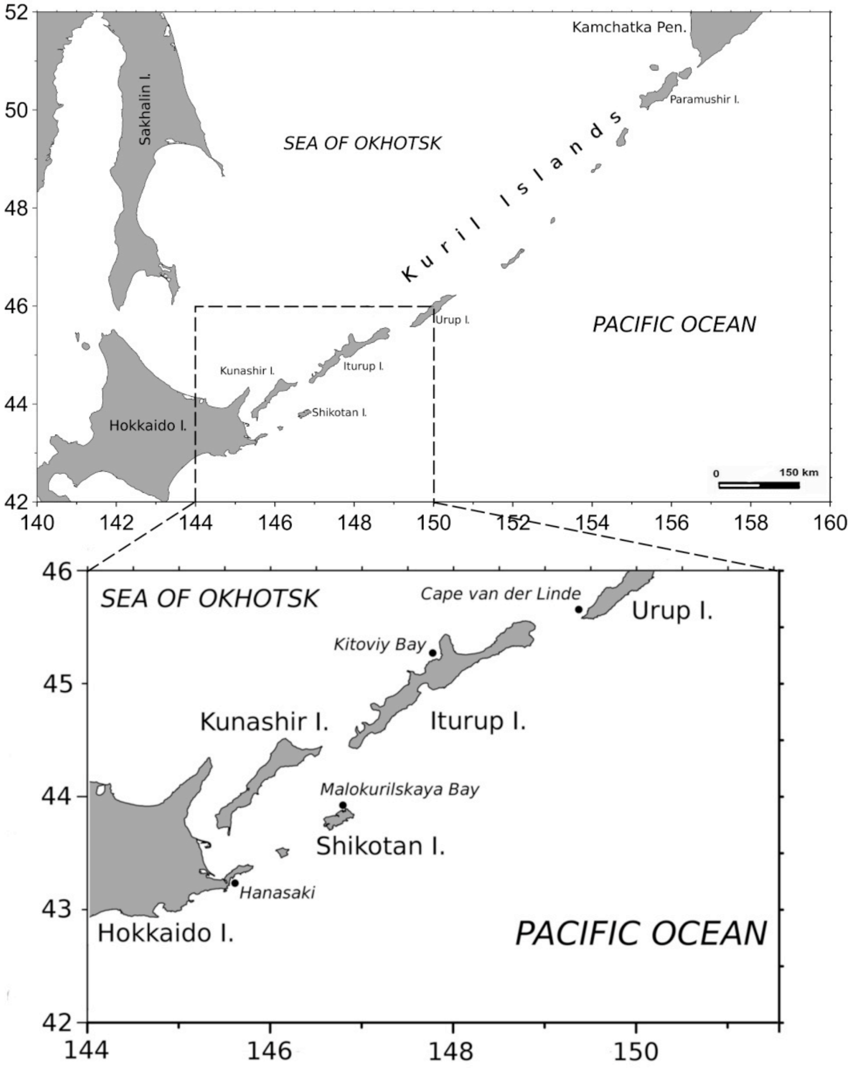

Figure 1. Location of gauges in South Kuril Islands

Measurements taken at these gauges had a sampling interval of 1 second, thus enabling the recording of heights and periods of both long period waves and wind waves. The methodology for converting bottom pressure measurements of wind generated surface wave heights has been developed and documented (Kabatchenko et al, 2007).

Bottom pressure gauges were used previously to record waves in the tsunami frequency range on the shelf and on the Kuril Islands continental slope (Zhak and Soloviev, 1971). The first offshore tsunami record was obtained on the shelf of Shikotan Island on February 23, 1980 (Dykhan *et al.*, 1981). This recording indicated a significant tsunami transformation in the near shore zone in comparison to the deep-sea region.

Autonomous bottom gauges were utilized to measure the hydrostatic pressure changes associated with sea level oscillations. Each gauge had a battery with enough power to continuously record for more than 180 days. In order to suppress energetic high-frequency swell and wind wave oscillations and avoid possible aliasing, a Kaizer-Bessel filter was used. One-minute data samples were collected filtered and archived. The forecasted tidal fluctuation was subtracted from the one-minute sea level time series. The residual series were subsequently analyzed to identify tsunami fluctuations or other anomalous long wave oscillations induced by weather related activity (typhoons, thunderstorms, squalls or abrupt atmospheric pressure jumps). The spectra of extreme events were compared with the background spectra, which corresponded to normal weather conditions.

The autonomous gauges were picked up and re-installed again in October 2008. The first phase of the experiment did not provide the anticipated results because only one weak tsunami and wave activity from one weak storm were recorded (Levin et al, 2009). However, during the next phase, which lasted from October 2008 to April 2009, more significant data was recorded – even though the two gauges installed near Cape Lovtsova and Cape Kastrikum were lost.

Records were obtained for two tsunamis during that period. The first of these was the tsunami of 3 January 2009, which originated in Indonesia and the second was the tsunami of 15 January 2009, which was generated by an earthquake in the nearby Simushir Island. Additionally, records were obtained for waves generated by several strong winter storms. The remotely generated tsunami from Indonesia was clearly evident in the Malokurilskaya gauge (Shikotan Harbor). However, this tsunami could not be identified in records from the other pressure gauge stations. Gauges in Malokurilskaya Bay, Kitoviy Bay and the gauge near Cape Van-der-Lind recorded the tsunami generated in nearby Simushir Island. All stations on January 23-24, 2009, recorded anomalous sea level oscillations resembling those of tsunami signal although no known strong earthquakes had occurred on these days anywhere in the Pacific and none was included in the NEIC's catalogue of seismic events. More than likely the recorded event was of meteorological origin (a "meteorological tsunami"). The present paper provides an analysis of the above events with emphasis on the tsunami of 15 January generated in nearby Simushir Island.

2. THE INDONESIAN TSUNAMI OF JANUARY 3, 2009

A major earthquake with moment magnitude Mw=7.6 (USGS) occurred near Irian Jaya in Indonesia at 19:43 UTC on January 03, 2009. Its epicenter was at 0.5º S; 132.8º E, about 93 miles WNW from Manoewari (Irian Haya) and its depth was 34.7 km (USGS). The quake generated a significant tsunami, which was recorded by tide gauges along southeastern Asia and Japan. The estimated and observed tsunami arrival times, as well as wave heights for various points of Pacific were given at NOAA's website http://wcatwc.arh.noaa.gov/about/tsunamimain.php.

Most of the tsunami's energy propagated in a northward direction. The first waves reached Kyushu Island in Japan in approximately 4 hours after the quake's origin time (Fig. 2). The tsunami waves continued toward the South Kuril Islands, reaching Shikotan Island about three hours later. As expected there was attenuation with distance and the amplitude of the waves decreased by the time they reached Shikotan. Although the tsunami wave heights were not even high close to Indonesia, there were appreciable tsunami fluctuations recorded by the Shikotan Island gauge. The unusual fluctuations were puzzling and required further detailed consideration and investigation.

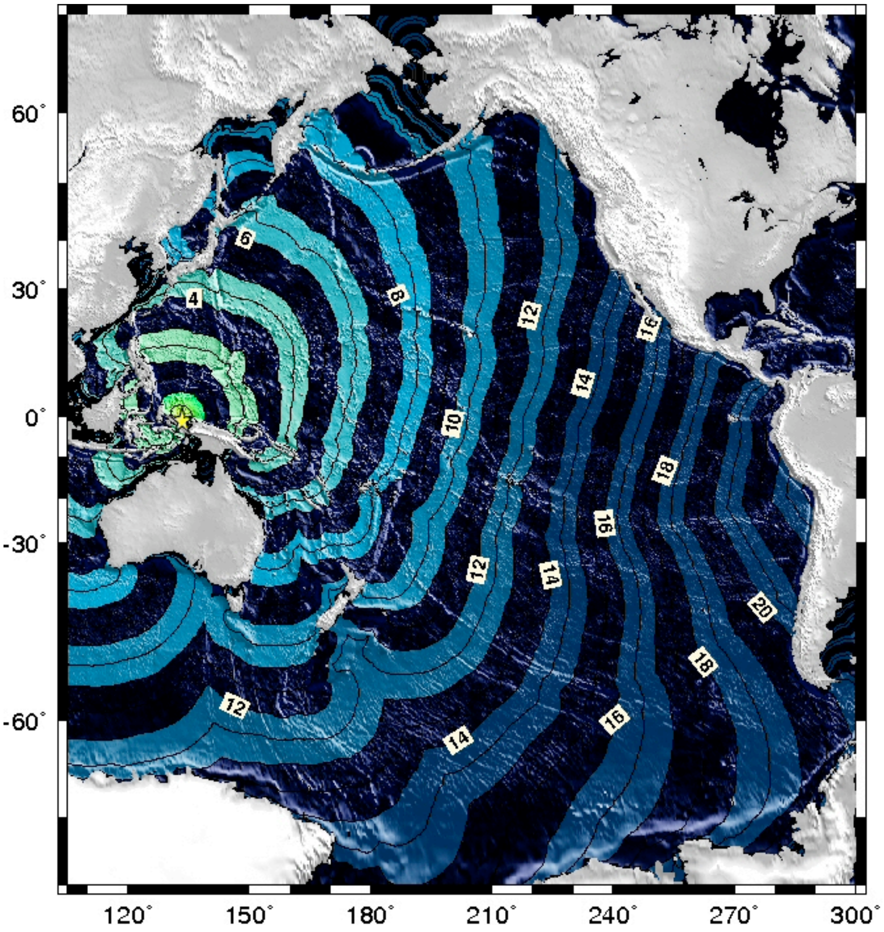

Figure 2. Calculated time travel map of Indonesia (Irian Jaya) tsunami (from NOAA website).

Daily segments of sea level recording of the January 2009 Indonesia tsunami were obtained from the gauges at Malokurilskaya Bay and from Hanasaki, as shown in Fig. 3. However, the tsunami could not be identified from records of gauges located at Kitoviy Bay and near Cape Van-der-Lind. The gauge at Malokurilskaya recorded a series of a well-distinguished group of waves with average periods of 18-19 min that corresponds to the zeroth (Helmholth) mode of the bay resonant oscillations (Djumagaliev et al, 1994). Such oscillations are routinely observed in the bay, so it is difficult to identify accurately the arrival time of the weak tsunami at this station.

Nevertheless, certain change in the character of fluctuations is noticed since 4:12 (UTC) was the most probable time of tsunami arrival at Malokurilskaya Bay. The maximum height (12 cm) in the first group of five waves was that of the fifth wave. Weak fluctuations were also observed after the first group within about an hour.

The first of the tsunami waves recorded at 6:48 of January 4th (UTC). Subsequently, about 10 fluctuations were recorded with an average period of 18 minutes and approximately identical heights (from a crest to trough) ranging from 17-19 cms. The apparent tsunami wave activity lasted for about 3 hours. At 9:00 UTC, the intensity of long-wave variations decreased to the background average level. According to NOAA's chart the tsunami travel time to Shikotan Island from the source region was 7.5 hours and the estimated time of wave arrival (ETA) was at about 3:10 – which was approximately four 4 hours ahead of the observed tsunami arrival. This is a point that needs special review. The NOAA website specified the ETA at Hanasaki stations to be at 3:05 (UTC) (see fig. 2). This estimate is approximately an hour sooner than that recorded at Malokurilskaya Bay, which was compatible with the numerical model calculation.

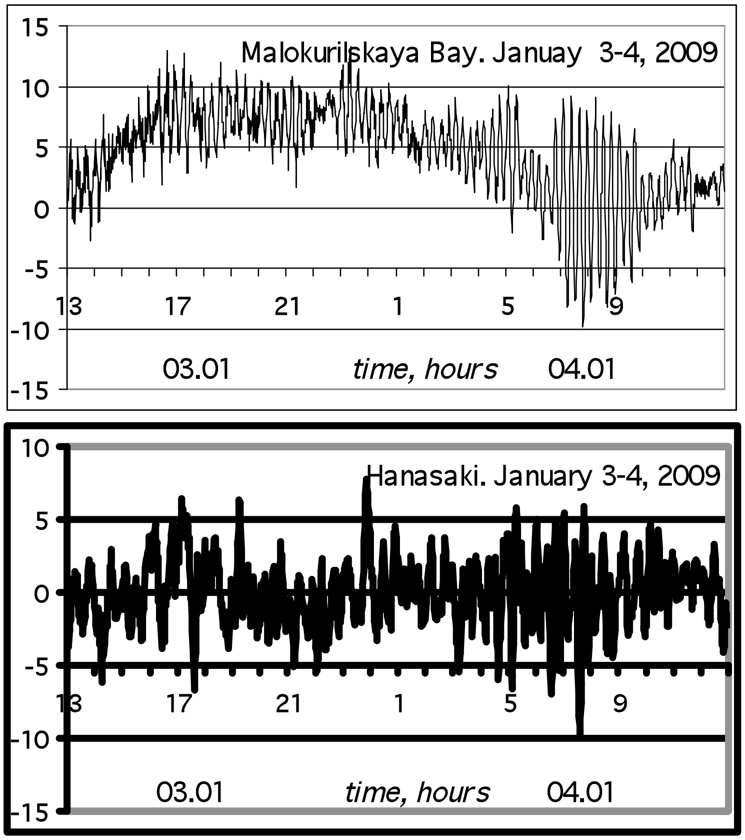

Figure 3. Residual (de-tided) sea level records (cm) in Malokurilskaya Bay and in Hanasaki (Hokkaido, Japan) from 13:00 on January 3 through 13:00 on January 4 (UTC).

The better-identified group of waves with periods 19-20 minutes was observed in this location about 2 hours later. The strongest fluctuation was observed at 7:37 (UTC) at the end of the wave group.

In order to determine the spectral properties of long wave oscillations recorded at each of the gauges, power spectral analyses were performed for two different data segments - both of one day's duration. The first analysis of the records was conducted for the day prior to the tsunami arrival and that was identified as "normal" and selected as being the background. The second analysis was on the records of the "tsunami period" that included the observed tsunami oscillations. Spectral analysis of the record from the Malokurilskaya Bay record represents the tsunami-caused amplification of resonant oscillations with a period of 18-19 minutes in comparison to the high-frequency oscillations (Fig. 4a). For example, values of spectral density on the resonant periods of 3.3 and 4 min were apparently decreased by tenfold – which was in good agreement with the visually observable "pure" signal of the tsunami.

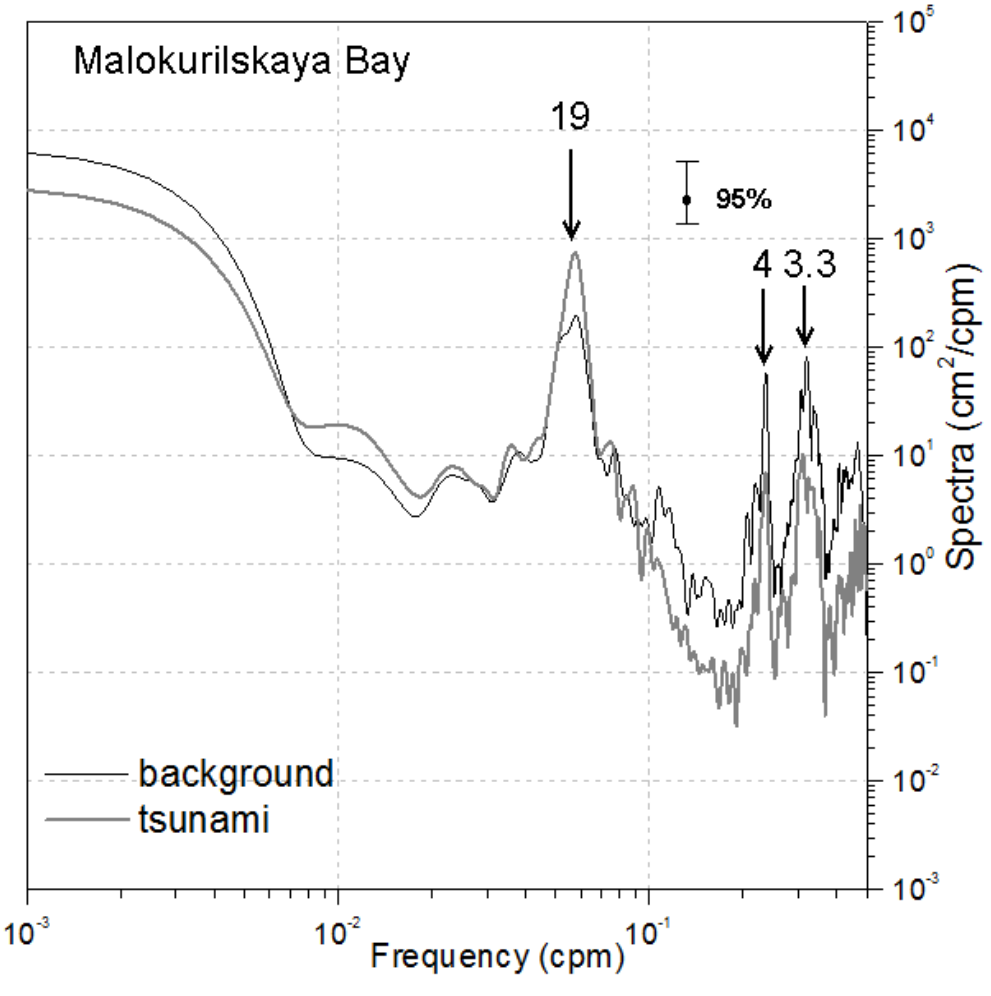

Figure 4a. Spectra of background and Indonesia tsunami-caused sea level oscillations in the Malokurilskaya Bay, Shikotan Island.

The Hanasaki station record shows that the tsunami caused significant amplification of the bay's resonant oscillations that had average periods of about 15 minutes. Also, maximum heights occurred on the bay's resonant oscillations that had periods of 19 and 35 minutes - which were absent in the background spectrum (Fig. 4b).

More than likely, the observed wave processes were caused by tsunami energy trapping and better energy retention by edge waves propagating on the shelf along the coast of Japan and traveling much slower than the long waves traveling in the open ocean (3 times deeper). The estimated time of wave front propagation along the coast of Japan - without considering the trapping effect - is about 2 hours. For the group of edge waves the estimated delay is about 4 hours and that corresponds to the actual observations.

The wave group period on the shelf of Japan and the resonant period near Malokurilskaya Bay were the reason of the clearly evident recording of the Indonesian tsunami in spite of its distant source. The edge waves did not reach the gauges near the Iturup and Urup Islands, so this was the probable reason that the Indonesian tsunami could not be identified in those records.

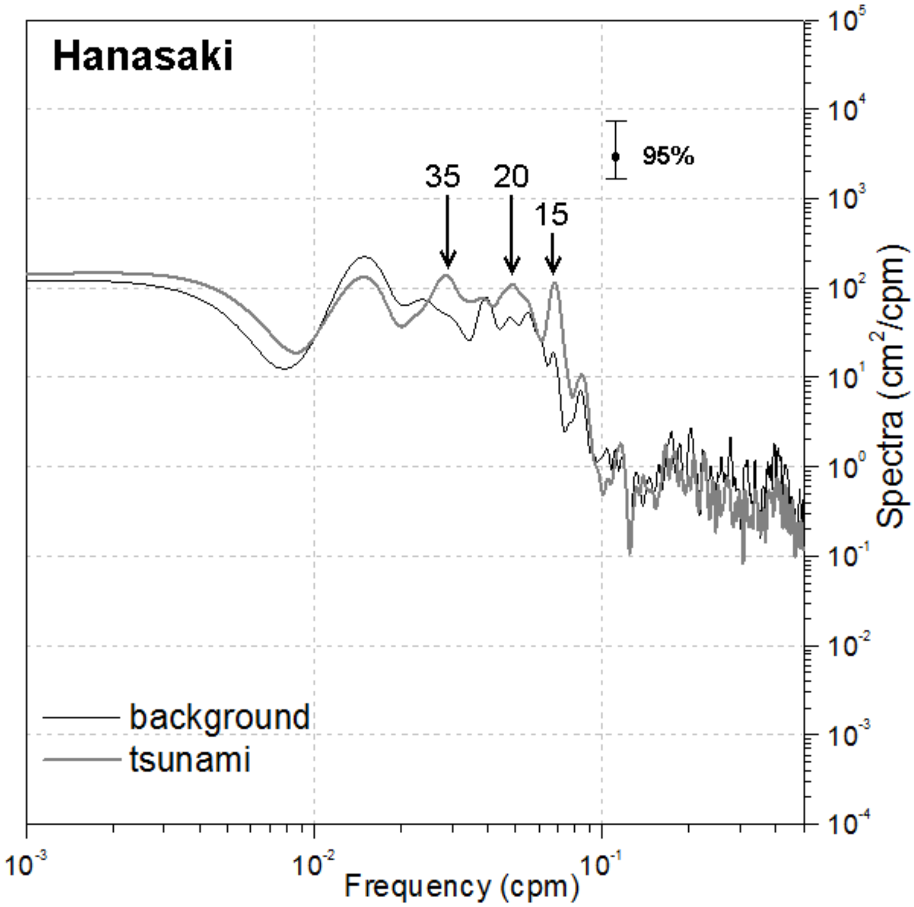

Figure 4b. Spectra of background and Indonesia tsunami-caused sea level oscillations. Hanasaki station, Hokkaido Island.

3. THE SIMUSHIR TSUNAMI OF JANUARY 15, 2009

At 17:49 UTC on 15 January 2009, a shallow earthquake (36.0 km depth) with moment magnitude (M=7.4, USGS) occurred in nearby Simushir Island. Its epicenter was at 46.9º S, 155.2º E - about 270 miles south from Severo-Kurilsk, Kuril Islands close to where the Simushir January 13, 2007 earthquake had occurred. (Fig. 5). Although similar in magnitude to the earthquake in Indonesia the 15 January Simushir event generated only a weak local tsunami.

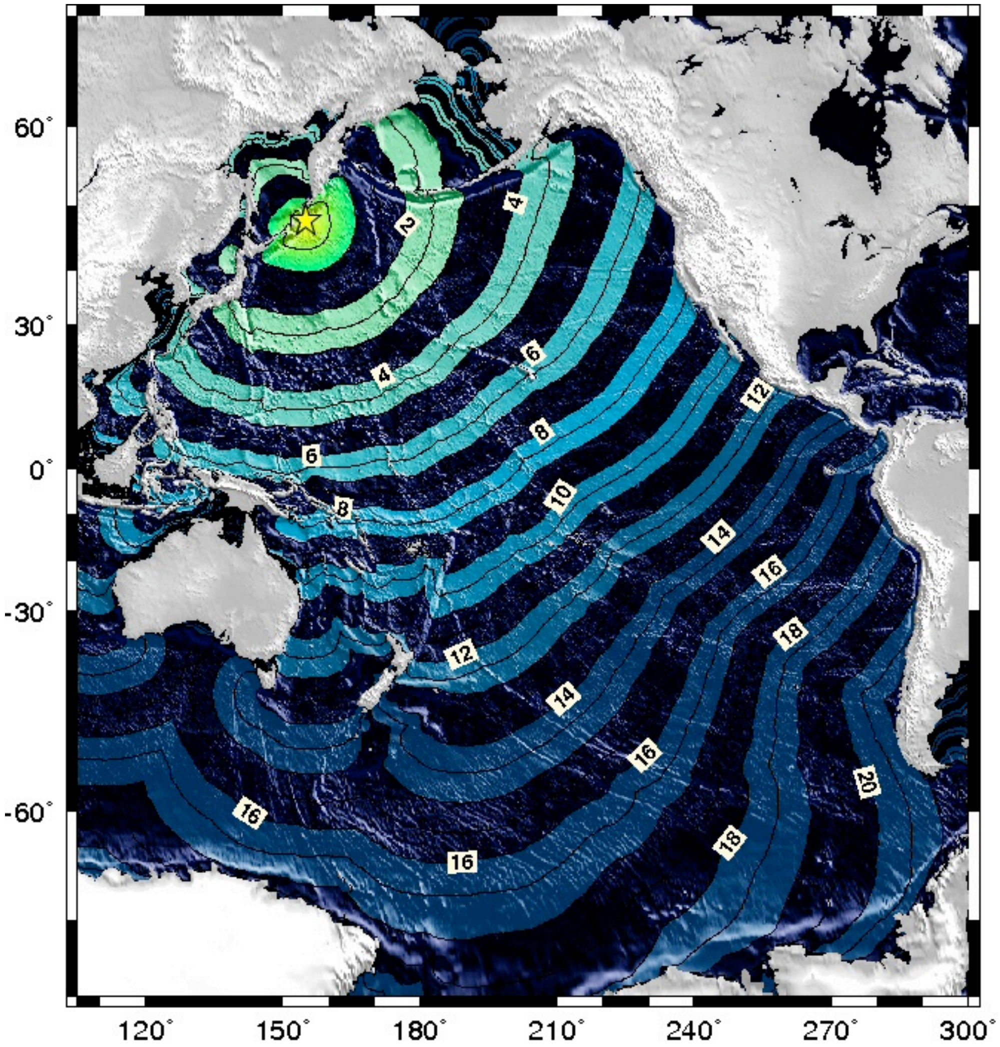

Figure 5. Tsunami Travel time chart of the January 15, 2009 tsunami (NOAA graphic).

According to NOAA modeling, the main energy flux of the tsunami was directed to the deep area of Pacific Ocean (Fig. 6). However, a significant portion of the tsunami wave energy was directed towards the Sea of Okhotsk. Similar wave energy distribution had been observed with two other tsunamis generated in November 2006 and January 2007 near Simushir Island.

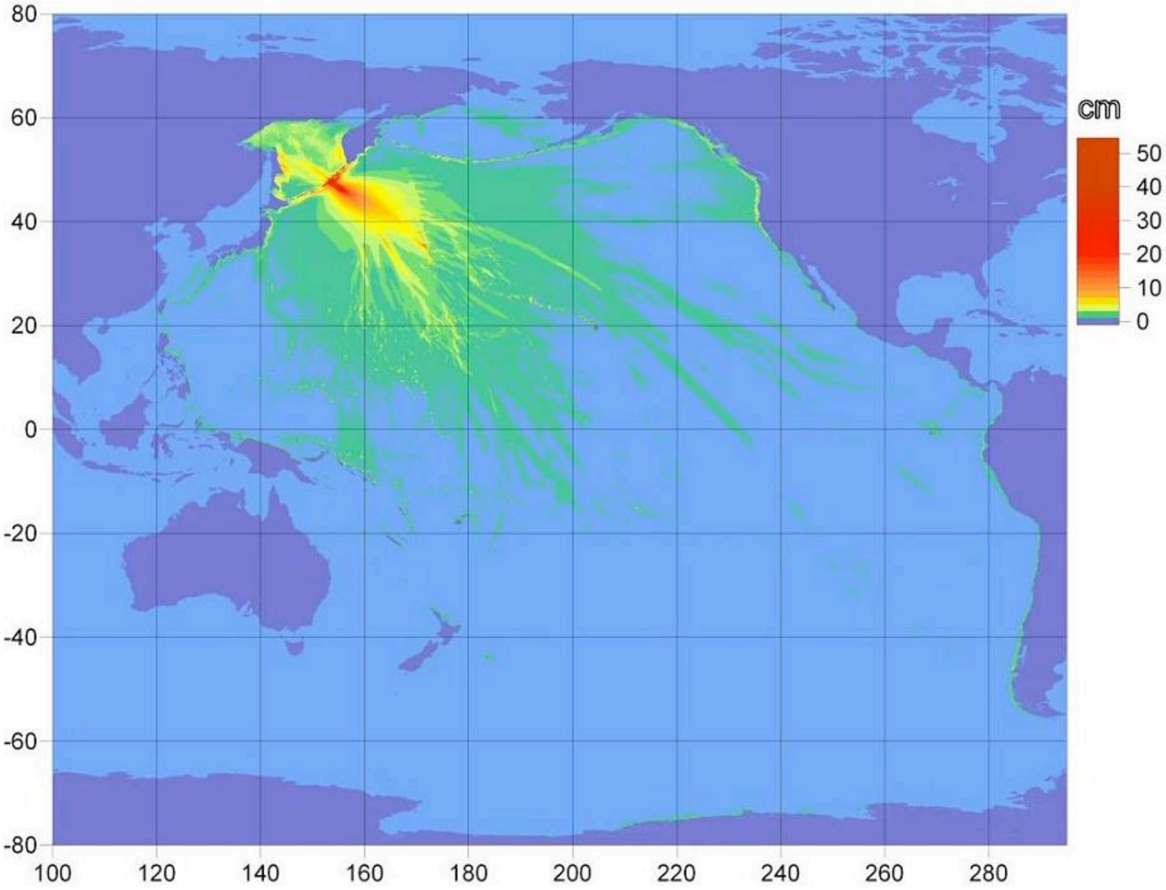

Figure 6. Calculated maximum amplitude graph of the Simushir tsunami (from NOAA website).

The tsunami waves were recorded on the bottom pressure gauges in Malokurilskaya Bay, in Kitoviy Bay and near Cape Van-der-Lind (Fig. 7).

Very high noise levels prevented the determination of tsunami wave arrival and recording of wave amplitudes at the last two stations. The background noise was caused by severe storms related to cyclone movement during that time period. Spectral estimates of wind waves for 12-hour intervals showed increasing energy at periods of 8-10 seconds to two orders of magnitude in comparison with the calm weather (Fig. 8). The maximum intensity of wind waves occurred in the first half of January 16. At that time the storm center was located near Simushir Island (Fig. 9), far from Shikotan Island and so the influence of the storm at Malokrilskaya Bay was not as powerful. Thus the tsunami was clearly recorded as a group of waves with periods of about 19 minutes and amplitudes ranging from 10-11 cms. The first wave of the group was recorded at 23:56 UTC and the duration of subsequent intense oscillations lasted for about 4 hours. Like with the Indonesian tsunami, the determination of Simushir tsunami arrival time at the Malokurilskaya Bay was complicated. Most probably, the ETA was 20:11 UTC, thus the tsunami travel time from the source area to the gauge at this bay was about 2 hours and 20 minutes – which was consistent with the estimated travel time of the Simushir tsunami of January 13, 2007 (Rabinovich et al, 2008; Lobkovsky et al, 2009)

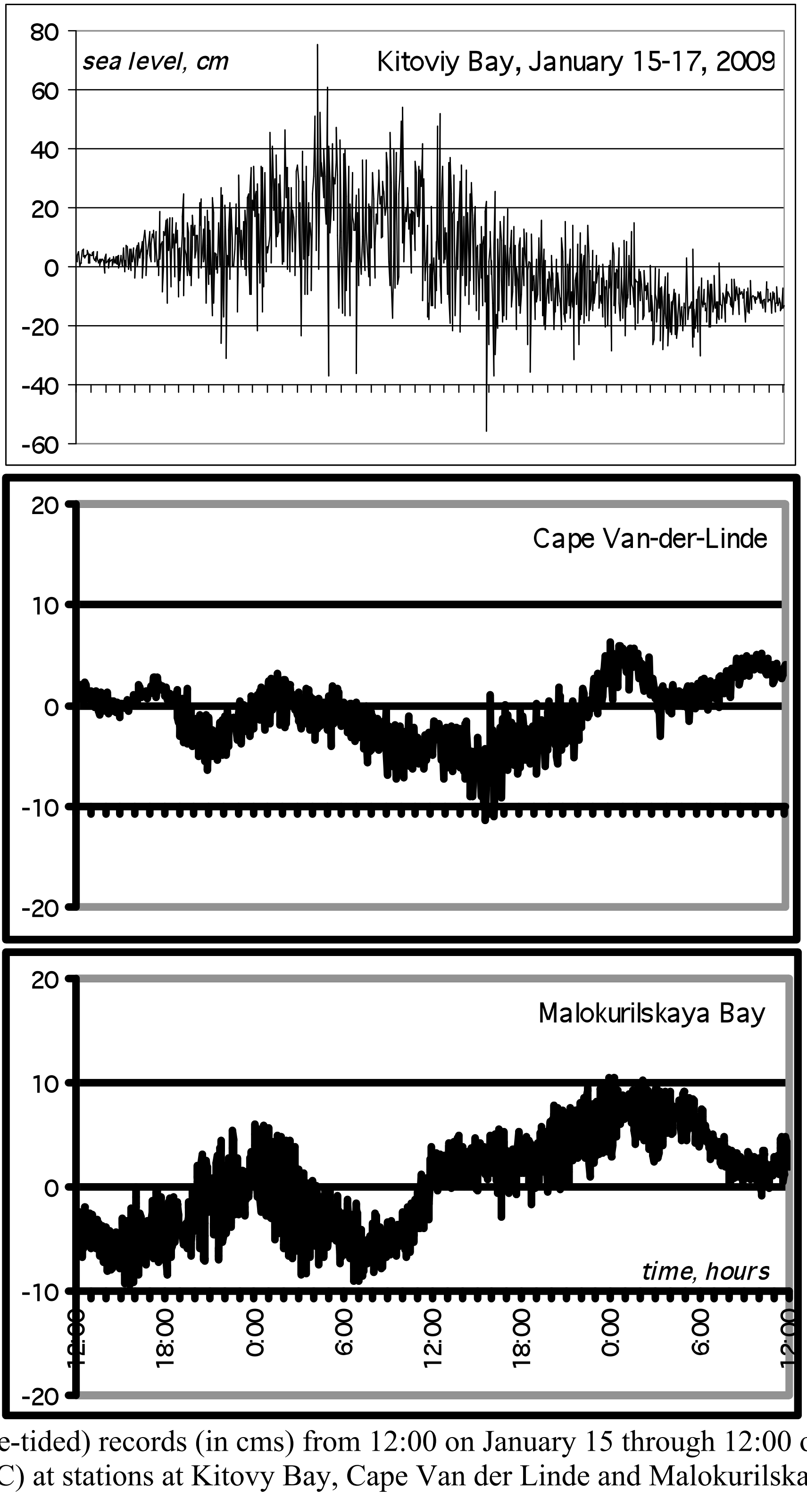

Figure 7. Residual (de-tided) records (in cms) from 12:00 on January 15 through 12:00 on January 17 (UTC) at stations at Kitovy Bay, Cape Van der Linde and Malokurilskaya Bay.

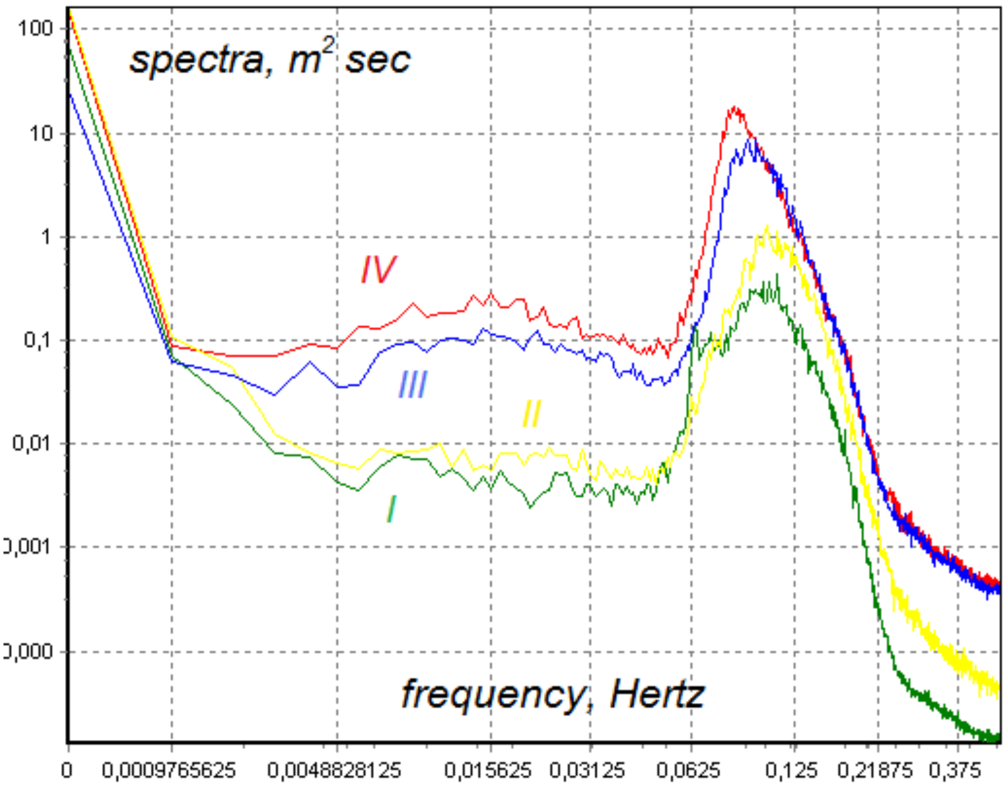

Figure 8. Wind waves spectra calculated for different time segments at the Cape Van der Linde gauge: a) from 0:00 to 12:00 on January 15 (I); b) from 12:00 to 24:00 on January 15 (II); c) from 0:00 to 12:00 on January 15 (I); d) from 12:00 to 24:00 on January 15 (II); e) from 0:00 to 12:00 on January 16 (III); f) from 12:00 to 24:00 on January 16 (IV).

For the tsunami of November 15, 2006, which was generated in the same general region, the maximum wave arrived 3 hours and 50 minutes after the first tsunami arrival. The delay was attributed to energy trapping by the shelf effect (Rabinovich et al, 2008). Similarly, the delay of the group of waves in 2009 can be attributed to the same effect.

To estimate the arrival time of the tsunami and of the wave height, we were forced to use averaging with a 3-minute time window. For the Cape Van der Linde record that was enough to suppress the high-frequency noise and determine exactly the characteristics of the tsunami. The arrival time of first wave was 18:49 UTC, one hour after the earthquake. The maximal wave heights ranging from 8-10 cms were observed much later, on January 16 from 15:43 to 16:49 UTC. The oscillations lasted for about 32 hours, which is a very long time for the weak tsunami. The arrival of waves with a maximum height a day after the earthquake was also very unusual. In the Malokurilskaya Bay, there was an increase of zeroth mode of resonant oscillations since 19:20. Probable reasons for these lasting wave oscillations can be either the arrival of reflected waves or the generation of more tsunami waves by subsequent strong aftershocks.

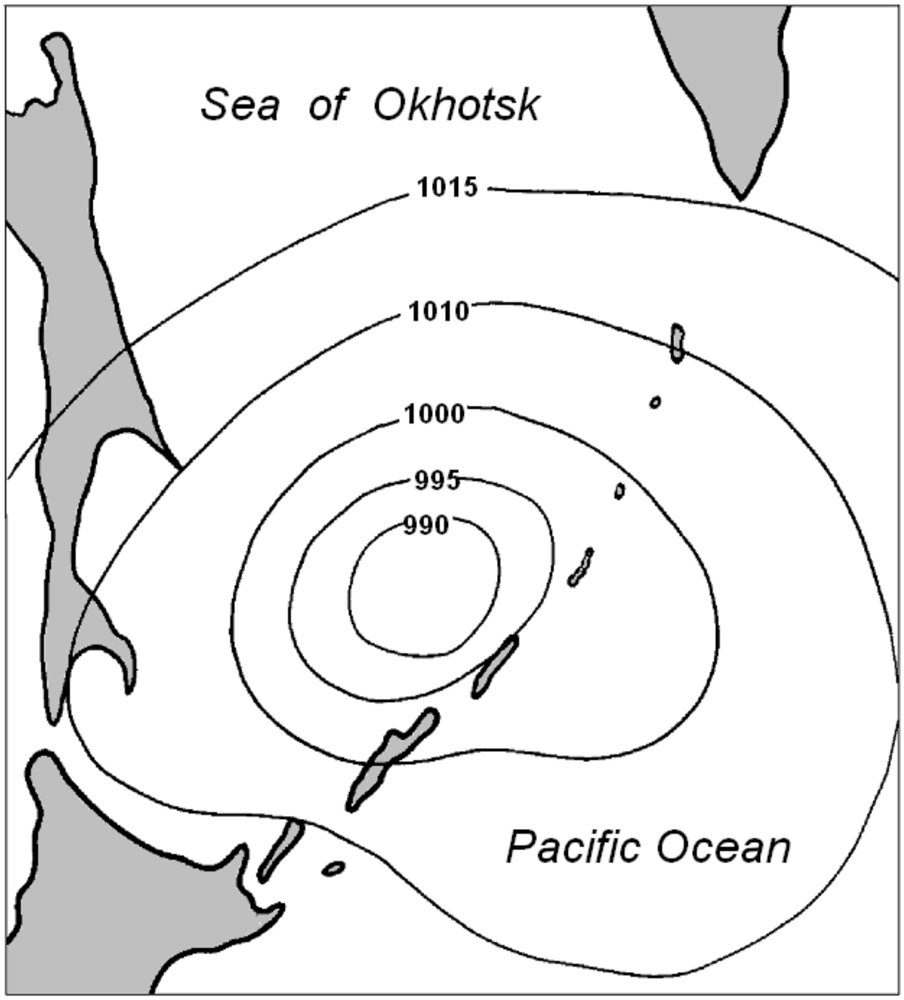

Figure 9. Atmospheric pressure spatial distribution from the weather map of Sakhalin hidrometeorological agency on January 16, 2009, 00:00 UTC.

The Sakhalin Department of Geophysical Survey (RAS) recorded two strong aftershocks on January 16. The first occurred at 15:14 UTC and had magnitude M=5.8 (preliminary estimate. Its epicenter was south of the main quake at 46.1 N, 155.9 E. The second occurred at 16:48, had a magnitude of M=5.9 and its epicenter was east of the main quake at 46.9 N, 155.8 E. It is difficult to evaluate the probability of tsunami generation by these aftershocks since the seismic information was not sufficient.

On the other hand, the probability of reflected waves influence is also low, since the tsunami was weak and the main flux of the wave energy was directed toward the open ocean. In view of these considerations the anomalous structure of the tsunami-caused oscillations, which could not be adequately explain.

More anomalous wave structure was observed in Kitoviy Bay and this can be related to certain superimposition of low- and high-frequency oscillations (Fig. 10a). Tsunami wave tsunami arrival time on this station could not be determined. The amplitude of long waves increased sharply since 15:27 UTC, about two hours before the earthquake. The reason of the increasing sea level oscillations was the strong cyclone in the area, which had a central pressure of 985 millibars. In the second half of January 15 the cyclone was over the Sea of Okhotsk near Iturup Island. The orientation of isobars indicated the direction of the wind toward Kitoviy Bay. The cyclone caused a severe storm in the port of Kurilsk, where the spectral energy of wind waves was amplified by about 200 times. The probability of the tsunami arriving concurrently with a strong storm is very small, since each of them is a rare event.

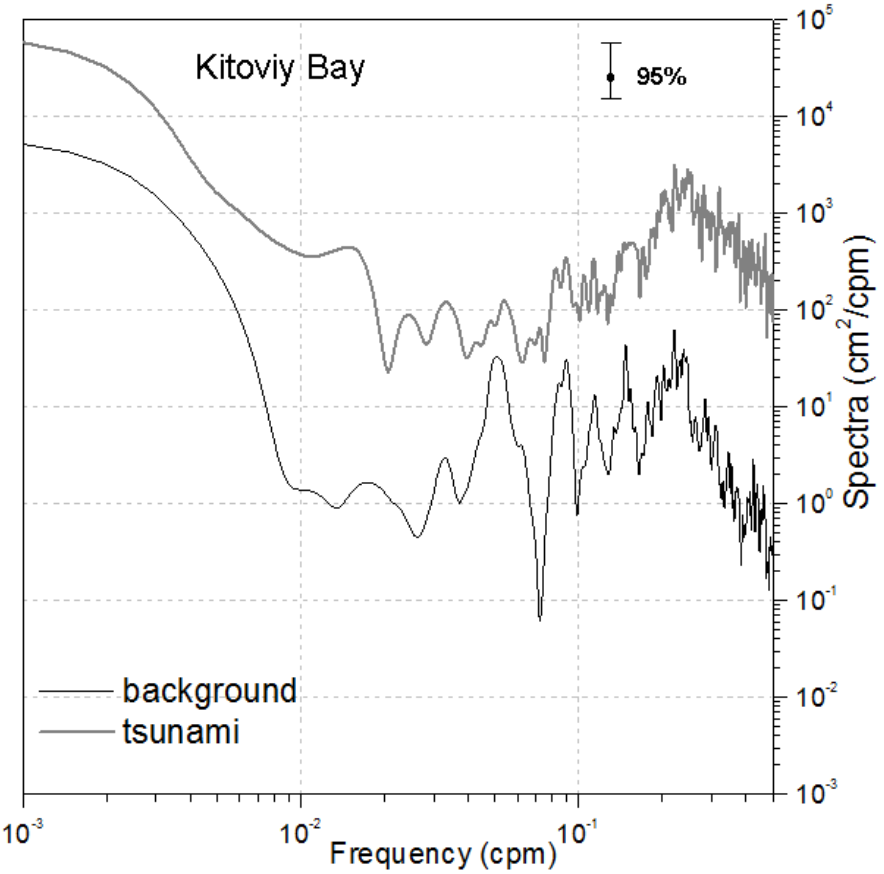

Figure 10a. Spectra of sea level oscillations of the background and of the Simushir tsunami at Kitoviy Bay, Iturup Island.

The intensity of sea level oscillations had steadily increased by 5:00 on January 16, when a maximum height of about 97 cms was recorded; A significant sea level lowering (ebb wave) can be seen in Figure 4. The high amplitude sea level fluctuations continued until 12:40. Another amplification of oscillations was recorded at 15:50, about the same time when the maximum waves arrived at the Cape Van der Linde gauge station. Decrease in the long wave intensity to a background level of occurred on January 17 at about 9:00.

The calculation of the spectra for the background signal and the tsunami-caused oscillations was performed in the same manner as for the Indonesian tsunami. The results are illustrated in Figure 6. In the Malokurilskaya Bay there was considerable distinctions in the energy level between the tsunami and the background spectra at the period of main resonant mode (18-19 min) and for the low frequency band at the periods 45-60 min. In contrast, the Cap Van der Linde gauge record analysis shows a significant increase in the tsunami spectra in the high frequency band (for periods less then 6 min) (Fig. 10b). Most probably, this increase was caused by the storm's action and not by the tsunami.

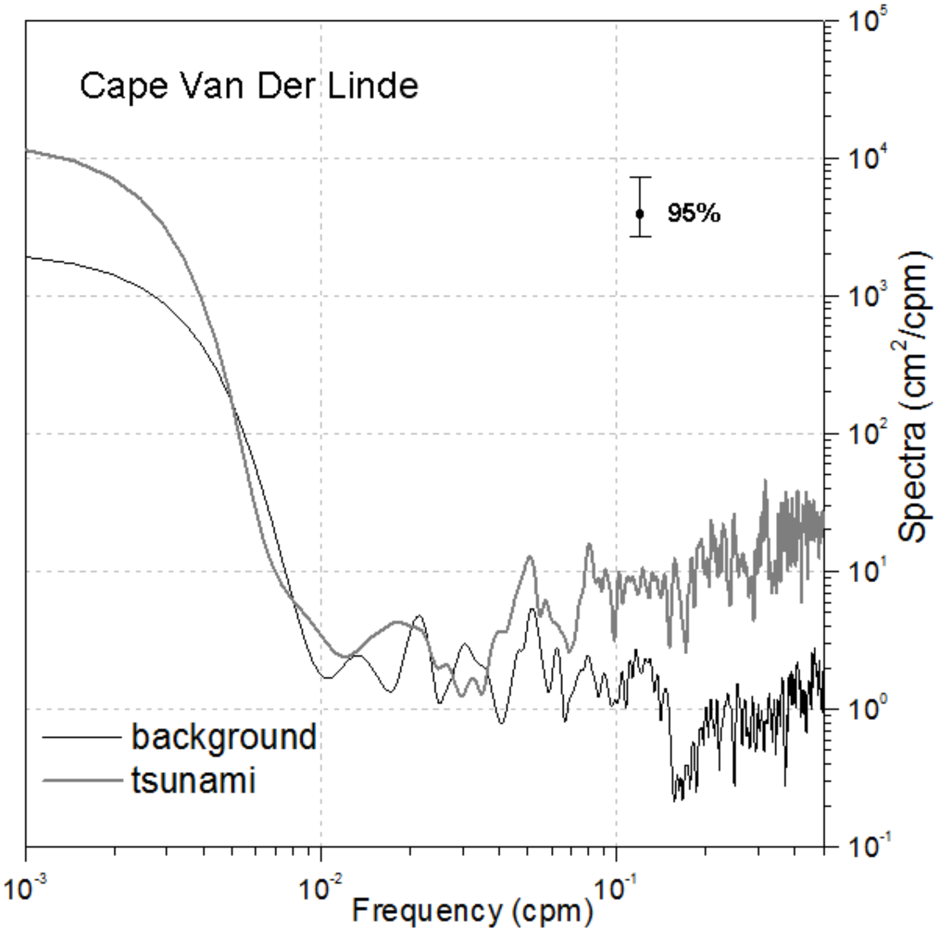

Figure 10b. Spectra of background and Simushir tsunami caused sea level oscillations. Van der Linde gauge, Urup Island.

The tsunami caused an increase of the main spectral peaks with periods of 12 and 20 minutes. These peaks were observed also in the background spectra in the first segment of the experiment and were related also to the influence of shelf resonance in the area (Levin et al, 2009).

The most significant distinctions in energy level of the tsunami and the background spectra were observed almost for the entire frequency band of the Kitoviy Bay record. The most significant increase in energy was found in the both high- and low-frequency bands of the spectrum (at the periods less than 5 min and 30-60 min). The energy increase in the high-frequency band was caused by the strong storm. The increase in energy fluctuations at low frequencies (although weaker) was observed at other stations as well.

Several well-expressed peaks in the spectra of background signal were found, which corresponded to the Kitoviy Bay resonant modes; however they were weakly expressed in the spectra of the tsunami. The most significant peak was observed in the 20-minute period. In contrast to the gauge recordings at Malokurilskaya Bay (Fig. 10c) and at Cape Van der Linde, energy increases in this period was found to be weak in Kitoviy Bay. What cause these differences is not known.

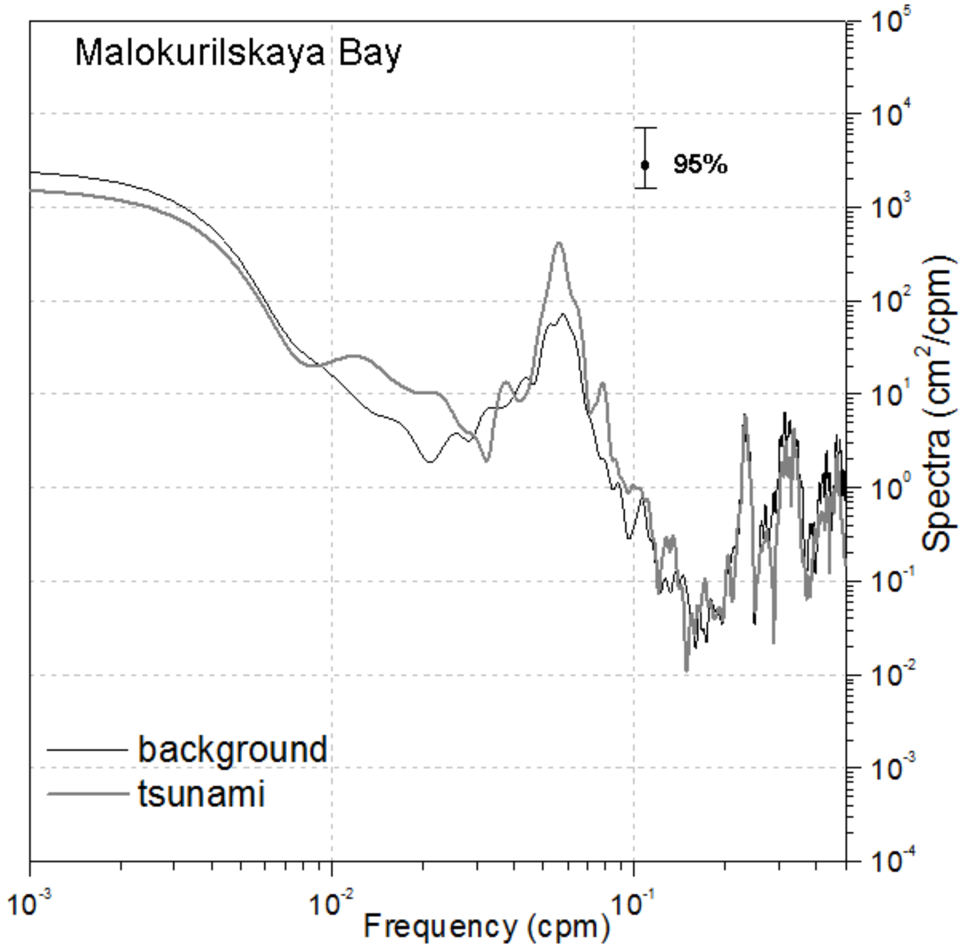

Figure 10c. Spectra of background and the Simushir tsunami as recorded at the Malokurilskaya Bay, Shikotan Island.

4. METEOROLOGICAL TSUNAMI OF JANUARY 23-24, 2009

All the autonomous gauges recorded the anomalous sea level oscillations on January 23-24, 2009. De-tided sea level records from 0:00 January 22 through 24:00 on January 24 are shown in Figure 11. These oscillations were found to be similar to tsunami signal, in particular to the above shown Simushir tsunami. However, there was no report in the NEIC seismological catalogue showing any strong earthquakes in the Pacific area on that day. More than likely, the recorded event was caused by meteorological forces (a "meteorological tsunami"). However, there were no observations of any cyclones in the area of South Kuril Islands during that period and only atmospheric fronts were observed.

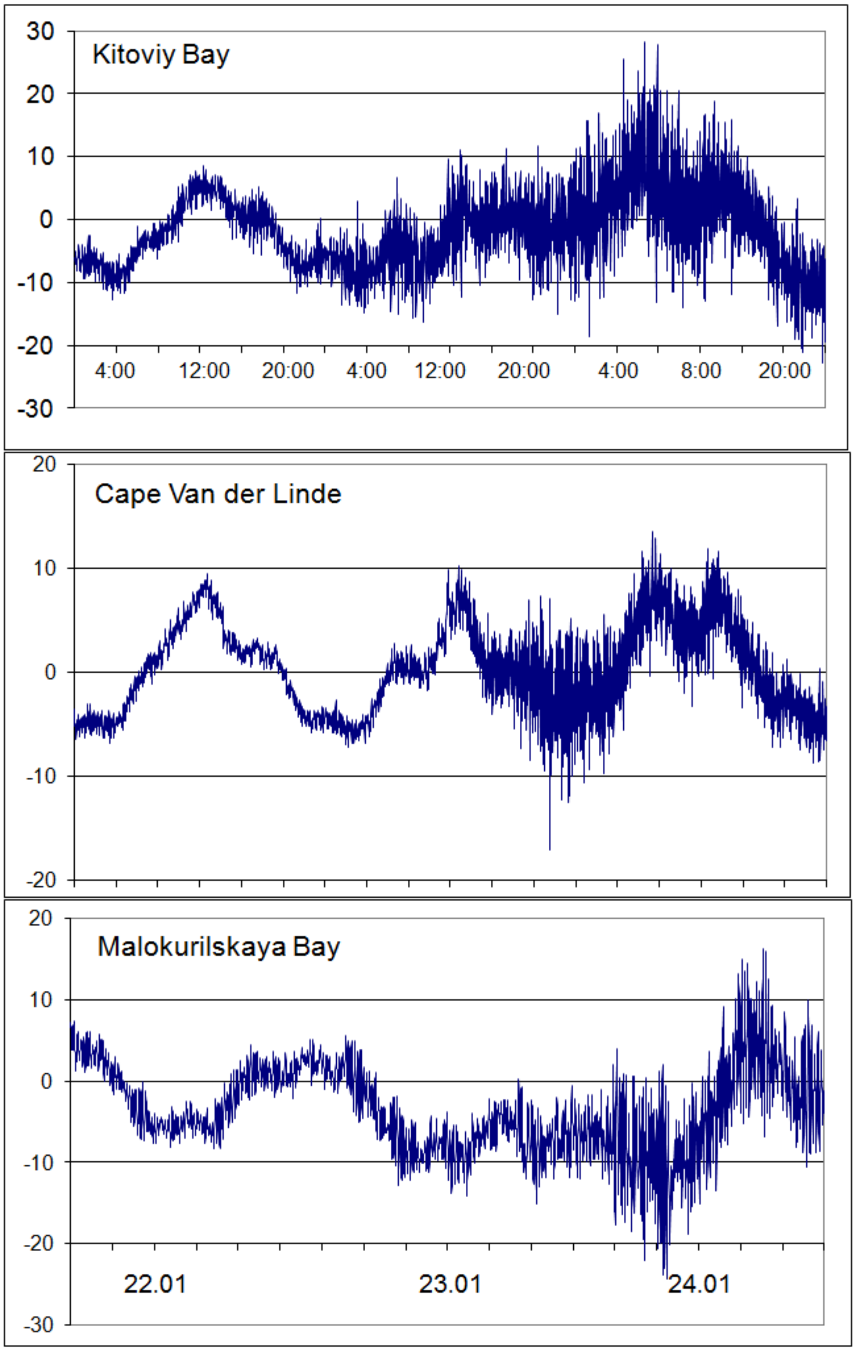

Figure 11. Residual (de-tided) sea level records (in cms) of gauge stations at Kitovy Bay, Cape Van der Linde and Malokurilskaya Bay from 0:00 of January 22 through 24:00 of January 24 (UTC).

The Kitoviy Bay gauge recorded the strongest oscillations. Increases in the amplitudes began on Jan.23 from 1:20 UTC. The most intense oscillations were observed on January 24 from 1:10 till 13:20. As with the records of the Simushir tsunami, both high-and low-frequency oscillations were manifested on January 23-24. During this period, the amplitude reached 10-12 cms. Considerable distinctions in the energy level between the assumed meteorological tsunami and the background spectra were observed almost in the entire frequency band (Fig. 12a).

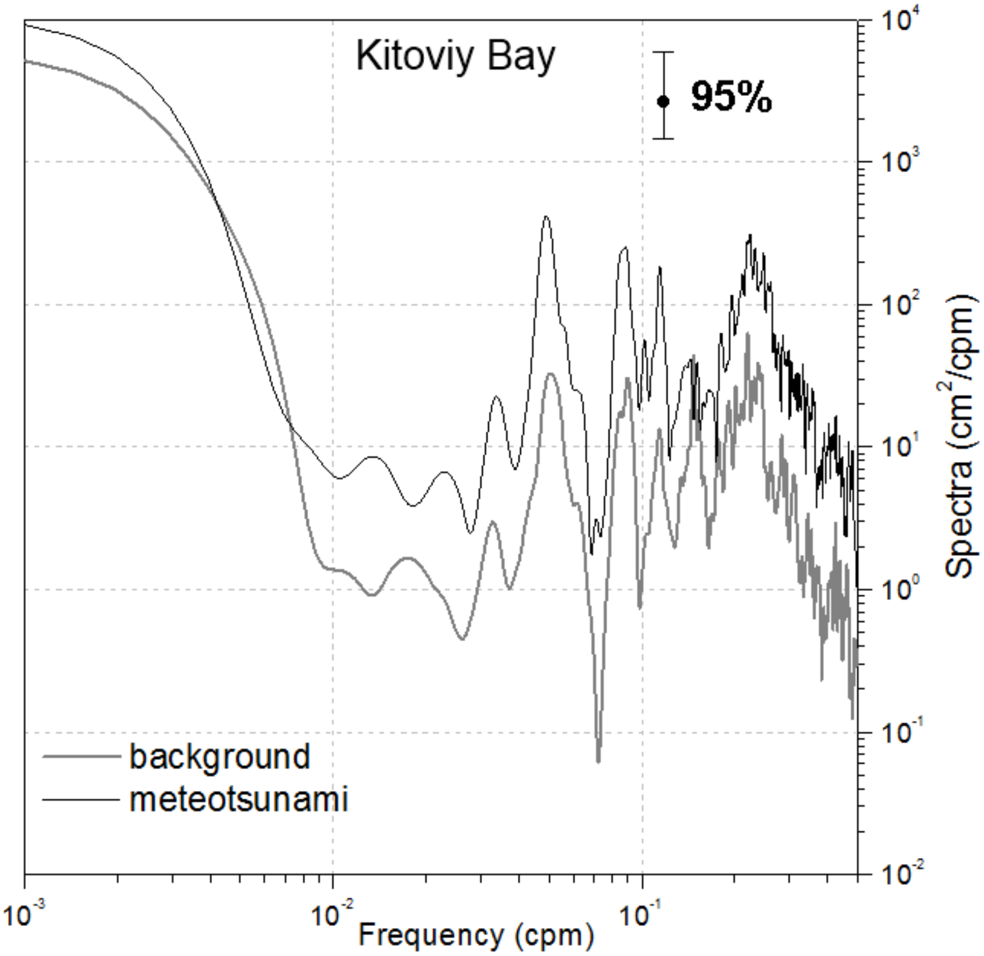

Figure 12a. Spectra of background and presumed meteorological tsunami oscillations in Kitoviy Bay, Iturup Island.

In contrast to the above shown record of the Simushir tsunami, all resonant peaks were found to be well expressed in the spectra of meteorological tsunami. The most significant increase (more than an order of magnitude) was observed at the main peak with a period of about 19 minutes.

At the Cape Van der Linde station the increase in amplitude began significantly later than in Kitoviy Bay. It occurred on January 23 beginning at 11:40 UTC. The most intense sea level oscillations were observed from 19:30 on Jan. 23 until 2:40 on January 24. During this period, the amplitude reached 7-8 cms. Spectra of the presumed meteorological tsunami were similar to the spectra of the Simushir tsunami. Considerable distinctions in the energy level between meteorological tsunami and the background spectra were observed almost for the entire frequency band, especially in the high frequency band (Fig. 12.b).

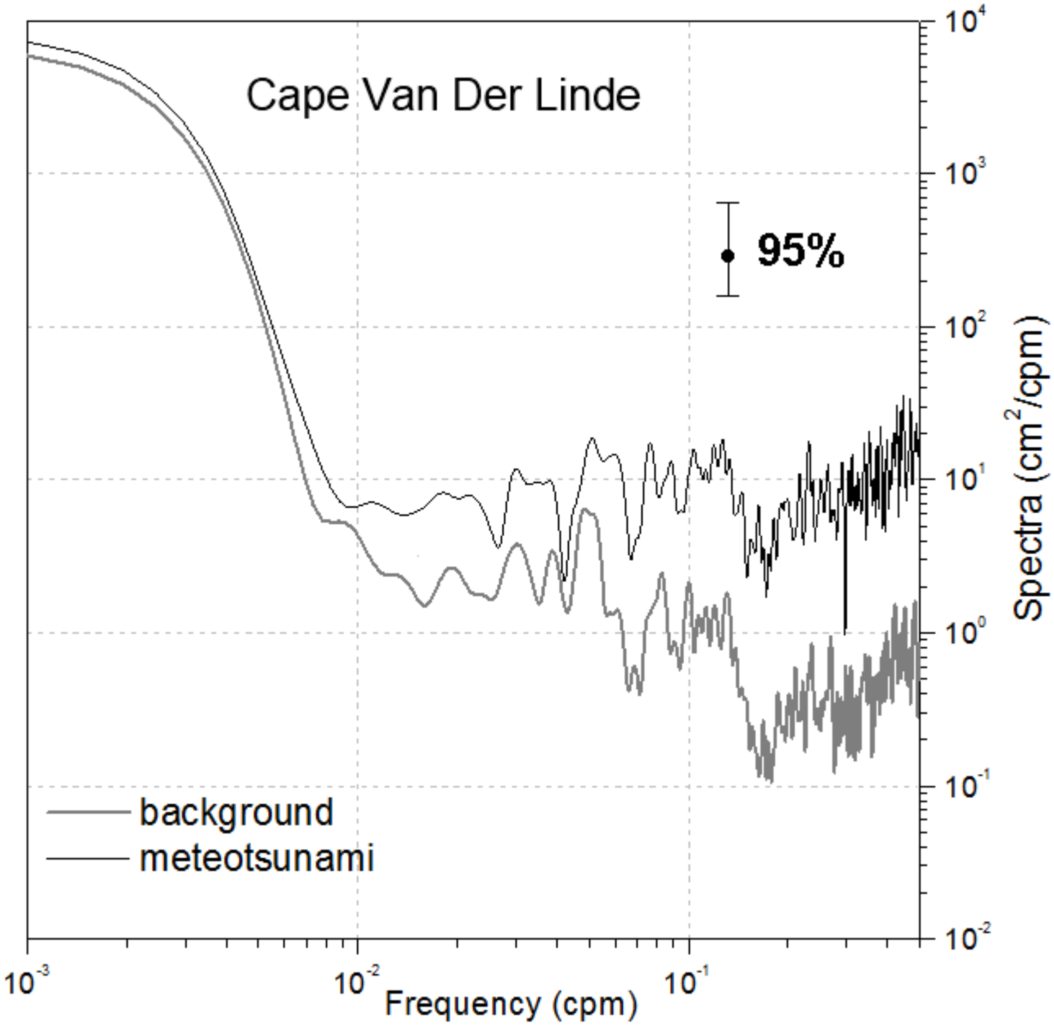

Figure 12b. Spectra of the background and of the meteorological tsunami sea level oscillations at the station of Cap Van der Linde, Urup Island.

At the Malokurilskaya Bay gauge an increase in amplitude began later than at the Cape Van der Linde. It began on January 24 at 3:40 UTC. The intense oscillations had an amplitude of about 10 cm and a period of 18-20 min.

Spectra of presumed meteorological tsunami were similar to the spectra of the Simushir tsunami as well. Considerable distinctions in the energy level between the meteorological tsunami and the background spectra were observed almost for the entire frequency band, especially in the low frequency end as opposed to that shown in Figure 12c.

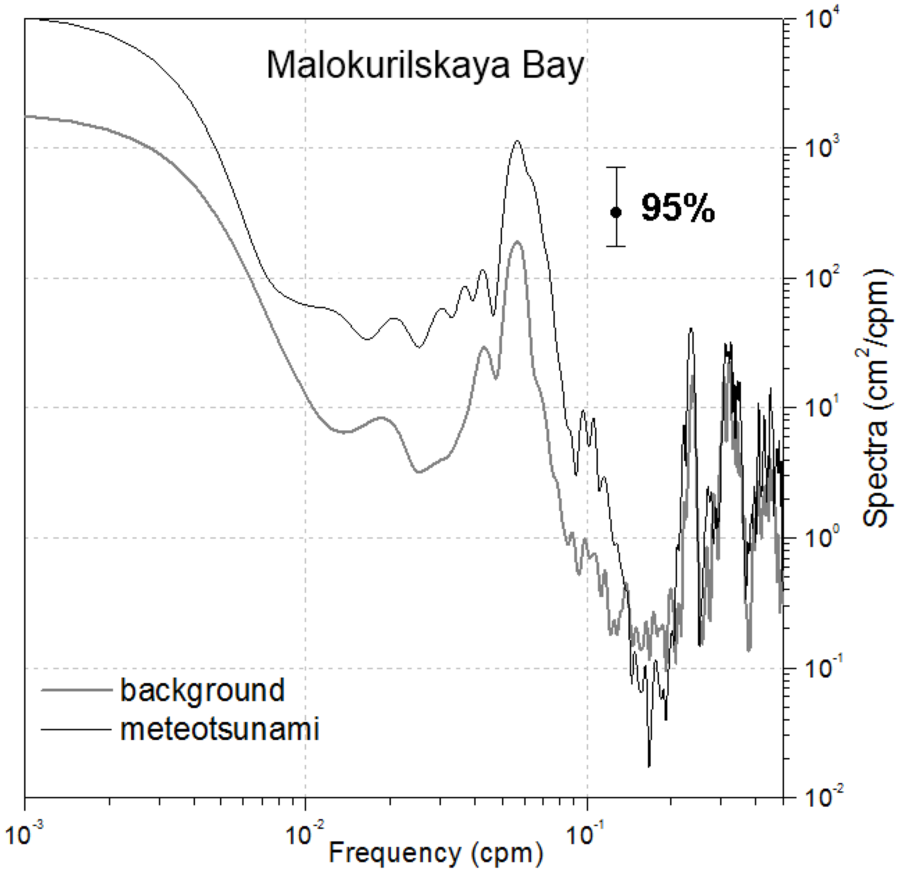

Figure 12c. Spectra of background and meteotsunami caused sea level oscillations in the Malokurilskaya Bay, Shikotan Island.

5. CONCLUSIONS

Joint recordings of well-expressed groups of waves at Hanasaki (on the oceanic coast of Hokkaido Island) and at Malokurilskaya Bay (Shikotan Island) and their considerable delay in comparison with the estimated times of arrival is a main characteristic feature of the Indonesian tsunami of January 4, 2009. The time discrepancy can be attributed to the effect of tsunami energy trapping by the shelf of Japan. The closeness of the wave group period on a shelf of Japan with resonant period of the Malokurilskaya Bay was clear evidence of the Indonesian tsunami recording in spite of the great distance from the source. Edge waves did not reach the gauges near the Iturup and Urup Islands, so the Indonesian tsunami could not be identified there.

The Simushir tsunami of 15 January was clearly recorded by the bottom pressure gauge in the Malokurilskaya Bay. A well-expressed group of waves was identified with the period of the main resonant mode occurring about four hours after the first wave arrival. The same delay was observed in the case of the Simushir tsunami on 15 November 2006. This delay was attributed to tsunami energy trapping by the shelf (Rabinovich et al, 2008). More than likely this same effect also caused the delay of the Simushir tsunami arrival on January 15, 2009.

We could not determine the tsunami arrival time and tsunami heights at the Kitoviy bay and Van der Linde gauges due to very high noise levels. This noise was caused by severe storm which was generated by deep cyclone in the southern part of the Sea of Okhotsk. To estimate the characteristics of the tsunami we were forced to use averaging with a 3-minute time window. The tsunami arrival time was 18:49 UTC at Van der Linde gauge, a one hour after of the earthquake. The maximal wave heights (8-10 cm) were observed much later, on Jan.16 from 15:43 to 16:49. Totally, the duration of oscillation was about 32 hours, which is very long for the relatively weak tsunami.

We did not determine a tsunami arrival time at Kitoviy Bay station. The intensity of sea level oscillations has steadily increased from 15:00 on Jan.15 to 5:00 on Jan. 16, when a maximum height of about 97 cm was recorded. The high amplitude sea level fluctuations continued long enough, until 12:40. The high intense oscillations also were recorded at 15:50, about at the same time, when the maximal waves were recorded at the Cape Van der Linde gauge.

The significant increase in energy was found in the both high- and low-frequency bands of the spectrum (at the periods 30-60 min and less than 5 min). The energy increasing in the high-frequency band was caused by strong storm. The weaker increase in energy fluctuations at low frequencies was observed at other stations too.

The anomalous sea level oscillations were recorded by all stations on January 23-24, 2009. We did not find any strong earthquakes in the area of Pacific Ocean in this day in the NEIC seismological catalogue. Most probably, this event was caused by meteorological forces (so-called “meteorological tsunami”). These oscillations were similar to Simushir tsunami-caused oscillation, the considerable distinctions in the energy level between meteotsunami and background spectra is observed almost for the entire frequency band.

The examples of Simushir tsunami on January 15 and meteotsunami on January 23-24, 2009 illustrate the difficulty of tsunami signal determination against the noise. The obtained results are important for the Sakhalin Tsunami Warning Service which has mostly shallow-water real-time tsunami recorders.

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