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OCEANOLOGY

New Data about Tsunami Evidence on Russia's Pacific Coast Based on Instrumental Measurements for 2009–2010

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In 2008, the Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences (IMGG FEB RAS), on the South Kuril Islands deployed a network of bottom hydrostatic pressure recorders to measure long waves of the range of tsunami periods. During 2008, a weak tsunami and a mild storm were recorded. During analysis of the record data, differences in the character of the response of th esea level to the seismic and meteorological events recorded at different stations were revealed [2].

In late 2009 on the Far East coast of Russia, the telemetric tsunami recorders of the Tsunami Warning Service (TWS) of Roshydromet were installed in accordance with the Federal target program "Reduction of Risks and Mitigation of Consequences ..." [1]. In addition, equipment was replaced at the Severo-Kurilsk station and new recorders were installed at the Nikolskoe (Bering Island), Petropavlovsk-Kamchatsky (Avachinskaya Guba Bay), and Vodopadnaya (the southeast coast of Kamchatka) stations (Fig. 1).

Autonomous tsunami recorders of the IMGG FEB RAS were installed on the South Kuril Islands (Fig. 1) for research purposes and were not used for real-time tsunami forecasting. The data obtained using the recorders are used for a posteriori study of the tsunami manifestations: determination of the arrival time and heights of the first and highest tsunami waves, the main periods of oscillation, etc.

Owing to the location of stations of the Tsunami Warning Service in the Kuril Islands and the Kamchatka Peninsula, the possibility to study the dangerous tsunami manifestations and related phenomena has appeared.

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During 2009 and the first half of 2010, tsunami waves caused by several strong earthquakes were recorded by the station network. In particular, a close earthquake (Simushir Island, Jan. 15, 2009) and several remote earthquakes (Indonesia, Jan. 3, 2009; Samoa, Sept. 29, 2009; Vanuatu, Oct. 7, 2009; Chile, Feb. 27, 2010) were recorded. In addition, a few strong storms (Jan. 23–24, 2009, and Aug. 3–4, 2010) were recorded. As a result, isolated anomalous fluctuations, similar in their characteristics to a tsunami, were observed. We consider these events as meteotsunamis, as they were probably caused by the passage of sharp atmospheric fronts.

In this work, a comparative analysis of tsunami records from two remote earthquakes (Samoa on September 29, 2009, and Chile on February 27, 2010), recorded in the northern (the TWS sensors) and the southern (an autonomous station of the IMGG FEB RAS) areas of the Kuril Islands was made. This work was aimed at obtaining the characteristics of the tsunamis manifested on the Far East coast of Russia and at evaluating the efficiency of the telemetry recorders installed for the Tsunami Warning Service (TWS).

SAMOA TSUNAMI ON SEPTEMBER 29, 2009

An earthquake with a magnitude of $M_w = 8$ on September 29, 2009, occurred at 17^h48^m UTC near the islands of Samoa. The epicenter coordinates were 15.56° S and 172.07° W, with a depth of 18 km (data by the U.S. Geological Survey, USGS). This earthquake caused a tsunami, which was recorded in many places of the Pacific coast. In about 10 hours, tsunami waves reached the Kuril Islands, where they were recorded by network sensors.

Figure 2 shows fragments of the tsunami waves records, recorded on September 30, 2009, on different flanks of the Kuril Islands at the stations of Severo-Kurilsk, Tserkovnaya Bay (Shikotan Island) (stations 4 and 11 in Fig. 1), as well as spectra of sea-level fluctuations.

Spectra were calculated on the basis of the daily time intervals, one of which contained tsunami evi-

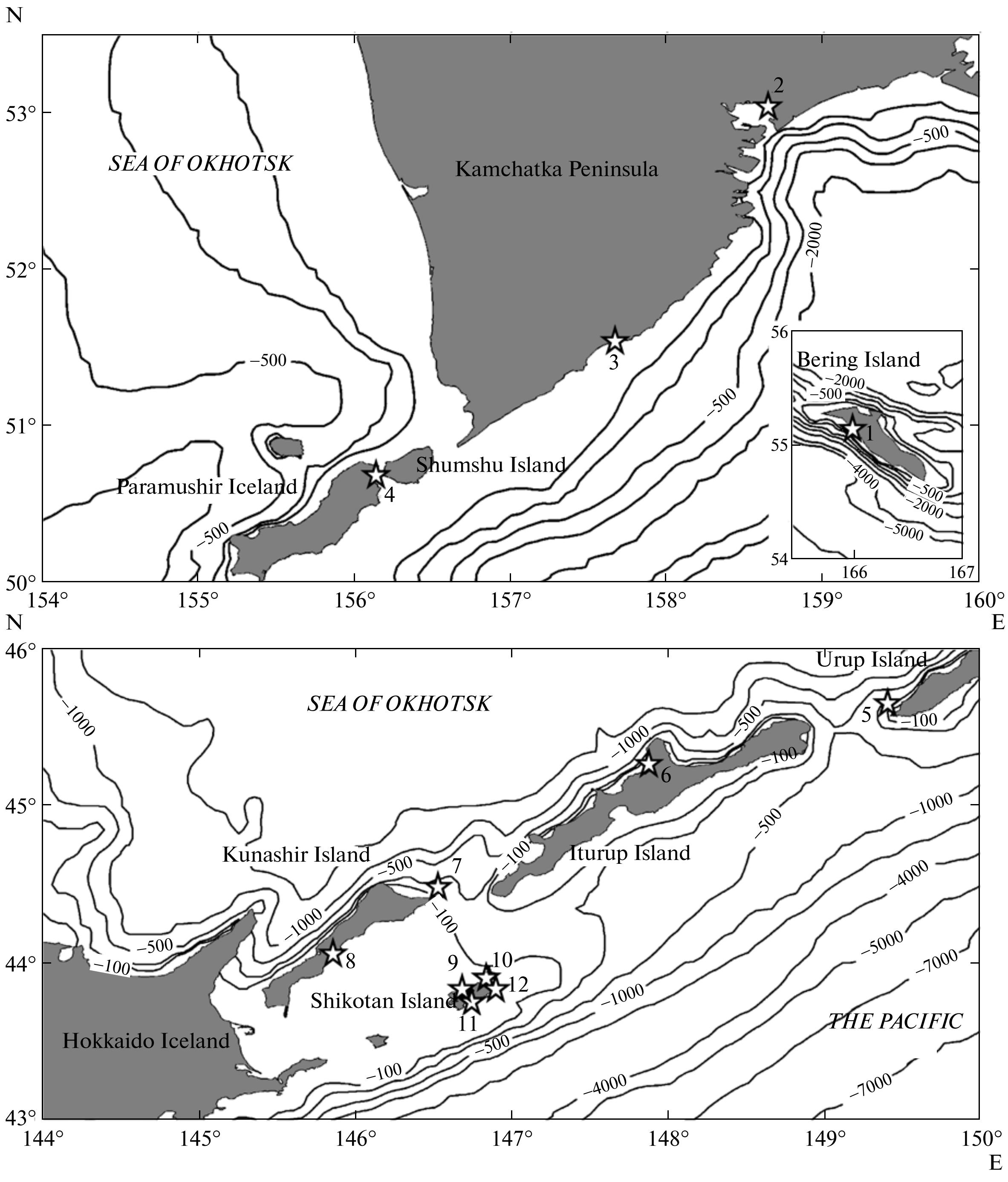

Fig. 1. Position of telemetric tsunami recorder stations: (1) Nikolskoe St.; (2) Petropavlovsk-Kamchatsky St.; (3) Vodopadnaya St., (4) Severo-Kurilsk St. (in the northern area of the Kuril Islands and autonomous stations of IMGG FEBRAS for tsunami prediction: (5) Cape of Van-der-Lind, (6) Kitovyi Bay; (7) Lovtsov Cape, (8) Yuzhno-Kurilsk, (9) Krabovaya Bay; (10) Malokurilskaya Bay; (11) Tserkovnaya Bay; (12) Mayachnaya Bay (in the southern area of the Kuril Islands).

dence, another one preceded it and was used to characterize the background conditions.

At the Tserkovnaya station, it was difficult to determine the arrival time of the first tsunami wave. Only the positive pulse with a height of 21 cm, recorded at 05^h08^m can be confidently attributed to the tsunami. The maximum wave (36 cm) was recorded at 11^h21^m. After 13^h00^m, the fluctuation intensity decreased gradually and by 20^h00^m came back to the normal level.

The problem with the identification of the first tsunami wave at the Severo-Kurilsk station is almost the same. Here, beginning at 04^h40^m UTC, a train of tsu-

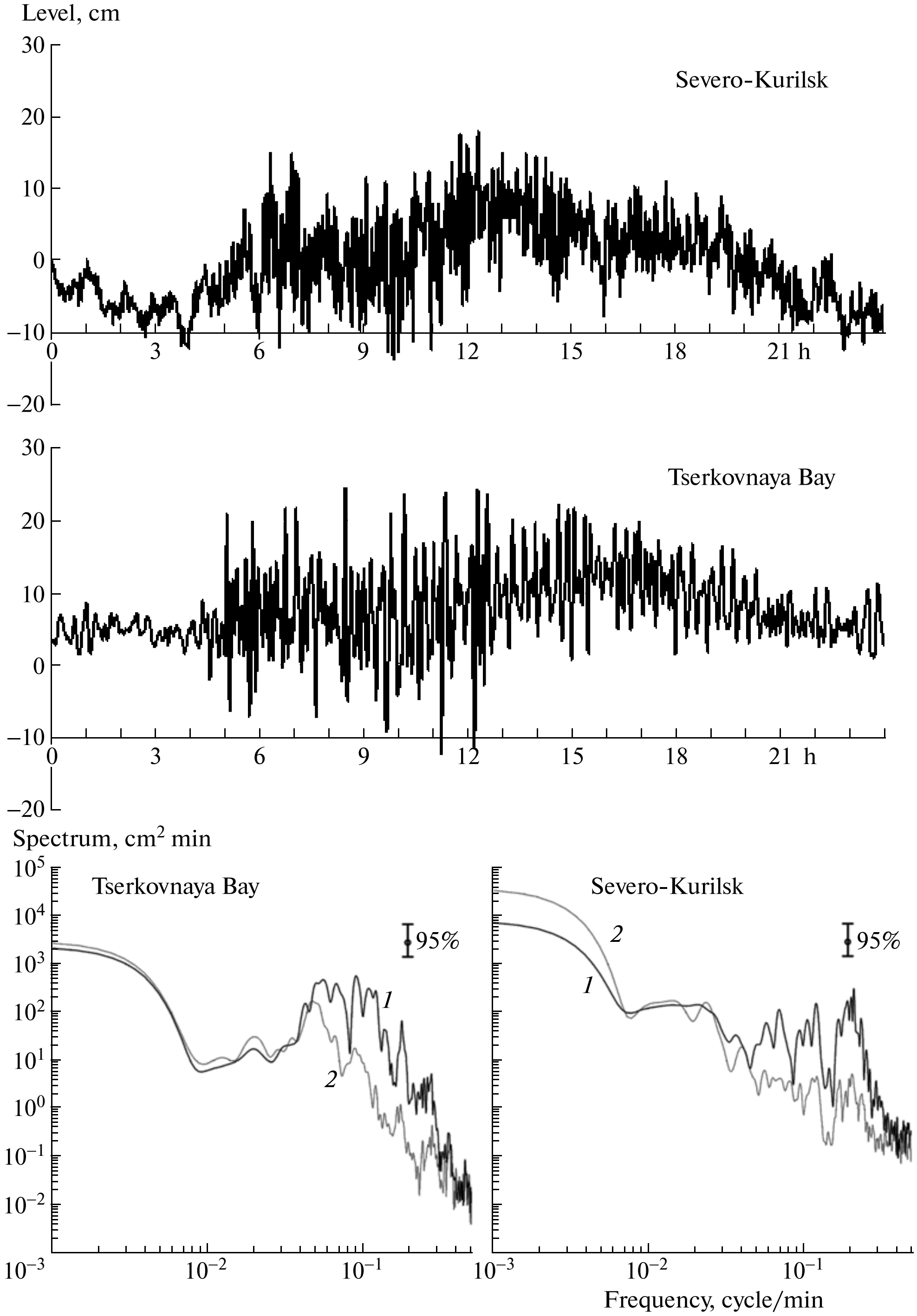

Fig. 2. Records of sea level fluctuations on September 30, 2009 (Samoa, tsunami), registered at the stations of Severo-Kurilsk (Paramushir Island) and Tserkovnaya (Shikotan Island) and spectra calculated on the basis of daily time intervals: *1*, the interval in which the tsunami occurred; *2*, the preceding interval, which was considered as background conditions.

nami waves was recorded for periods of about 12 min and amplitudes of 5–6 cm. Then the character of the fluctuations changed considerably: the amplitude increased up to 15–20 cm; the period, on the contrary, decreased. The maximum wave height (25 cm) was recorded at $10^{h}54^{m}$.

Within Tserkovnaya Bay, the intensity in fluctuations increased from 4 to 20 min. The last fluctuation corresponds to the zero mode of natural fluctuations in the bay, though in the spectrum of the natural long wave background, it shifted slightly leftward. Other resonance peaks, corresponding to periods of about 4, 6, and 11 minutes are well expressed both under the usual conditions and with the tsunami manifestation.

At the Severo-Kurilsk station, the Samoa tsunami evidence was recorded in the period range from 3.5 to 20 min, but the most significant manifestation was for a period of about 5 min (the fluctuation energy level increased by more than two orders of magnitude), 8 and 16 minutes. The periods of 8 and 16 minutes in the tsunami spectra were recorded earlier at this station, while the peak with a period of 5 minutes was not. Perhaps, its appearance can be connected with the reconstruction of the port.

In general, the Samoa tsunami was manifested on the coast of the Kuril Islands mainly in the period range of 5–20 min.

This is not typical for remote tsunamis, which normally cause low-frequency fluctuations, since short waves dampen rapidly during propagation over long distances.

The relatively low heights of these tsunami waves were probably connected with this fact, while the other feature of a tsunami from distant sources (a significant length of the wave process) was manifested in this case to the full extent.

CHILEAN TSUNAMI ON FEBRUARY 27, 2010

An earthquake with a magnitude of $M_w = 8.8$ occurred on February 27, 2010, at 06^h34^m UTC near the Chilean coast. The epicenter coordinates were 35.846° S and 72.719° W, with a depth of about 35 km (data by the U.S. Geological Survey, USGS). This earthquake caused a tsunami wave with a significant height, which could have been a serious threat for most of the Pacific coast, including the Far East coast of Russia. A similar strong earthquake, which occurred on May 22, 1960, off the coast of Chile caused a tsunami with wave heights up to 6–7 meters on the shores of the Kuril Islands and Kamchatka.

The time of tsunami propagation from the source to the Far East coast of Russia was about 21 hours. First, the tsunami waves reached the Commander Islands, the Kamchatka Peninsula, and then the North Kuril Islands, and substantially later, the South Kuril Islands. The first entry of the tsunami was recorded at the Nikolskoe station (station 1 in Fig. 1, insert map) on February 28 at 03^h5^m UTC. However, the character and small fluctuation amplitudes unusual for stations at the open coastline (a maximum wave height of 24 cm) at this station lead us to consider these data with care. The records made at the Vodopadnaya station on the southeast coast of Kamchatka (station 3 in Fig. 1) are more informative for the purpose of operational tsunami forecasting. The first wave (a positive pulse with a height of 34 cm) was recorded here at 03^h40^m, about 25 minutes after it was recorded at the Nikolskoe station. The first of the waves with a significant height (89 cm) reached this station in 1 h 25 min (at 05^h05^m). A maximum ocean wave with a height of 118 cm arrived 55 minutes later.

The data obtained at another telemetry tsunami warning station located in Severo-Kurilsk are also important for tsunami prediction.

The telemetric tsunami recorder is located in the port on the Second Kuril Strait shore at a distance from the ocean shore. The first wave (a weak positive pulse) was recorded at 04^h28^m UTC, 48 minutes after it was recorded at the Vodopadnaya station. The maximum wave with a height of 228 cm was recorded at 08^h20^m UTC, that is, nearly 4 hours after the tsunami entry (Fig. 3). This is an essential time-delay. According to the existing TWS standards, as a rule, the all-clear signal that a tsunami is no longer expected is announced during this time. A similar situation arose during the Simushir tsunami arrival on November 15, 2006, in Malokurilskaya Bay (station 10 in Fig. 1), when a dangerous wave came about 3.5 hours after the first wave entry [3]. The acuteness of this problem can be alleviated to some extent by the installation of telemetric tsunami recorders for operational monitoring of the wave process in endangered areas.

On the southern flank of the Kuril Islands, telemetric recorders are not installed. Due to this, the instrumental data on the sea-level fluctuations within this area, obtained by autonomous stations of the IMGG FEB RAS, cannot be used for operational purposes. These data are required for analysis of tsunami manifestations and the planning of installation of telemetry TWS recorders.

In Tserkovnaya Bay the first tsunami wave with a height of 22 cm was recorded at 04^h53^m. Intense sea-level fluctuations with wave heights of more than 1 m were observed up to 16^h00^m, and even at the end of the day the water had not returned to the normal level. The first significant change in the water level with a height of 165 cm was recorded at 06^h50^m, almost 2 hours later. The maximum wave with a height of 184 cm was recorded at 08^h16^m.

The power spectrum graph recorded at the Severo-Kurilsk station shows that an increase in energy fluctuations was observed during the tsunami passage in the range of periods from 5 min to 2 hours. Moreover, the most essential increase was for periods of 45 and 60 min (of 3.5 order, approximately) (Fig. 3). Note that for other tsunamis recorded at this station, a similar picture is observed [1].

In Tserkovnaya Bay an energy increase was observed from the period of 3 min, which corresponds to the spectral mode of the bay.

The peak for the period of the dominant mode (19 min) is well defined. Moreover, one can note peak splitting, which is a characteristic feature of the modulated signal. However, the most significant increase in the spectral density is observed in the low-frequency spectrum area for periods of 30–80 minutes. It is espe-

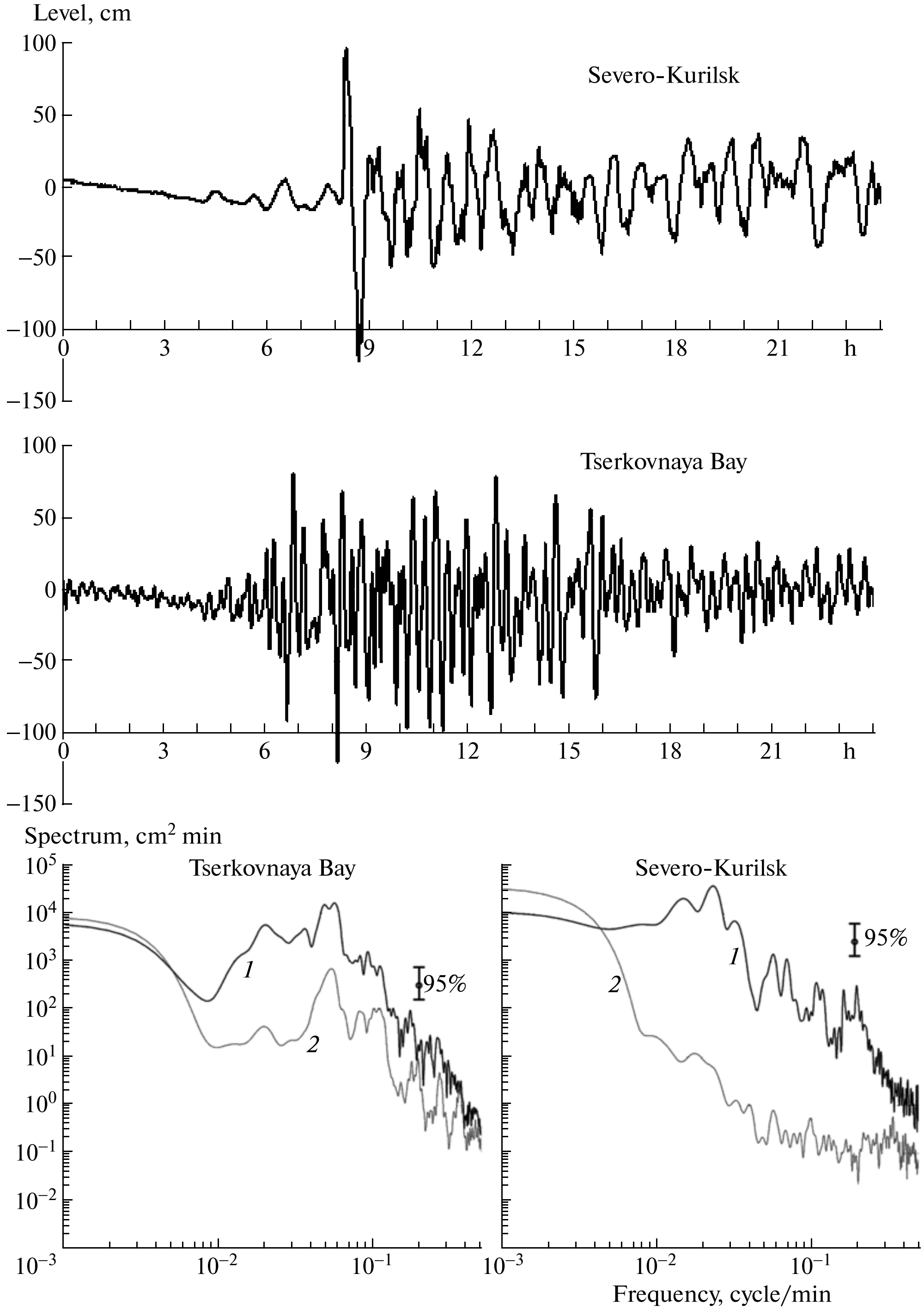

Fig. 3. Records of sea level fluctuations on February 28, 2010 (Chilean tsunami), registered at the stations of Severo-Kurilsk (Paramushir Island) and Tserkovnaya (Shikotan Island) and spectra calculated on the basis of daily time intervals: *1*, the interval in which the tsunami occurred; *2*, the preceding interval, which was considered as background conditions.

cially notably for a period of about 50 minutes, with a weak maximum in the background spectrum.

The difference revealed in the frequency distribution of energy during the Samoan and Chilean tsunamis is caused by the character of the radiation directivity in the source. In the first case, the dominant radiation energy was directed to the southwest and northeast. Due to this, the maximum waves were recorded on Pacific Islands and the coast of the United States (http://wcatwc.arh.noaa.gov/about/tsmamimain.php).

Accordingly, short and weak waves propagated towards the Pacific coast of Russia and Japan. In the second case, the main flow of energy was directed to the north-northwest and relatively low-frequency waves propagated towards the Kuril Islands [1]. These examples show that the radiation directivity can have a significant affect on the character of the tsunami manifestations on the coast, even in the case of remote sources.

In general, the analysis carried out shows that the Chile tsunami on February 28, 2010, reached on the Far East coast of Russia a wide range of periods from 5 min to 2 hours. Moreover, the main peak in the spectra was registered at all stations for periods of about 45–50 minutes, regardless of whether it is resonant for the station locality or not. This points to the fact that these variations are due to the processes in the tsunami source, while the peaks for periods of 30 and 60 min in the North Kuril Islands and on the southeastern coast of the Kamchatka Peninsula are related to the resonance properties of the adjacent shelf zone.

Thus, using the network of telemetric tsunami recorders of the Tsunami Warning Service (TWS) of Roshydromet and autonomous stations of the IMGG FEB RAS on the Kuril Islands, tsunami waves from a close earthquake and several remote earthquakes were recorded. New information about the tsunami manifestations on the Far East coast of Russia was obtained.

The main feature of the tsunamis registered is the considerable time delay (3–4 hours) between the arrival of the first wave and that of the highest waves.

In all cases considered, the high intensity of sea-level fluctuations caused by the tsunami was preserved for a long time (16–18 hours).

The difference in periods of excited fluctuations during the tsunami passage was revealed. In the Samoan tsunami, relatively short waves with periods of less than 20 min were predominant. For the stronger Chilean tsunami, an increase in the energy level fluctuations was observed for periods of 30–80 min.

Such a difference in the character of the tsunami manifestations can be explained by the radiation directivity at the source. The influence of this factor in the case of remote earthquakes is usually ignored. However, according to our study, this is not always justified.

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