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MARINE PHYSICS

MAJOR TSUNAMIS IN THE SEA OF JAPAN BASED ON INSTRUMENTAL OBSERVATIONS

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Abstract. The Sea of Japan is a seismically active zone that is under high risk from tsunami waves. The destructive tsunamis that occur in this region can cause severe damage and loss of life. An overview of the most important tsunami events observed in this region in 20–21 centuries is presented. Eight events in the Sea of Japan were selected for consideration, including one volcanogenic tsunami: 1940 (M_w 7.5), 1964 (M_w 7.5–7.7), 1971 (M_w 7.3), 1983 (M_w 7.7–7.8), 1993 (M_w 7.7), 2007 (M_w 6.2), 2011 (M_w 9.0–9.1) and 2022 (volcanogenic). Particular attention was paid to the tsunamis of 1983 and 1993. Numerical simulations of the tsunami waves arising from these two events were compared to the corresponding waveforms derived from actual tide gauge records. Of the eight tsunami events examined, the 2011 Tohoku and 2022 Tonga events had external sources located outside of the Sea of Japan but generated tsunamis directly within the sea: (1) The 2011 Tohoku earthquake had its source area in the Pacific Ocean east of Japan, but caused a horizontal displacement of the Japanese islands, which, in turn, created tsunami waves westward from these islands; (2) The Hunga–Tonga–Hunga–Ha'apai volcanic eruption in the central Pacific produced strong atmospheric Lamb waves that induced tsunami waves upon arrival in the Sea of Japan.

Keywords: *Sea of Japan, tsunami, earthquake, volcanic eruption, meteotsunami, numerical modeling*

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1. INTRODUCTION

The Sea of Japan is a large marginal sea in the Pacific Ocean basin, connected by the Strait of Tartary and La Pérouse Strait to the Sea of Okhotsk, the Tsugaru (Sangara) and Kanmon Straits to the Pacific Ocean, and the Korea Strait to the East China Sea. The coast of the Sea of Japan is as susceptible to the threat of tsunami waves as other coasts in the Pacific basin. Transoceanic tsunamis can penetrate into the Sea of Japan through straits, but they are strongly weakened and do not pose a significant hazard to the Sea of Japan coast [7, 28]. The main threat to the coast of the Sea of Japan is associated with strong tsunamis caused by earthquakes occurring in the waters of this sea. Such events have been observed in this sea repeatedly and have resulted in serious destruction and loss of life. Regional tsunamis are the main subject of this study.

Four major earthquakes have occurred in the Sea of Japan in the last 100 years: 1940 (M_w 7.5), 1964 (M_w 7.5–7.7), 1983 (M_w 7.7–7.8), and 1993 (M_w 7.7). [33, 61]. Their focal zones were located near the west coast of Honshu and Hokkaido islands (Japan) (Fig. 1). In the same area there is a small volcanic island of Oshima (Fig. 1), where in 1741 a volcanic eruption and landslide caused a destructive tsunami and numerous human casualties [24, 40, 72].

In the catalog of Soloviev and Go [15] a number of other significant historical tsunamigenic earthquakes with sources off the coast of Japan are mentioned: 701, 887, 1614, 1644, 1793, 1833, and 1872. In 1927 in the southern part of Honshu Island, a catastrophic earthquake (M_w 7.0), known as the "*Kita Tango* earthquake", occurred near Kyoto [45]. The earthquake caused serious damage and a large number of casualties (~2.9 thousand people) in Kyoto Prefecture, but the resulting tsunami waves were relatively small (about 1.2–1.5 m high) and did not pose a serious threat to the coast. Apparently, this is due to the fact that the main part of the source was located on land.

In the 21st century, there were two transoceanic tsunamis observed along the entire Pacific coast (and even beyond), but for the Sea of Japan they had some characteristics of a regional event:

(1) The 2011 Tohoku megatsunami caused by a massive earthquake (M_w ~9.1) off the northeastern

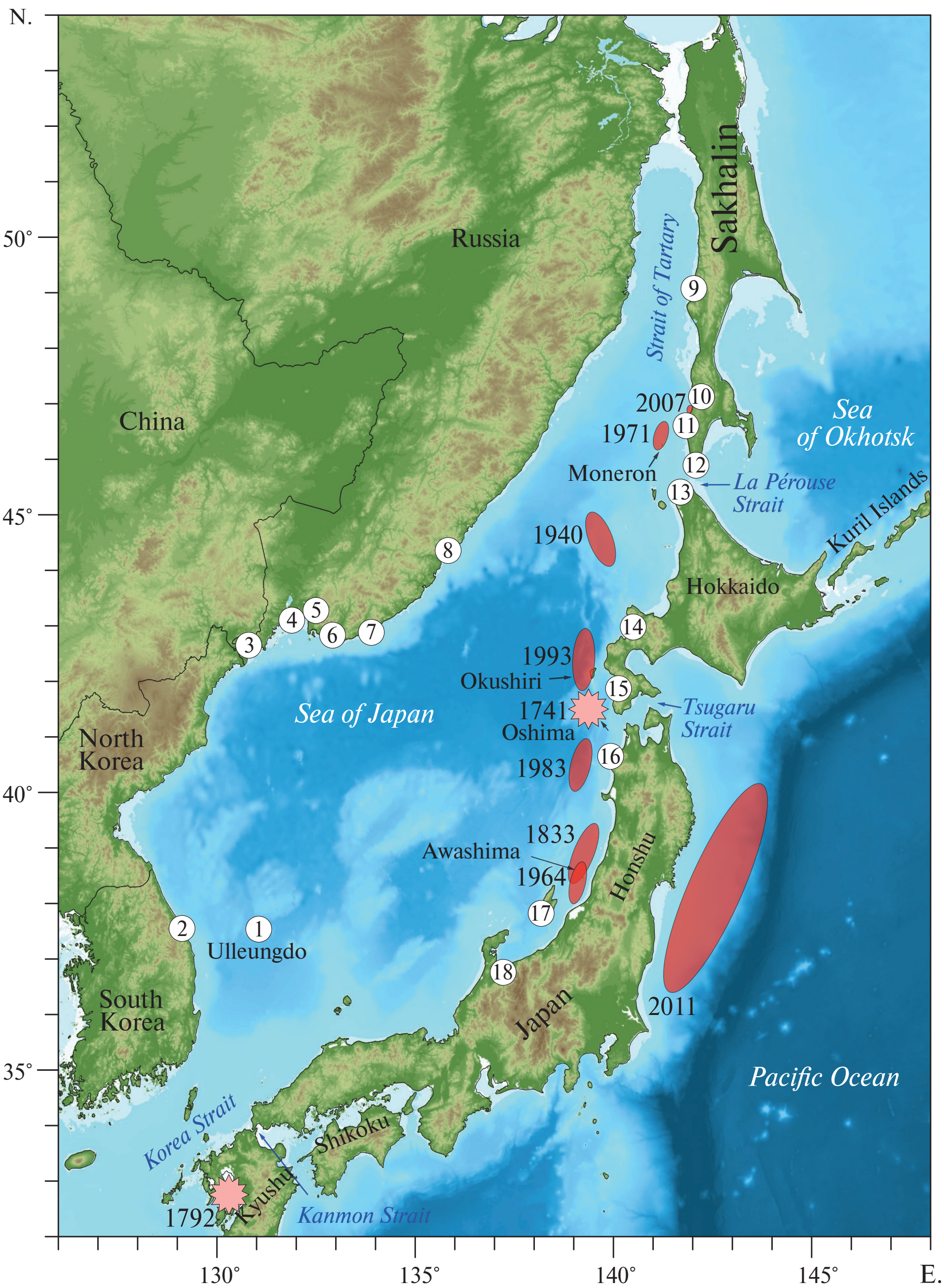

Fig. 1. Map of the Sea of Japan showing the sources of the major earthquakes (red ovals), tsunamigenic volcanic eruptions (pink multibeam stars), and tide gauge stations used in this study; station names and coordinates are given in Table 1.

coast of Honshu (Fig. 1). As the results of [60] have shown, horizontal shifts of the continental slope and displacement of Honshu Island caused tsunami directly in the Sea of Japan immediately after the earthquake;

(2) The 2022 Tonga tsunami generated by the eruption of the Hunga–Tonga–Hunga–Ha'apai volcano in the South Pacific Ocean (see, e.g., [8, 26, 53, 54]). This eruption generated two types of tsunami waves [41, 55, 85]: "oceanic" waves generated directly in the source area, and "atmospheric" tsunami waves ("meteotsunami") caused by the propagation over the ocean surface of atmospheric Lamb waves from the eruption. As was shown in [83], waves of the second type, i.e., generated in the Sea of Japan rather than coming from outside, were predominantly observed in the Sea of Japan.

Two more earthquakes that occurred in the northern part of the Sea of Japan (Fig. 1) and generated tsunamis recorded off the coasts of Sakhalin Island

Table 1. List of stations used

No	Station	Country	Latitude (°N)	Longitude (°E)
1	Ulleungdo	South Korea	37.49	130.91
2	Mukho	South Korea	37.55	129.12
3	Posyet	Russia	42.65	130.80
4	Vladivostok	Russia	43.10	131.93
5	Bolshoy Kamen	Russia	43.10	132.34
6	Nakhodka	Russia	42.83	132.92
7	Preobrazhenie	Russia	42.88	133.89
8	Rudnaya Priestan	Russia	44.36	135.83
9	Uglegorsk	Russia	49.07	142.03
10	Kholmsk	Russia	47.06	142.04
11	Nevelsk	Russia	46.66	141.85
12	Cape Crillon	Russia	45.89	142.08
13	Wakkanai	Japan	45.41	141.69
14	Iwanai	Japan	42.98	140.50
15	Esashi	Japan	41.87	140.13
16	Fukaura	Japan	40.65	139.93
17	Sado	Japan	38.32	138.52
18	Toyama	Japan	36.76	137.22

Hokkaido Island: Moneron earthquake on September 6, 1971 (M_w 7.3) [19, 20] and Nevelsk earthquake on August 2, 2007 (M_w 6.2) [9].

2. SEISMICITY OF THE REGION

Most earthquakes in the Sea of Japan occur along the Japan–Sakhalin Island Arc, the strongest of them – off the west coast of Hokkaido and Honshu Islands. Along the coast of Russia and Korea there are mainly deep focal earthquakes with hypocenter depth more than 100 km. Fig. 2 shows earthquakes from 1904 to 2018 from the ISC-GEM catalog[1], distributed by hypocenter depth. Earthquakes with hypocenter depth more than 50 km are located in the central part of the sea and near the western coast, while shallow-focal earthquakes are grouped near the eastern coast of the sea. Most tsunamis are generated by earthquakes with sources at depths less than 50 km, which explains why most tsunamis originated in this area.

In 1944, C. Gutenberg and B. Richter [34] described the relationship between the number of earthquakes with a certain magnitude and their recurrence in time in a particular region (Gutenberg-Richter law):

$$\log_{10} N_c = a - bM_w \quad (1)$$

where M_w – moment magnitude, N_c – frequency of earthquakes with magnitude $\geqslant M_w$ per year, a and b – empirical coefficients. These coefficients are determined by rock, mechanism and depth of earthquake hypocenter in a particular region. The value $T = 1/N_c$ determines the average interval (period) of recurrence of earthquakes with a magnitude greater than or equal to M_w in the region under consideration

The cumulative frequency-magnitude distribution of earthquakes with hypocenter depth less than 50 km was used to estimate the recurrence period of potentially tsunamigenic earthquakes. For moment magnitude M_w in the Sea of Japan, parameters a and b were estimated as 4.02 ± 0.13 and 0.74 ± 0.02, respectively (Fig. 3). The average recurrence period of tsunamigenic earthquakes with $M_w \geqslant 7.0$ in the Sea of Japan is 14.6 years, and with $M_w \geqslant 7.5$ is about 34 years.

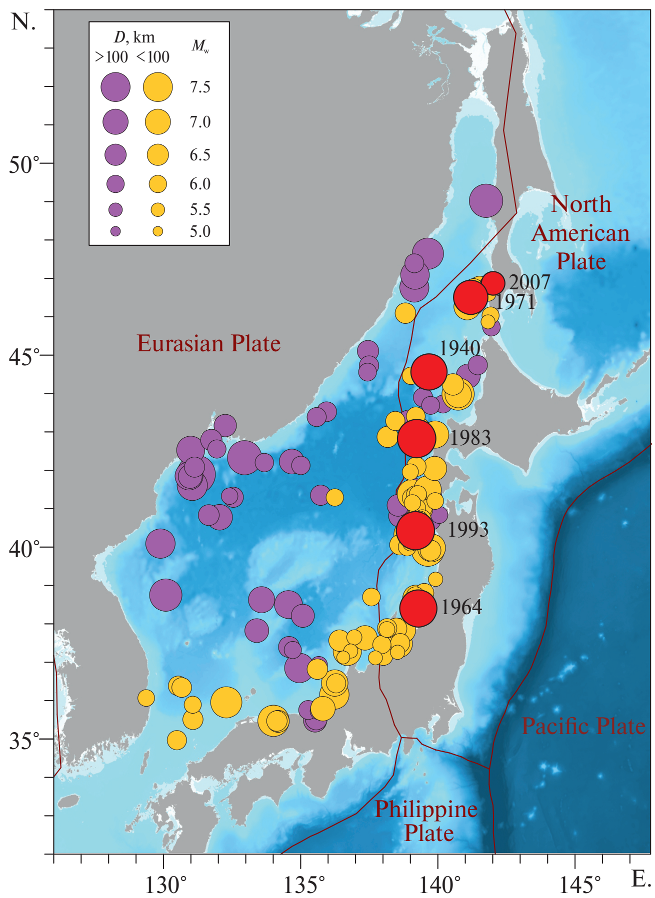

Fig. 2. Earthquakes in the Sea of Japan from 1904 to 2018 from ISC-GEM data with magnitude $M_w > 5$. Earthquakes of 1940, 1964, 1971, 1983, 1993 and 2007 are marked in red.

[1] Global Instrumental Earthquake Catalogue [30].

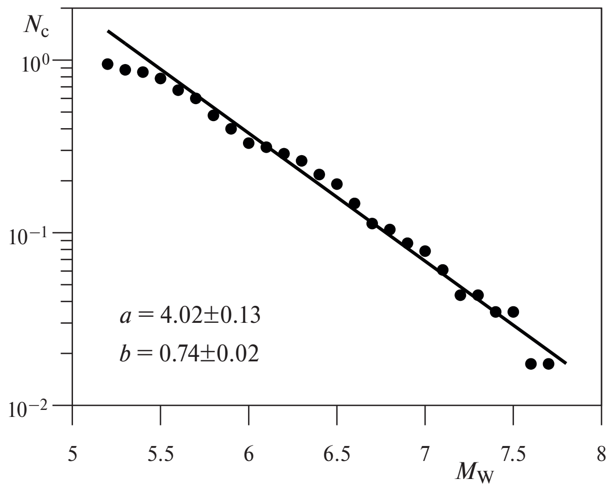

Fig. 3. Frequency-magnitude distribution of earthquakes with hypocenter depth less than 50 km in the Sea of Japan according to ISC-GEM data from 1904 to 2018. N_c – frequency of earthquakes per year, M_w – moment magnitude, a and b – empirical coefficients in equation (1).

3. HISTORICAL EVENTS

This section considers a number of historical events that caused the strongest tsunami waves in the Sea of Japan during the instrumental period.

3.1. Seismic tsunamis

The Tetyukha tsunami of August 1, 1940

The earthquake with magnitude M_w 7.5 (*1940 Shakotan-oki earthquake*) occurred on August 1, 1940 at 15:08 UTC in the Sea of Japan. The earthquake's epicenter was located to the north-west from Shakotan peninsula (Hokkaido Island) (Fig. 1) and had dip-slip mechanism with hypocenter depth according to different data from 15 km (ISC-GEM) to 30 km [4, 32]. The earthquake caused a strong tsunami: 10 people were killed and 24 others were injured on the coast of Hokkaido Island [36, 61]. This event was the first instrumentally registered tsunami in the Sea of Japan. Tsunami runups reaching dangerous heights were recorded in many places in Japan, on the coasts of Korea and the USSR. On Hokkaido island, the maximum vertical runup reached 3 m (Rishiri Island and the port of Tomamae), but generally did not exceed 2 m [4, 36].

One of the features of this tsunami is that the observed runup heights in the far zone were greater than in the near zone. Thus, according to the data obtained as a result of field surveys and eyewitness testimony [4, 36, 47], the highest runups were observed in Primorye: up to 3.5 m in Tetyukha (Rudnaya Pristan) and up to 5 m in Kamenka village. According to records obtained on some tide gauges and eyewitnesses' reports, it can be seen that tsunami waves reached the western coast of the Sea of Japan less than an hour after the earthquake (Fig. 4). According to eyewitnesses[2], the height of the first wave reached 5 m, followed by a series of waves with heights up to 3.5 m[3] [4]. In the USSR, this tsunami was named "Tetyukha tsunami" because it was felt most strongly in this area [13, 17].

The Niigata tsunami of June 16, 1964

The strong earthquake occurred on June 16, 1964 near Niigata city (western coast of Honshu Island, Japan) at 04:02 UTC with magnitude M_w from 7.5 to 7.7 by different estimates, hypocenter depth – about 15 km, focal mechanism – reverse fault [21, 32, 35]. The earthquake has caused severe destructions on Honshu Island: 3534 houses were completely destroyed, more than 11 thousand houses badly damaged [50]. The earthquake caused soil *liquefaction* over a wide area. The bore caused by the tsunami wave spread several kilometers upstream of the Shinano River (Fig. 5a), where the 307-meter Showa Bridge collapsed as a result of strong vibrations (Fig. 5b-c) [27].

At the time of the earthquake, Awashima Island, located 8 km north of the epicenter, rose more than

[2] The tsunami in Tetyukha Bay was witnessed by geologist V.A. Yarmolyuk [13], from 1966 to 1986 deputy minister of geology of the USSR [1]

[3] In [13] there is eyewitness reports that the first wave was 1.5–2 m, and the second wave 20–30 min later was 3.5 m.

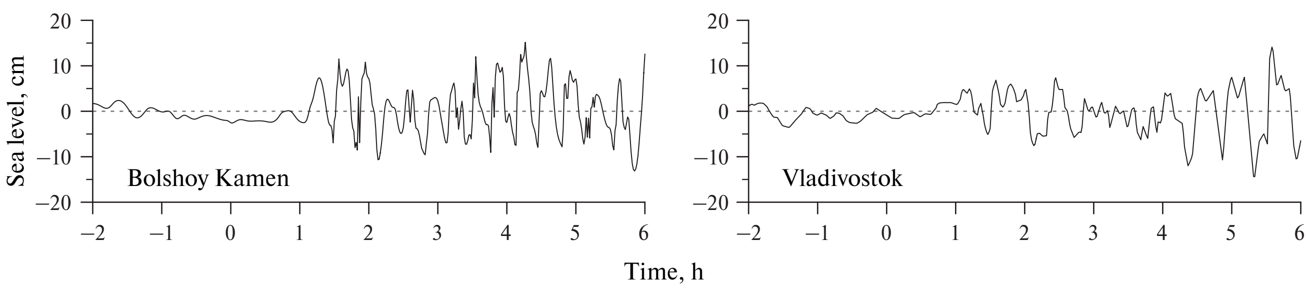

Fig. 4. Tide gauge records of the 1940 Tetyukha tsunami for stations Bolshoy Kamen and Vladivostok, relative to mean sea level. Time is counted from the moment of the earthquake.

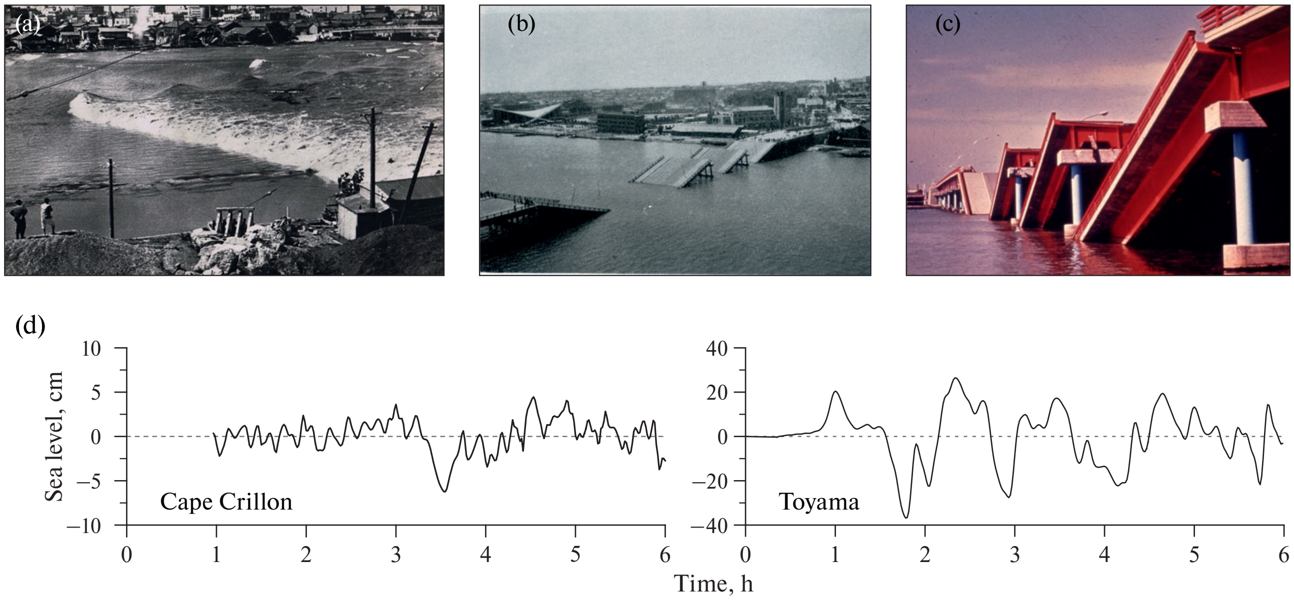

Fig. 5. Consequences of the 1964 Niigata tsunami: (a) tsunami bore on the Shinano River (photo from Niigata Nippo newspaper); (b–c) Showa Bridge destroyed by the earthquake (https://tsunami-dl.jp/document/145; http://homepage2.nifty.com/yoshimi-y/niigata1.htm); (d) tide gauge records of the 1964 tsunami for stations Cape Crillon and Toyama, relative to mean sea level. Time is counted from the moment of the earthquake.

2 m relative to sea level as a result of coseismic deformations [21]. The tsunami waves hit the city of Niigata 15 minutes after the earthquake started. On the coast near the earthquake source (Niigata prefecture, Iwafune and Fuya) the runup height reached 4–4.5 m [35], and on some sandy parts of the coast – 5.8 m [15, 44]. In contrast to the 1940 tsunami, the Niigata tsunami on the coast of Korea, Primorye and on the southwestern coast of Sakhalin was weak: it was not visually observed and was registered only by tide gauges (Fig. 5d). In general, wave heights were less than 0.3 m [16].

The Moneron tsunami of September 5, 1971

The 1940 and 1964 tsunamis described above were caused by earthquakes, the sources of which were located near the coast of the Japanese Islands, i.e., in the main seismic active zone of the region (Fig. 2). The northern part of this sea is less active, but quite strong earthquakes can also occur there. So, on September 5, 1971 at 18:35 UTC (September 6 at 05:35 Sakhalin time) in the Strait of Tartary, northeast of Moneron Island, there was an earthquake with a magnitude M_w ~7.3 and hypocenter depth 15–20 km. The focal mechanism of the earthquake was also reverse-fault, but with a small shear component [10].

Visual observations showed that the first wave arrived at the coast at about 19:00 UTC and was the largest: with a height of about 2 m [19, 20]. Tide gauge records of the Moneron tsunami were obtained on Sakhalin Island, in Primorye, in the Kuril Islands, and in Japan. The maximum wave heights, 30–40 cm, were recorded at the stations Nevelsk, Kholmsk and Wakkanai, i.e., at the three stations closest to the source. The typical period of the recorded oscillations was 10–20 min and their duration was about one day. In Kholmsk, the tsunami was stronger than in Nevelsk (Fig. 6).

During the next three weeks, 4 more strong aftershocks with $M_w > 6.2$ occurred in the same area; all of them generated weak tsunamis observed at Kholmsk (7–9 cm) and Nevelsk (3–4 cm).

The Sea of Japan tsunami of May 26, 1983

One of the strongest tsunamis of the last century in the Sea of Japan was the tsunami that occurred on May 26, 1983 at 03:00 UTC as a result of the earthquake with magnitude M_w 7.7–7.8 (*1983 Nihonkai Chubu-oki earthquake*). The epicenter was located southwest of Aomori Prefecture, Honshu Island. (Fig. 1); the hypocenter depth was 14 km, and the source mechanism was reverse-fault [70]. The rupture involved two separate faults, the northern one with a NNW-SSE strike, and the southern one with a SSW-NNE strike; the rupture started on the southern fault and then continued on the northern fault after a ten-second delay.

The earthquake caused a strong tsunami that spread throughout the Sea of Japan. About 100 people died from the tsunami waves in Japan, and three more died on the coast of South Korea [23]. The first wave was recorded in the town of Fukaura about 7 minutes

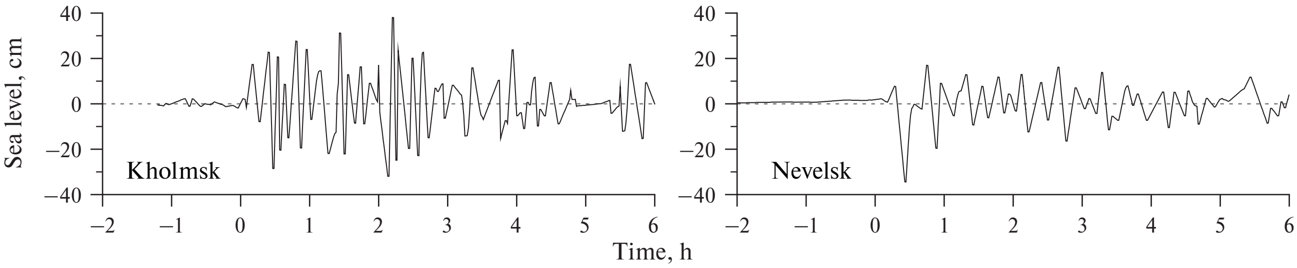

Fig. 6. Tide gauge records of the 1971 Moneron tsunami for stations Kholmsk and Nevelsk, relative to mean sea level. Time is counted from the moment of the earthquake.

(according to the tide gauge) after the earthquake. The maximum heights of the observed tsunami waves near the source were more than 10 m [74], and a maximum runup of more than 14 m was found on the coast of Akita (Minehama village) [74]. The tsunami was destructive not only for Honshu Island, but also for the islands of Hokkaido and Okushiri, where runup reached 7 m [23]. Significant wave heights were observed on the coast of South Korea (the maximum tsunami height on one of the islands exceeded 5 m [23]) and in Primorye. In some locations in Primorye (e.g., Lidovka Bay), the wave height was about 7 m [11]. The tsunami travel time to all sites in Primorsky Krai was less than 1 h (Fig. 7g). In Vostok and Nakhodka Bays, a sea level range of up to 2.5 m was observed; in the closed Zolotoy Rog Bay (port of Vladivostok), the tsunami wave height was up to 0.7 m, and in Posyet Bay, the sea level range reached 1–1.5 m [3]. In the open bays of the Ussuri Bay, a sea level rise of up to 4 m was observed; tsunami waves 5 m high were observed in Tikhaya Bay (Vladivostok) [3, 11]; boathouses were damaged, motor boats were carried out to sea, and ships, including military vessels, standing in the bay were damaged (Fig. 7a-c).

In many respects this tragedy influenced people's attitude to the tsunami phenomenon, and 10 years later (the Okushiri tsunami on July 12, 1993) some people hurriedly evacuated the first shocks recorded on Okushiri Island.

The Okushiri tsunami of July 12, 1993

The most destructive seismic tsunami in the Sea of Japan was caused by the earthquake with M_w 7.7 (*1993 Hokkaido Nansei-oki earthquake*), which occurred on July 12, 1993 at 13:17 UTC to the southwest of Hokkaido Island, near Okushiri Island (Fig. 1). The earthquake source had a complex character with hypocenter depth of about 10 km [77]. The complex structure of the source created serious problems for scientists in building numerical models of tsunami waves caused by this earthquake (see, for example, [61, 77, 80, 81]).

The earthquake generated destructive tsunami waves that hit the nearby Okushiri Island (Fig. 8g) less than 5 minutes after the main shock. A total of 230 people were killed or missing as a result of the earthquake and tsunami, 185 of them on Okushiri Island. The southern and southwestern coasts of the island took the main impact. Almost along the entire coast, runup heights were about 16 m; as a result, the village of Aonae in the southern part of the island was completely destroyed (Fig. 8a–d). In the small Monai Valley (Fig. 8b), as a result of the superposition of waves that bypassed the small islands of Hira and Muen at the entrance to the valley, the maximum tsunami runup was 31.7 m [52, 75].

The western and southern coasts of Hokkaido Island were seriously affected; the maximum height of the runup on these coasts was over 10 m. On the western coast of Honshu Island, the maximum tsunami wave heights were about 2 m. The total damage to Japan from this tsunami amounted to 1.2 billion dollars [73]. The Okushiri tsunami was also noticed on the coast of South Korea; the wave reached the coast in 1.5–3 h; the maximum wave heights were recorded at the Mukho (2.1 m), Sokcho (1.3 m), and Busan (1.0 m) stations [64].

According to observations on the Russian coast, the maximum wave height of 4.3 m was recorded in Glazkovka (Kit Bay), in Rudnaya Pristan the wave height was 3.8 m, in Valentin Bay – 4.0 m, in Kamenka village – 2.8 m, in Moryak-Rybolov village – 2.0 m, in Vladimir Bay – 1.2–2.0 m. The maximum runup reached 1.2–2.0 m in Olga Bay, and 1.0 m in Nakhodka [5]. The maximum inland inundation of more than 140 m was recorded in Zerkalnaya Bay [12]. In the south and north of Primorye, the observed tsunami waves were much smaller: from 0.6 m (Andreeva Bay) to 1.5 m (Cape De-Levron Bay) and from 0.5 m (Svetlaya settlement) to 1.3 m (Plastun Bay) [5]. Several tide gauge records of this tsunami are shown in Fig. 8d. The total damage from the Okushiri tsunami for the Russian coast was estimated at 10 billion rubles (in 1993 prices) [5].

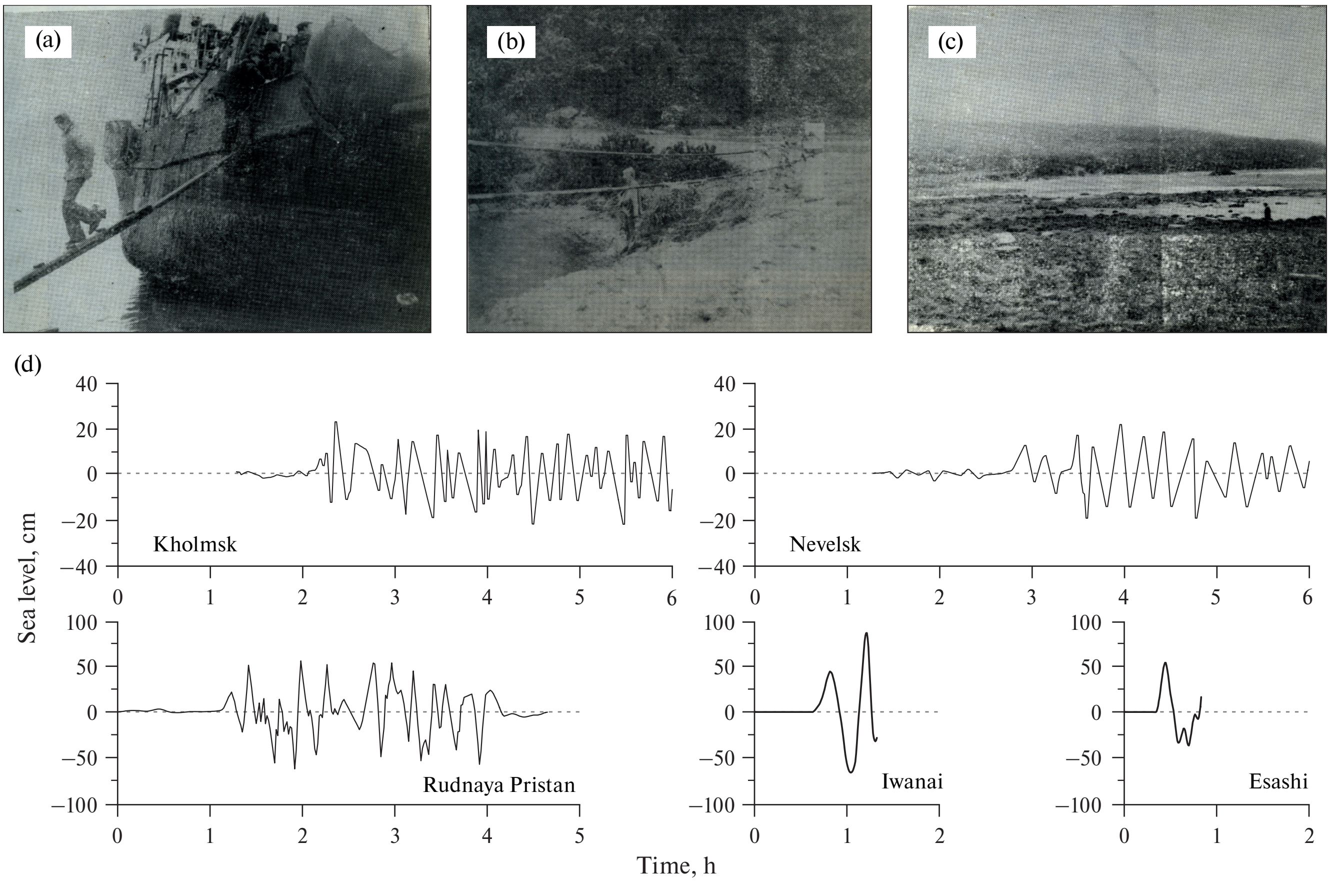

Fig. 7. Consequences of the 1983 Sea of Japan tsunami at the coast of Primorye: (a) Valentin Bay: the gangway of the small fishing seiner lying on the coastal stone slab was lowered directly to the shore (photo: [11]); (b) Lidovka Bay: seagrass hanging on the bridge railings, left by the incoming wave (photo: [11]); (c) Lidovka Bay: reinforced concrete structures scattered by the tsunami can be seen in the swampy lowland (photo: [11]); (d) tide gauge records of the Sea of Japan tsunami for five stations of the coast of Russia and Japan, relative to mean sea level. Time is counted from the moment of the earthquake.

The Nevelsk tsunami of August 2, 2007

On August 2, 2007 at 02:37 UTC the earthquake with M_w 6.2 and focal depth ~10 km (Fig. 1) occured on the south-western shelf of Sakhalin Island near Nevelsk town. Despite the relatively small magnitude, the earthquake caused severe damage in Nevelsk and Kholmsk and resulted in the death of 2 people, 14 more were injured, the total damage was estimated at 8.5 billion rubles [6]. The earthquake caused a significant tsunami in the northern part of the Sea of Japan with maximum runup in the area of Zavety Ilyicha and Lovetskoye settlements – 3.2 m, and in the area of Yasnomorskoye – 2 m. According to the tide gauge data (Fig. 9), the tsunami wave heights in Kholmsk were 40–50 cm [9]. At the western coast of Hokkaido Island, waves with a height of 10–20 cm were recorded at Rumoi and Wakkanai stations.

The Tohoku tsunami of March 11, 2011

On March 11, 2011 at 05:46 UTC near the north-eastern coast of Honshu Island in the area of Tohoku region there was a catastrophic earthquake with M_w 9.0–9.1 (Fig. 1). This earthquake is one of the strongest in the history of instrumental observations. The earthquake caused a destructive tsunami that struck the nearby coast of Honshu Island and spread across the Pacific Ocean, even beyond its boundaries [66, 68, 79]. This event became known as the 2011 Tohoku earthquake and tsunami and the *Great East Japan Earthquake*. The maximum runup height in the Tohoku region reached a value of 42.1 m [59]. At present, the number of dead and missing due to the tsunami is estimated at 18428 people (according to [62], https://www.ngdc.noaa.gov/hazard/tsu_db.shtml). Despite the fact that the earthquake occurred in the Pacific Ocean, it caused a tsunami in the Sea of Japan as well, not only due to the waves that passed through the straits, but also directly due to the horizontal displacements of Honshu Island. GPS-analysis data [84] show that the Tohoku earthquake caused the eastward displacement of this island by more than 5 meters. As a result, tsunami waves caused by the hor-

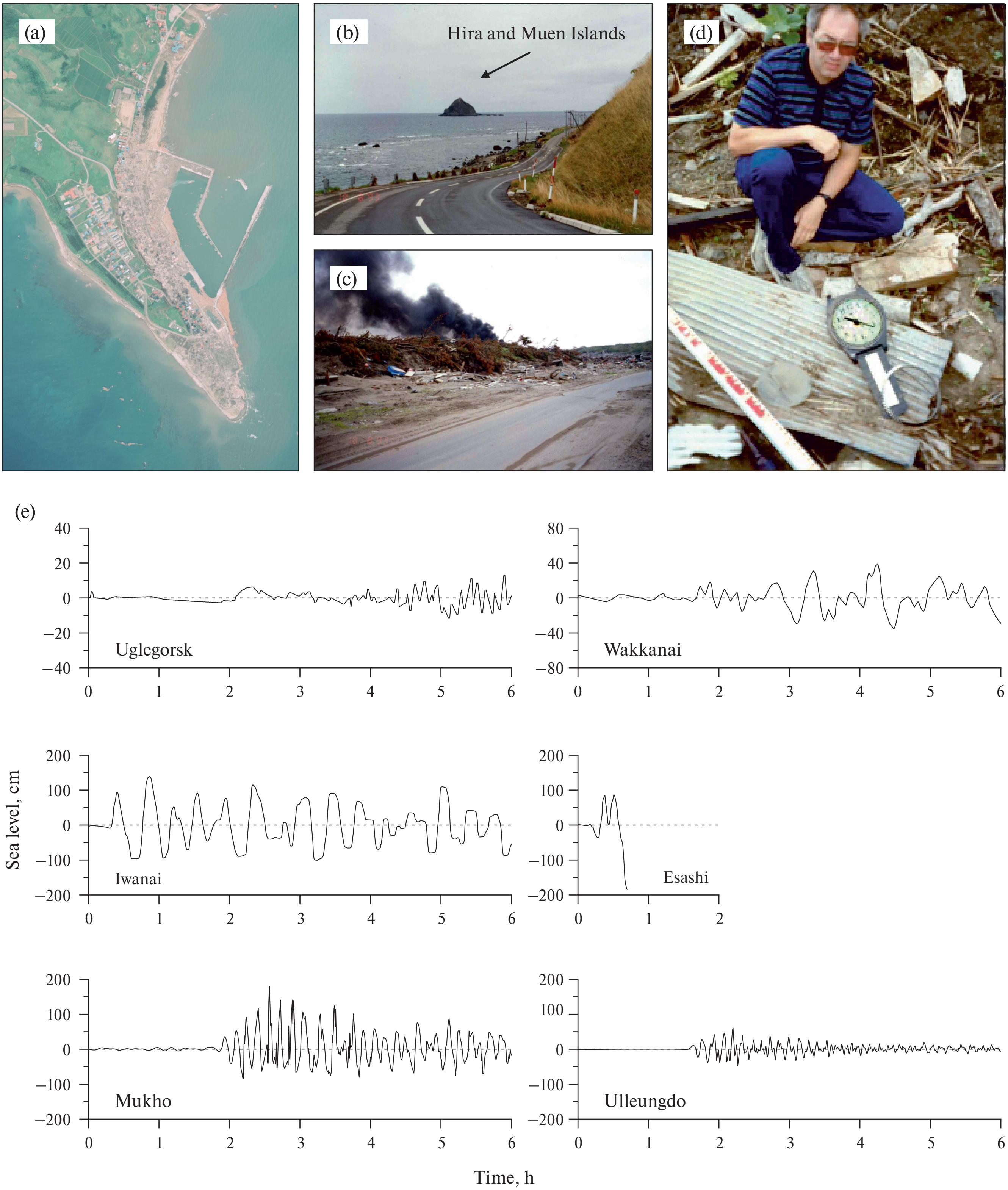

Fig. 8. Consequences of the 1993 Okushiri tsunami: (a) destructions in Aonae village on the southern coast of Okushiri Island (photo: The Geospatial Information Authority of Japan 14.07.1993); (b) the southern coast of Okushiri and Hira and Muen islands (photo: A.B. Rabinovich, 1993); (c) destructions on Okushiri Island (photo: A.B. Rabinovich, 1993); (d) a wall clock found in the Monai Valley on the southwest coast of Okushiri Island during field survey of the island coast: the clock stopped 5 min after the earthquake onset, at the moment of tsunami wave arrival (photo: A.B. Rabinovich, who participated in the field survey of the island coast; August 1993); (e) tide gauge records of the Okushiri tsunami for six stations of the coast of Russia, Japan and South Korea, relative to mean sea level. Time is counted from the moment of the earthquake.

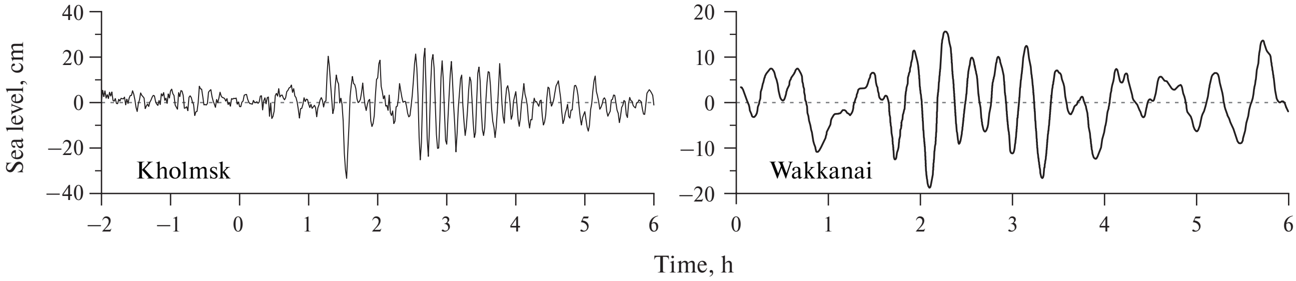

Fig. 9. Tide gauge records of the 2007 Nevelsk tsunami for stations Kholmsk and Wakkanai, relative to mean sea level. Time is counted from the moment of the earthquake.

izontal displacement were generated in the Sea of Japan almost immediately after the main shock. Their amplitudes were relatively small, the maximum height of these oscillations, about 30 cm, was recorded at Noto station [60]. About an hour and a half later, tsunami waves "from outside" (Fig. 10), which did not exceed 20 cm at the Russian coast, came to the Sea of Japan through the Tsugaru and La Pérouse Straits.

3.2. Volcanic tsunamis

In assessing the tsunami hazard in the Sea of Japan, attention should be paid not only to seismic but also to volcanic sources. The prediction of tsunamis from volcanic eruptions is very difficult because the magnitude of such events is much smaller than that of tsunamigenic earthquakes, and the modern tsunami warning agencies evaluates the hazard of each event based primarily on the magnitude of the corresponding earthquake. In addition, the tsunami waves generated by a volcanic explosion are complex in nature [65]. Even a large number of nearby sensors does not always allow for timely detection of the occurrence of such tsunamis. An example is the eruption of an underwater volcano near Tokyo on October 9, 2023, when no tsunami alert was issued, although, as it turned out, tsunami waves formed and exceeded 60 cm on nearby islands [69].

There are several volcanoes in the Sea of Japan basin that were active in the Holocene. An example is the volcano located on Ulleungdo Island, 120 km off the Korean Peninsula (Fig. 1). Volcanological and paleo studies have revealed at least five historical eruption episodes of this volcano [51]. The possibility of an eruption of Ulleungdo volcano cannot be ruled out in the future.

The largest tsunami waves in the Sea of Japan were probably caused by the eruption of the Oshima-Oshima volcano in 1741, which had previously been dormant for about 1,500 years. The island is located southwest of Hokkaido (Fig. 1). The period of activity of the volcano lasted from 1741 to 1790. The strongest eruption occurred on August 18, 1741 and caused destructive tsunami waves that resulted in the death

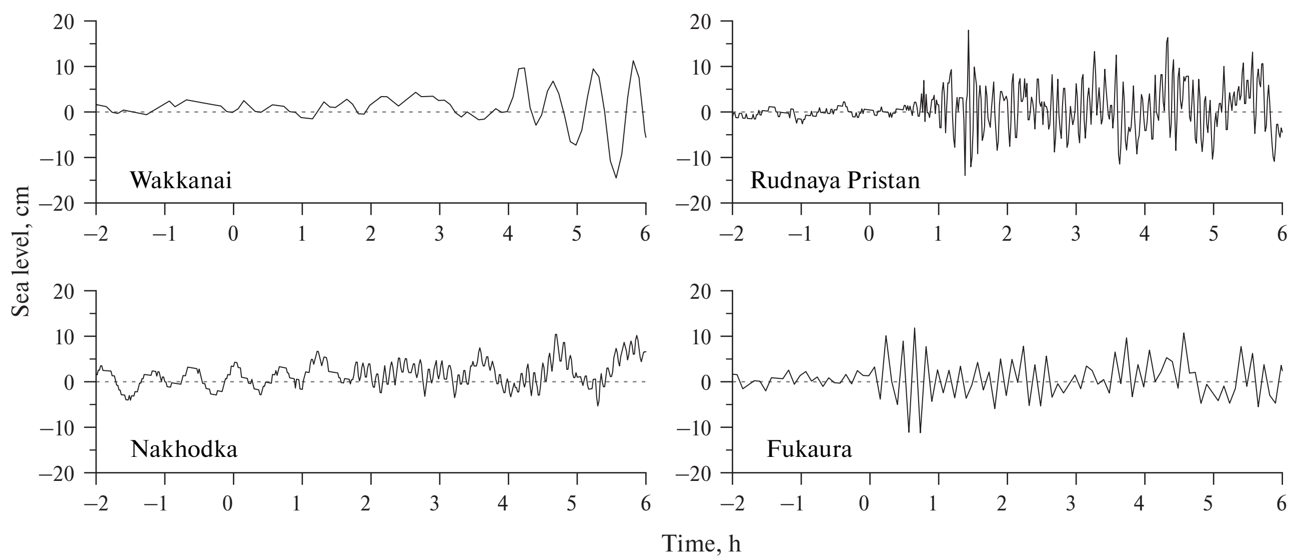

Fig. 10. Tide gauge records of 2011 Tohoku tsunami for four stations on the coasts of Russia and Japan, relative to mean sea level. Time is counted from the moment of the earthquake.

of about 1475 people [49]. Tsunami runup on the island amounted to 15 m [38, 72] and, according to some data, even reached 34 m[4] [72]. On the coast of the Korean Peninsula, wave heights were up to 3–4 m [72].

The Hunga–Tonga–Hunga–Ha'apai volcano eruption of January 15, 2022

On January 15, 2022, the the Hunga–Tonga–Hunga–Ha'apai volcano erupted near the Tonga Islands and generated tsunami waves that affected the entire world ocean. It was found that these waves had two main generation mechanisms [41, 55, 85]:

(1) waves caused directly by the volcanic eruption and coming from the source area at the speed of long ocean waves (~200–220 m/s);

(2) waves formed under the influence of atmospheric Lamb waves caused by the eruption (see, e.g., [26, 54]) that propagated at the speed of sound (~315 m/s) and created an ocean level response that had the character of tsunami waves (meteotsunami).

The results of [8, 83] show that both mechanisms of tsunami wave generation were realized at the coast of the Sea of Japan: i.e., both waves that came from "outside" and waves formed directly in the sea as a result of atmospheric impact on the sea surface were observed. The maximum tsunami waves were observed at the stations Preobrazheniye (34 cm), Mukho (34 cm) and Rudnaya Pristan (44 cm).

4. NUMERICAL MODELING

The 1983 Sea of Japan tsunami and the 1993 Okushiri tsunami were the most notable events that occurred in the Sea of Japan since the beginning of the 20th century (Table 2). In particular, the earthquake of July 12, 1993 caused abnormally high tsunami waves that reached 31.7 m on Okushiri Island [52, 75]. This tsunami was one of the first for which a thorough field survey was conducted for the two most affected areas, Okushiri Island and the southwestern coast of Hokkaido, and detailed estimates of the observed tsunami runup were obtained (Fig. 8a-d). This event has become a kind of "*benchmark*" that is used to test the quality of various existing numerical models for tsunami calculation [76]. At the same time, the main attention in the previous studies was paid to the Japanese Islands, especially to Okushiri Island and the Esashi and Iwanai stations on Hokkaido Island [73, 80, 81].

It was due to the importance of the 1983 and 1993 tsunamis that their numerical modeling was carried out. A numerical hydrodynamic model [31, 57, 67] similar to the TUNAMI model [46] was used to calculate tsunami wave propagation. The model implements a finite-difference approximation of the shallow water equations (without considering vertical acceleration). The GEBCO 2014 digital bathymetry array with a spatial step of 30″ was used in modeling.

The Sea of Japan tsunami of May 26, 1983

The source model proposed by Aida [24] (Fig. 11a) consisting of two segments was used as initial conditions. The calculation results showed that the main tsunami energy flux was directed toward the nearby coast of Honshu Island and the Primorsky Krai. The maximum calculated wave height was more than 7 m (Fig. 11b). Comparison of the tide gauge data with the modeling results shows a fairly good match (Fig. 11c), which indicates that the model seismic source corresponds to the real one. In particular, the model correctly reproduces the observed tsunami wave amplitudes. Some discrepancy in the periods is probably explained by the lack of reliable data on bathymetry in the area of the sites under consideration.

The Okushiri tsunami of July 12, 1993

The seismic source model DCRC-17a developed by Takahashi et al. was used for numerical simulation of the Okushiri tsunami [77]. It should be noted that this source has a complex character, which is reproduced in the modeling by three segments with different parameters (Fig. 12a). The modeling results show that, as for the 1983 earthquake, an appreciable part of the 1993 tsunami energy propagated toward the Primorsky Krai. In general, the directionality of the 1993 and 1983 tsunami energy has a similar character (Fig. 11b and Fig. 12b). On the Russian coast, the

Table 2. The strongest tsunamigenic earthquakes in the Sea of Japan and the corresponding maximum recorded heights or observed runup. Coordinates of the earthquake epicenter are given. Runup heights are given from the catalog of V.K. Gusyakov [63]

Date	M_w	Latitude (° N.)	Longitude (° E.)	Maximum splash height, m
01.08.1940	7.5	44.561	139.678	5.0
16.06.1964	7.7	38.399	139.290	5.8
05.09.1971	7.3	46.505	141.199	2.0
26.05.1983	7.8	40.462	139.102	14.9
12.07.1993	7.7	42.851	139.197	31.7
02.08.2007	6.2	46.83	141.75	3.2
11.03.2011	9.1	38.297	142.373	0.3*

* in the Sea of Japan.

[4] Prof. Kenji Satake [72] notes that this meaning is based on oral traditions and is unreliable.

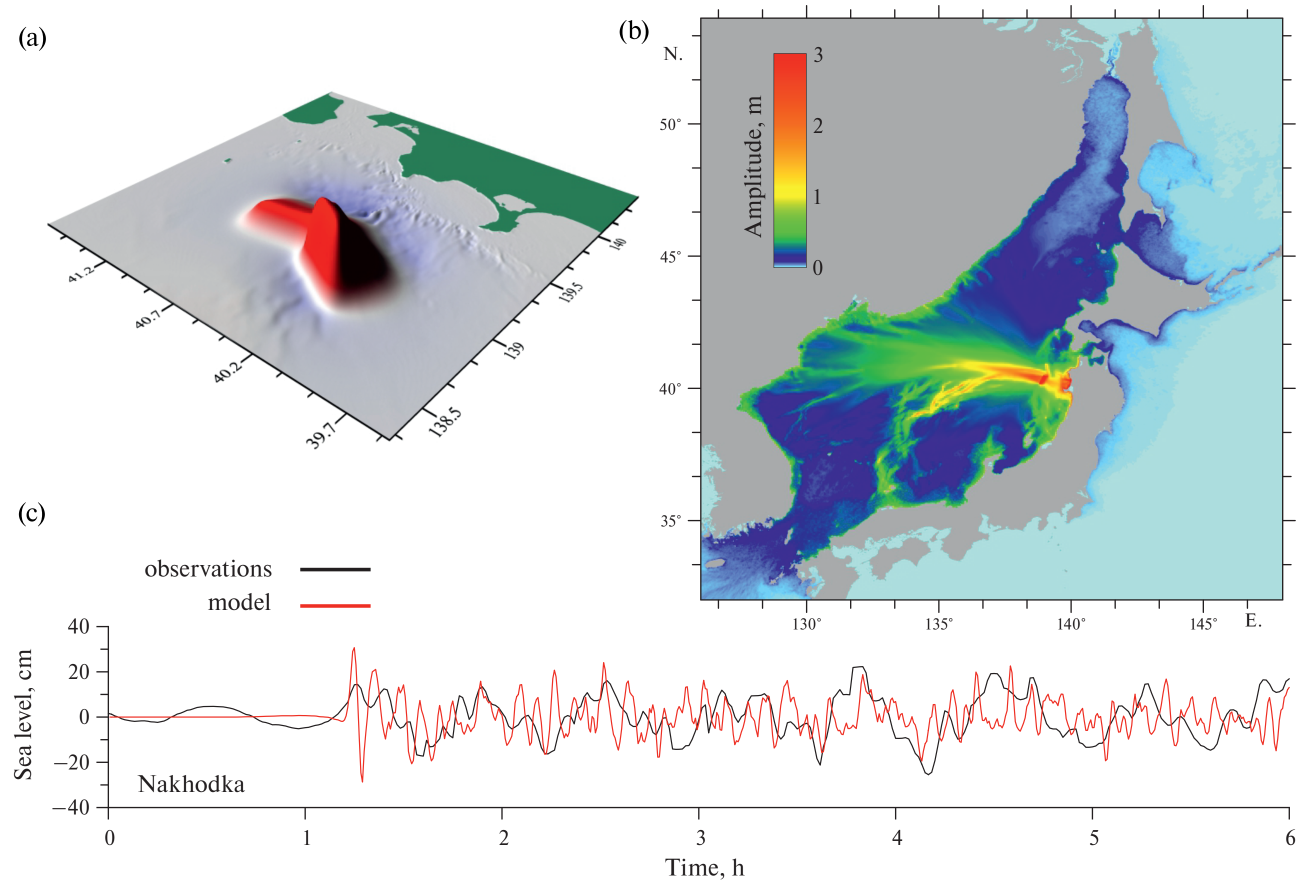

Fig. 11. (a) Bottom deformation for the 1983 Sea of Japan earthquake according to the model of I. Aida [24]; (b) map of maximum tsunami wave amplitudes by modeling results; (c) comparison of modeling results (red line) and tide gauge records (black line) at Nakhodka station, relative to mean sea level. Time is counted from the moment of the earthquake.

maximum tsunami wave height was ~6 m (Fig. 12b). A good agreement between the amplitudes and phases of the recorded waves and the modeling results was obtained (Fig. 12c). In addition to the near-field zone, high tsunami waves were recorded on the coasts of the Primorsky Krai, as well as the Chugoku region (Japan), which is probably related to wave trapping by the Yamato Ridge.

5. DISCUSSION AND CONCLUSIONS

Analysis of observed tsunami waves in the Sea of Japan shows that this phenomenon poses a serious threat to coastal countries, in particular to the coast of Russia. Over 120 years (1904–2023), six strong tsunamis with heights of more than 2 m have been registered in the Sea of Japan. It can be concluded from the analyzed events that tsunamis generated by earthquakes in the Sea of Japan are stronger than those generated by subduction earthquakes in the Pacific Ocean with a similar seismic moment [22, 37, 71]. According to Hatori [37], this is due to the properties of the corresponding seismogenic faults. The Sea of Japan is characterized by a larger dip angle than the Pacific Ocean, and since tsunamis are predominantly generated by vertical displacements of the seafloor, the Sea of Japan is more “efficient” for tsunami generation [48]. In [22], the author talks about the difference in the shear modulus: earthquakes with a shallower hypocenter depth (up to 30 km), and thus with a smaller shear modulus, prevail in the Sea of Japan than in the Pacific Ocean. For the corresponding seismic moments, the magnitude of the fault site displacement becomes larger, which, according to the formula:

$$M_0 = \mu \bar{D} S, \tag{2}$$

where M_0 is seismic moment, μ is shear modulus, $\bar{D}$ is fault site displacement, S is fault area, leads to an increase in vertical displacements.

The spatial parameters of the source area also influence the magnitude of fault site displacement. In the Sea of Japan, the size of the site is on average

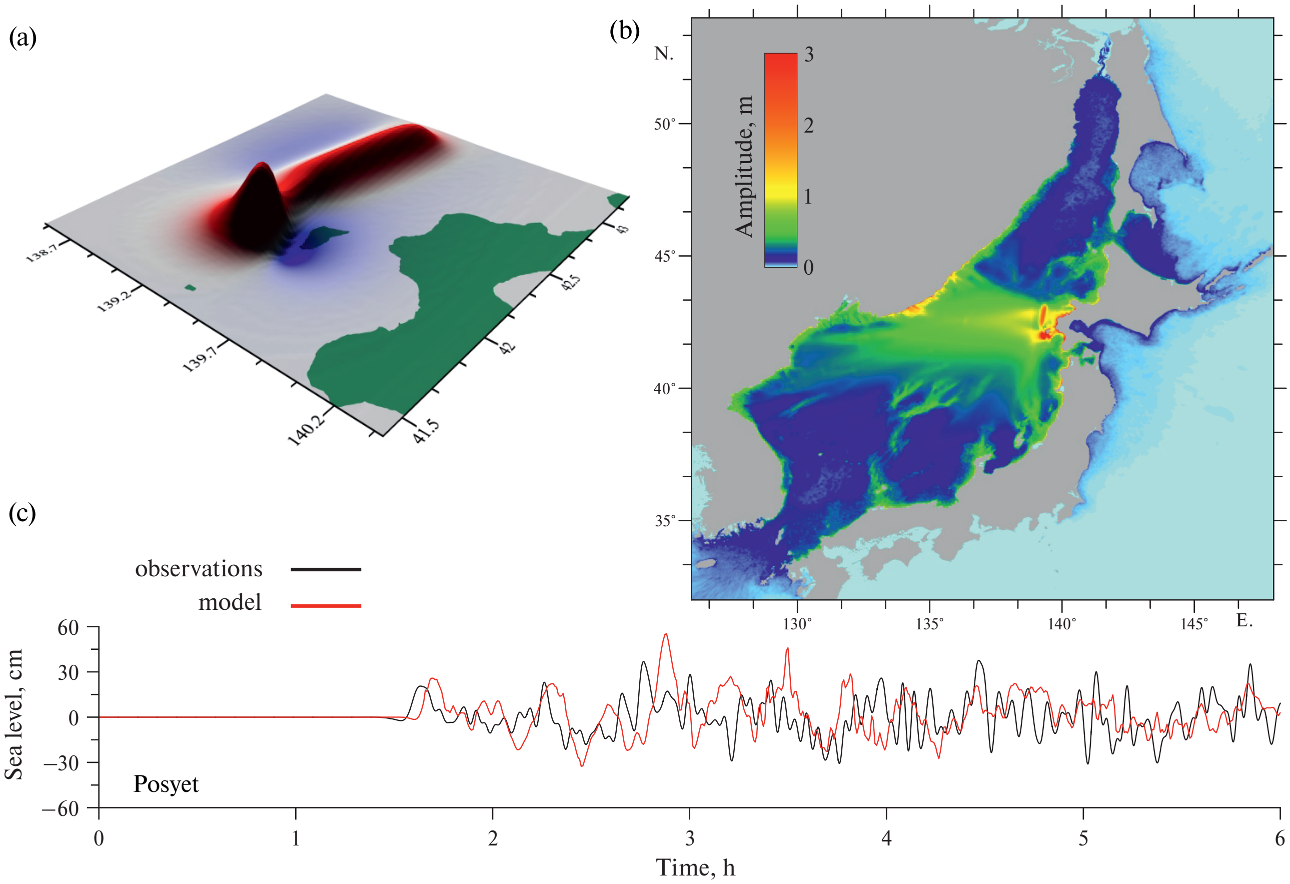

Fig. 12. (a) Bottom deformation for 1993 Okushiri earthquake according to the DCRC-17a model [77]; (b) map of maximum tsunami wave amplitudes by modeling results; (c) comparison of modeling results (red line) and tide gauge records (black line) at Posyet station, relative to mean sea level. Time is counted from the moment of the earthquake.

1.5 times larger than in the Pacific Ocean, which is due to the more elongated shape of the source. For this region, the ratio of the site length to its width is $L/W = 3$, while in the Pacific Ocean, on average, $L/W = 2$ [71].

One of the strongest historical tsunamis in the Sea of Japan was generated by the earthquake on December 7, 1833 at about 14:00 UTC (*1833 Shonai-oki earthquake*). The epicenter of the earthquake was located northeast of Sado Island. The magnitude M_w was about 8.0 [25, 29, 39, 78]. The tsunami killed about 150 people and destroyed 475 houses in Shonai village [39]. In Niigata Prefecture, the wave height was 9 m, and the waves also reached the coast of Hokkaido [15, 40]. According to the results of tsunami sediment studies, the waves also reached the coast of Primorsky Krai: on Russky Island, the runup height exceeded 1 m [2].

Volcanic tsunamis also pose a certain threat to the Sea of Japan. Tsunami waves can be caused by eruptions of volcanoes located both directly in this sea (Ulleungdo, Oshima) and on nearby islands adjacent to this sea. Thus, in 1792 on the southwestern coast of Kyushu Island, at the entrance to the Sea of Japan, there was an eruption of the volcano Undzen-Mayuyama (Fig. 1); as a result of the eruption and the accompanying landslide, a catastrophic tsunami wave was formed: the maximum runup height reached 57 m, the total number of victims exceeded 15 thousand people [43, 82]. The tsunami entered the Sea of Japan through the Korea Strait and affected the southern part of Honshu Island.

The catastrophic eruptions of the Oshima-Oshima (1741) and Undzen (1792) volcanoes, as well as recent events elsewhere in the world's oceans (Anak Krakatau – 2018 and Tonga – 2022), show the threat posed by such eruptions and associated tsunamis.

In addition to volcanic tsunamis, meteotsunamis are another type of hazardous nonseismic tsunami waves [58]. In the waters of the Sea of Japan, meteotsunamis can be generated by the passage of typhoons, atmospheric fronts, squall winds, and other types of atmospheric disturbances. For example, typhoons Maysak and Haishen in September 2020 in addition to low-frequency storm surge, also caused intense high-frequency seiches (of the "meteotsunami" type) observed in some ports of the Sea of Japan [14, 56]. The superposition of various wave processes, in particular, the coincidence of the storm surge peak, high tide, and intense high-frequency sea level fluctuations, poses an extreme danger. Catastrophic meteotsunamis, known locally as Abiki, are regularly observed on the southwest coast of Japan [42]. The height of these waves in the port of Nagasaki can reach 5 m [58]. This phenomenon is due to the approach of long waves to the coast of Japan caused by atmospheric processes in the East China Sea and amplified as a result of Proudman resonance [58]. Their further amplification – as at resonance coincidence of the eigen frequencies of bays and frequencies of baric disturbances ("harbour" resonance, see, for example, [58]). A similar phenomenon, although less strong, is observed in a number of ports on the Russian coast of the Sea of Japan, for example, in the port of Kholmsk, Sakhalin Island [18]

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