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Assessment of Tsunami Hazard Due to Regional and Remote Sources: The Coast of the Sea of Okhotsk

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Abstract—The tsunami hazard for the coast of the Sea of Okhotsk requires a careful analysis, because this sea will be a zone of responsibility for the Tsunami Warning Service for the Far East coast of Russia. While it is not subject to such hazards on the part of seismogenic zones that can produce dangerous tsunamis, nevertheless the Sea of Okhotsk is open for penetration of tsunamis that can be produced by sources in other tsunami-generating zones of the Kuril–Kamchatka region, as well as those of the entire Pacific Ocean. The tsunami hazard for the coast of the Sea of Okhotsk is examined here on the basis of historical observations and the results of numerical simulation for tsunami propagation from hypothetical rupture zones of near and distant earthquakes. It is shown that the real tsunami hazard can only emanate from those regional earthquakes with magnitudes 8.5 or greater that occur in the Kuril–Kamchatka seismogenic zone. Among the remote tsunami-generating zones in the Pacific, the most dangerous locations are the rupture zones of mega-earthquakes of the class M9 that come from the South America zone and from Papua–New Guinea. These can produce water waves with amplitudes as great as 5 m along the entire coast of the Sea of Okhotsk.

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INTRODUCTION

One of the goals in the “Risk Reduction and Mitigation of the Impacts from Natural and Man-Induced Emergency Situations in the Russian Federation until 2015” Federal Target Program is to incorporate the coast of the Sea of Okhotsk in the responsibility zone of the Tsunami Warning System that has been operated in the coastal areas of the Russian Far East since 1958. Here, the implementation of the relevant measures requires evaluation of the tsunami hazard for the coast based both on the available historical evidence and on the results of numerical modeling. While the Sea of Okhotsk does not contain seismogenic zones that could produce dangerous tsunamis, it is nevertheless open to the penetration by tsunamis due to sources in the Kuril–Kamchatka earthquake-generating zone, as well as in other, more remote, earthquake-generating zones in the Pacific. The problem of tsunami hazard for the coast of the Sea of Okhotsk is discussed on the basis of analysis of historical observations and the results of numerical simulation of tsunami propagation from simulated rupture zones of near and distant tsunami-generating earthquakes. Since an analysis of the content in the database (*Integrated* ..., 2014) shows that undersea earthquakes produced over 95% of all dangerous tsunamis in the Russian Far East during the historical period (since 1737), we shall restrict our discussion to earthquake-induced tsunamis. The possible contribution due to tsunamis of different origins (volcanogenic or landslide-induced) will be briefly considered below.

The Sea of Okhotsk is a marginal sea of the Pacific basin and is separated from the Pacific Ocean by Hokkaido Island. in the south and by the Kuril Islands and Kamchatka in the east. The Tatar Strait connects the Japan Sea and the Sea of Okhotsk through the Nevelskoi Strait, the Amur Estuary, and the Sakhalin Gulf in the north, while the La Perouse Strait connects the Sea of Okhotsk and the Japan Sea in the south. However, because the above straits are narrow and shallow, the water exchange with the Japan Sea is insignificant (*Gidrometeorologiya* ..., 1998). The numerous Kuril Islands straits connect the Sea of Okhotsk and the Pacific Ocean. The straits are wide (their total width is approximately 500 km) and deep (as deep as 2000 m occasionally), which maintains intensive water exchange, as well as allowing a free penetration of currents and tsunami waves from the Pacific Ocean into the Sea of Okhotsk basin.

Tectonically, the Sea of Okhotsk lies on the Okhotsk plate, which is part of the Eurasian plate. The crust

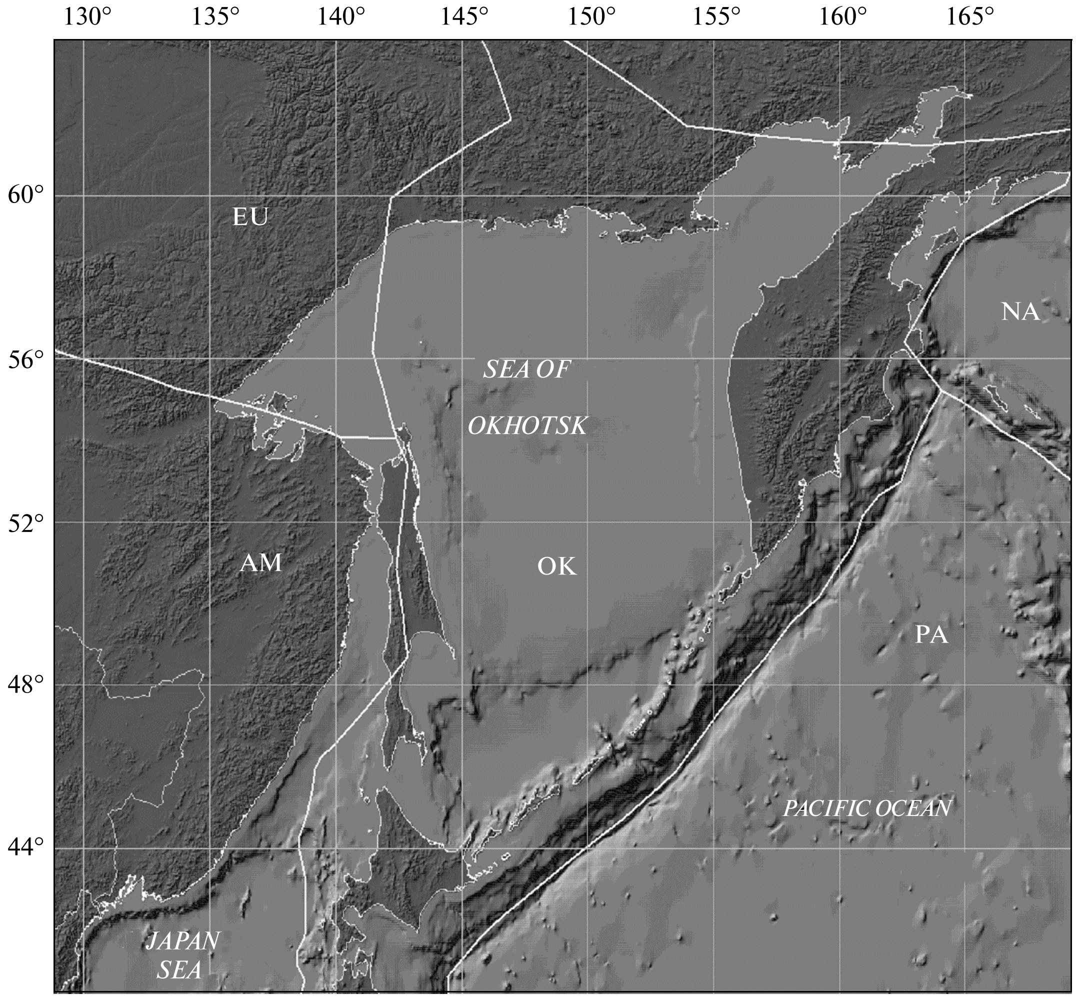

Fig. 1. A review map of the Sea of Okhotsk seafloor relief. The continuous white lines mark plate boundaries (PA, Pacific plate; NA, North American plate; OK, Sea-of-Okhotsk plate; AM, Amurian plate; EU Eurasian plate).

beneath most of the Sea of Okhotsk is continental in type. The leading morphologic elements in the Sea of Okhotsk relief are the shelf (depths 0–200 m) and the continental slope (depths 200–2000 m); individual hills and valleys stand out, the main one is the Kuril deep-sea (occasionally deeper than 2500 m) basin in the southern Sea of Okhotsk (Fig. 1).

One important feature in the Sea of Okhotsk is the presence of an ice cover during the larger part of the year (6–9 months on average). The ice is both fast ice and drift ice, which is the main form of ice in the Sea of Okhotsk. In January and February ice covers all the northern and middle parts of the sea, amounting to 75% of the sea surface. The ice thickens during the winter, reaching 0.8–1.0 m (*Gidrometeorologiya* ..., 1998). Violent storms and tidal currents break the ice cover in many parts of the sea, making hummocks and extensive clearings. The southern boundary of a comparatively stable ice cover commonly runs from the La Perouse Strait to Cape Lopatka at the southernmost tip of Kamchatka. Although the southernmost part of the sea is usually free of ice, it receives considerable ice masses that are transported into it from the north. These are driven by northwesterly winds and are pressed to the Kuril Islands to jam some of the straits.

The results that are presented in this paper are confined to consideration of earthquake-induced tsunamis. These furnish the leading contribution to the tsunami hazard in the region of study, as demonstrated by the historical evidence. However, there are certain morphologic features along much of the Sea of Okhotsk shore that favor the origination of dangerous landslide tsunamis that are produced by undersea and shore landslides (Vazhenin, 2005; Vazhenin and Lebedintsev, 2006).

A special problem for the Sea of Okhotsk shore is presented by volcanogenic tsunamis, which can be generated by explosions and the collapse of calderas on undersea and island volcanoes (Vazhenin, 2006). Collapses of this kind can be due to seismic excitation resulting from the overall seismotectonic process in the zone and can also be directly produced by volcanic eruptions that do not necessarily occur on a specific volcano.

Three cases of volcanogenic tsunamis have been recorded in the Sea of Okhotsk during historical times. The relevant atlas (*Tikhii okean ...*, 1974) contains a mention of a tsunami of this kind that occurred in the middle of the Kuril Islands chain in 1918. A violent tsunami was produced by a volcanic explosion on January 8, 1933, which destroyed the upper half of the central cone of Severgin Volcano on Harimkotan Island (Vazhenin, 2006). The waves were as high as 9 m on the adjacent islands (Solov'ev, 1978); three waves were observed to transport large ice masses onto the shore. The November 13, 1946 eruption of Sarychev Volcano on Matua Island produced "giant waves" on the northwestern coast of the island (Solov'ev, 1978). The actual heights of these waves remains unknown, since no field surveys of tsunami impact were carried out at the time.

Compared with the typical earthquake-induced waves, those generated by volcanic explosions, caldera collapse events, as well as by coastal landslides and rockfalls, show quite different directivity diagrams and different laws of decay for wave height with distance. They are generally dangerous only near the source. Now the Tsunami Warning System cannot predict such tsunamis fast enough, but the potential for such tsunamis should be incorporated in the planning of protective measures for specific population centers.

DATA ON HISTORICAL TSUNAMIS IN THE SEA OF OKHOTSK

The data on tsunami occurrences in the Sea of Okhotsk are scanty; however, no systematic search for such occurrences in primary sources has yet been carried out. The first mention of a tsunami in the Sea of Okhotsk seems to be that in the reports of S.P. Krasheninnikov (1994) on the catastrophic Kamchatka earthquake of October 10, 1737. This marked the beginning of the earthquake catalog for the entire Russian Far East. The earthquake occurred off the eastern coast of Kamchatka, approximately where another Kamchatka earthquake ruptured the same crustal volume in 1952. The information concerning the 1737 tsunami, as reported by Krasheninnikov, is mostly relevant to the Pacific coasts of the North Kuril Islands and Kamchatka where the highest waves were observed on Paramushir Island (64 m). Waves as high as 30 m were observed in the Avacha Bay area. The tsunami was obviously much lower on the western side of Kamchatka. The waves rolled freely 25 km south of Bol'sheretsk to penetrate to a lake that was connected by a stream to the Bol'shaya River. The waves could be between 2 and 5 m in height.

There are slightly more data on the occurrences in the Sea of Okhotsk due to the Kamchatka earthquake of November 4, 1952, whose moment magnitude is presently estimated to be 9.0; however, these data are also far from complete. The waves were 5 m high on the western side of Cape Lopatka; 10-m waves were observed on the oceanic coast of this cape. The height at the village of Ozernoe varied between 3 and 5 m; it was a mere 0.5 m at the village of Kolpakovo (*Historical evidence ...*, 1998).

The waves on the western shore of Cape Vasil'ev on Paramushir Island were occasionally as high as 4.5 m (6.6 m on the oceanic side), between 3 and 6 m at the village of Shelekhovo on the northern coast of the island, 1.5 m on Alaid Island, 1 m on Sakhalin (at Korsakov), and 2 m at Magadan (Solov'ev, 1978). According to the information reported by Savarenskii et al. (1958), the last observation concerns the maximum amplitude as recorded by a tide gauge at Magadan. This value is very important, both as regards the evaluation of possible heights along the continental Sea of Okhotsk coast during largest regional earthquakes and in view of possible testing of numerical models for regional tsunamis.

The Chilean tsunami of May 22, 1960 was caused by the largest (Mw = 9.5) earthquake to have occurred off the Chilean coast during the entire instrumental period of seismological observation (*The Chilean Tsunami ...*, 1961). The earthquake gave rise to a transoceanic tsunami that traveled across the Pacific Ocean and reached its opposite shores with all of its destruction potential in full force. The maximum runups for the Russian Far East coast, 7 m, were measured on the eastern shore of Kamchatka, in the Morzhovaya and Russkaya bays (Zayakin, 1996). This tsunami penetrated into the Sea of Okhotsk through the Kuril Is. straits and caused considerable oscillations in water level that lasted for more than 2 days. Sea-level oscillations occurred during 2 days (May 24 and 25) in the Nagaev Bay; the period of oscillation is that of free oscillations in the bay (approximately 1 h 10 min) and the amplitudes occasionally reached 2 m (Vazhenin, 2010). The motorboats and barges that were at anchor in the port were rising and descending. An unusually rapid drift of ice was observed to occur toward the bay head, in spite of the low tide and lack of wind, which resulted in coarse-block ice filling the bay and the port at an intensity of 8 (*Historical evidence ...*, 1998). The tide gauge in the Nagaev Bay recorded several consecutive wave trains. The first included ten large oscillations that lasted approximately 12 hours and whose maximum range was 2.67 m (Kim and Rabinovich, 1990). The waves of this tsunami on the Sakhalin coast were substantially lower, reached 1.2 m at Korsakov, 0.8 m at Poronaisk, 0.6 m at Katangli, 0.4 m at Cape Crillon, and 0.1 m at Khomsk (Solov'ev, 1978).

The second largest transoceanic tsunami of the 20th century came from Alaska on March 28, 1964. It was not large along the Russian Far East coasts. The maximum rise in the water level was 1 m (at the village of Podgornyi and along the eastern shore of Paramushir I.). The tide gauges recorded waves 0.8 m high at the town of Severo-Kuril'sk and 0.7 m at the village of Babushkino on Shumshu I. (Solov'ev, 1978). The highest wave of this tsunami for Sakhalin was recorded at Korsakov (0.4 m). No data are available for this tsunami along the Sea of Okhotsk coasts.

The Chilean tsunami of February 27, 2010, which was due to an Mw 8.8 earthquake, was recorded by a tide gauge at Magadan. Its maximum height was approximately 0.8 m (Shevchenko and Ivel'skaya, 2013), which is only 1.5 times smaller than the maximum height of this tsunami (1.19 m) as recorded by a tide gauge in the Vodopadnaya Bay in the eastern coast of Kamchatka (Shevchenko et al., 2012).

The most recent transoceanic tsunami, the Tohoku event of March 11, 2011, caused dangerous sea-level oscillations along the eastern coasts of the Kuril Islands and Kamchatka that lasted longer than 24 hours at several locations. The maximum wave heights (up to 3 m) were recorded in the Krabovaya Bay along the western coast of Shikotan Island; the runup values were 1.5 m at the most along its eastern shore. The tide gauge at Malokuril'sk recorded oscillations of 2.3 m in range. The maximum runup reached 2.5 m at Severo-Kuril'sk and 2 m at Burevestnik on Iturup Island. Mere background oscillations of the water level were observed along the Sakhalin shore; the maximum wave height as recorded by tide gauges was 0.47 m (Korsakov), 0.33 m (Starodubskoe), and 0.38 m (Poronaisk) (Kaistrenko et al., 2011). However, the tide gauge at Magadan recorded substantially larger oscillations with amplitudes that reached 1.0–1.1 m; these maximum oscillations up to 2 m in range were observed for 7–9 hours after the arrival of the first wave (Tyurnin, 2014).

The water oscillations due to ordinary tsunami-generating earthquakes that occur in the continental slope of the Kuril Islands chain seem to be able to penetrate into the Sea of Okhotsk to a limited extent, including even those that produced dangerous (with heights greater than 5 m) tsunamis on the nearest shore. One such great earthquake occurred in the Iturup I. area on November 7, 1958. Although the magnitude was high (Ms = 8.1), the maximum runup along the nearest shore was only 5 m (Solov'ev, 1978). The tide gauge at Korsakov recorded oscillations of the water level up to 0.2 m in range. No data are available for the Sea of Okhotsk shores.

The next large undersea earthquakes occurred off Urup Island on October 13 and 20, 1963. The magnitude of the former of these was estimated to be 8.1; it produced a 5-m tsunami at the nearest shore. The energy of the second event was much lower (Ms = 7.2), but the tsunami was 15 m high at the nearest shore. The tide gauge at Kuril'sk recorded a rise of 0.7 m in water level due to the first earthquake. On Sakhalin, oscillations of amplitude 0.4 m were recorded at Korsakov, Katangli, and on Cape Crillon. Waves were also recorded by tide gauges at Magadan (0.1 m) and at Ayan (0.2 m). Waves due to the second earthquake (October 20) at the same sites were considerably lower; they were 0.3 m at Kuril'sk, and 0.1 m at Korsakov, Katangli, and on Cape Crillon (Solov'ev, 1978). No data are available for the Magadan coast.

Two large tsunami-generating earthquakes occurred in the South Kurils area east of Shikotan Island on August 11, 1969 (Mw = 8.2) and on October 4, 1994 (Mw.3). The maximum runup values at the nearest shore (the eastern shore of Shikotan I.) were 5 m and 10.4 m, respectively. Both of these events also caused only background oscillations of the water level in the Sea of Okhotsk. In 1969 the Kuril'sk tide gauge recorded a wave 0.6 m high; the respective figures were 0.25 m for Korsakov and 0.3 m for Crillon. The maximum wave height on records that were made at Kuril'sk was 0.2 m in 1994; the Korsakov tide gauge was not recording at the time and no data have been found for Cape Crillon. No data on these two events are available for the Sea of Okhotsk shores.

Lastly, the most recent large tsunami-generating earthquakes occurred in the middle of the Kuril Islands chain. These are the Simushir earthquakes of November 15, 2006 (Mw = 8.3) and January 11, 2007 (Mw = 8.1). There were no longer any permanent residents on the islands that were the nearest to the earthquake rupture zones (Simushir, Ketoi, Rasshua, and Matua), so that the data on wave runup were only acquired through an expeditionary survey at the locations during the summer of 2007 (Levin et al., 2008). The highest runup values (20 m) were identified for the eastern shore of Matua Island. Several features testified to these as being due to the tsunami that was produced by the first earthquake (November 15, 2006). It is supposed that the waves due to the second earthquake were a few times lower and did not exceed a few meters at the nearest islands (Lobkovskii et al., 2009).

The tsunami waves due to the November 15, 2006 earthquake were distinctly recorded by the Magadan tide gauge as a train of 8–10 water oscillations with a period of approximately 1 hour and a maximum range of 0.63 m (Lobkovskii et al., 2009). The second tsunami could not be identified on the Magadan records owing to the low signal/noise ratio. No instrumental records of both Simushir tsunamis were recorded on the northeastern coast of Sakhalin, because no tide gauges were operated there.

We will now consider cases in which tsunamis were excited by seismic sources that were in the Sea of Okhotsk basin proper. Even though the Kuril–Kamchatka Benioff zone extends far into the Sea of Okhotsk, its dipping attitude leads to the fact that the depths of focus reach values as great as 80–100 km in the backarc part, and this dramatically reduces their tsunami-generating potential. Actually, the Far East catalog contains no reliable cases in which tsunamis were produced by undersea earthquakes with hypocenters west of the Kuril island arc.

The largest (for the entire history of instrumental observation) deep-focus (the hypocenter was 630 km deep as reported by the US Geological Survey) earthquake with magnitude Ms = 8.3 occurred on May 24,

2013. The ground motion due to this event was felt in a vast area westward, as far as Nizhny Novgorod and Moscow. Although the Sakhalin Tsunami Center issued a warning following the event, no appreciable occurrences on land were detected.

The only case of tsunami generation in the Sea of Okhotsk proper is mentioned in a Japanese tsunami catalog (Iida, 1984). It was due to an Ms 6.2 earthquake of March 5, 1956 at a depth of 20 km off the northern shore of Hokkaido. The tsunami wave as recorded by a tide gauge at Abashiri was 0.4 m high. There are no records by tide gauges on Sakhalin.

The tsunami database that is supported by the Institute of Computational Mathematics and Mathematical Geophysics of the Siberian Branch of the Russian Academy of Sciences (ICMMG SB RAS), ITDB/WLD, 2014, contains only two events that are connected with Sakhalin earthquakes whose hypocenters may have been located in the Sea of Okhotsk. One of these, with a magnitude of Ms = 6.8, occurred on March 15, 1924 in the Uglegorsk area, when "strong surface roughness of water in the river" was noticed (Solov'ev, 1978). The other is the damaging Neftegorsk earthquake of May 27, 1995 with Ms = 7.5, which was followed by sea-level oscillations with amplitudes below 0.1 m.

The seismicity of the Sea-of-Okhotsk shelf as recorded instrumentally is rather low. The highest magnitude that has been recorded in the area during the entire period of instrumental observation does not exceed 6.6 (the Magadan earthquake of July 15, 1931). Earthquakes of this magnitude could not by themselves cause dangerous tsunamis, but they can initiate an undersea landslide or a shoreline slide, resulting in a local tsunami with practically any run-up value.

Considering the seismicity based on macroseismic observations, the resulting longer time interval helps to reveal that much larger earthquakes occurred around the Sea-of-Okhotsk coasts in the past. One example is the Yama R. earthquake of November 27, 1851 with magnitude 6.5 ± 0.5 (*Novyi* ..., 1977) which occurred 150 km east of Magadan. Still larger Holocene earthquakes, as large as magnitude 7.5, have been identified from paleoseismological data (Vazhenin, 2000).

Thus, analysis of available historical evidence for tsunamis on the shores of the Sea of Okhotsk shows that really dangerous events are caused by great regional earthquakes of magnitude Mw 8.5 upward that occur in the continental slope of the Kuril–Kamchatka zone, in addition to very great (magnitude Mw 9.0 or greater) undersea earthquakes in other tsunami-generating zones, although far from all of these zones, in the Pacific Ocean. We did a series of calculations on tsunami generation and propagation for the purpose of a more accurate determination of magnitude thresholds that pose a hazard to the Sea-of-Okhotsk coasts and of the locations of earthquake occurrence. The results are presented below.

AN ANALYSIS OF TSUNAMI OCCURRENCES DUE TO REGIONAL EARTHQUAKES: NUMERICAL MODELING

We analyzed the manifestation of tsunamis along the coast of the Sea of Okhotsk due to regional sources by performing a series of computations using the MGC software package (Chubarov et al., 2011). The package is based on the McCormack computational scheme, which approximates classical nonlinear shallow-water equations written in spherical coordinates (Shokin et al., 2008). The tsunami source was simulated by static displacements of the seafloor as computed for a 3D dislocation source based on the formulas that were derived in (Gusiakov, 1978; Okada, 1985). The seismic moment of such a source, M_0, is given by

$$M_0 = \mu LWD_0,$$

where μ is the modulus of rigidity of the material (its value was assumed to be 5×10^{10} Nm^{-2}), L is the fault length, W the fault width, and D_0 the slip. The seismic moment vs. moment magnitude relation for simulated sources was that due to Kanamori (1977):

$$Mw = (\log M_0 - 9.1)/1.5.$$

The displacements, as computed for a plane boundary of a homogeneous half-space, were imposed on the actual sea-bottom relief in the source region; the resulting additional disturbances (e.g., disturbed stability of undersea slopes) and the contribution due to the horizontal displacements were neglected. The bottom displacements were assumed to be instantaneous, since the actual duration of slip for tsunami-generating earthquakes (50–100 s) is still too short compared with the typical periods of tsunami waves (5–15 min for regional tsunamis and as long 30–40 min for transoceanic tsunamis). This approach is currently accepted and is used by most researchers for tsunami simulations in specific areas of the world ocean, both in Russia and abroad.

We simulated the generation and propagation of waves in the Sea of Okhotsk that are generated by model tsunamigenic earthquakes whose moment magnitudes vary in the range between 7.8 and 9.0. The rupture zones of these earthquakes (we shall refer to them as "basic" ones in what follows) were on the eastern slope of the Kuril island arc in a strip approximately 100 km wide at depths of between 5 and 35 km (Fig. 2). Their mechanisms were typical of tsunamigenic earthquakes in this zone; this was a low-angle (approximately 15°) rupture plane between the subducted oceanic crust and the overhanging island-arc wedge of continental lithosphere (Lobkovskii and Baranov, 1982).The distance between the epicenters of basic earthquakes varied between 125 km for Mw 7.8

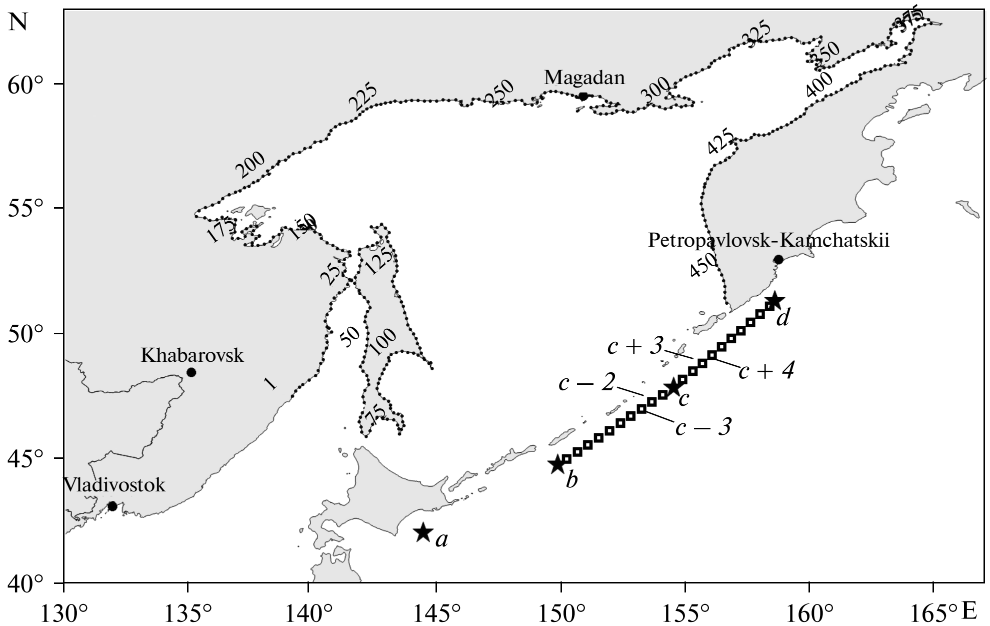

Fig. 2. A fragment of the scheme of the computation region for simulation of regional tsunamis. Filled circles show the locations of virtual tide gauges, the numbering corresponds with the distributions of extreme (maximum positive and minimum negative) wave amplitudes as shown in Figs. 4 and 7. Stars mark the centers of earthquake rupture planes for simulated Mw = 9.0 earthquakes, the squares indicate the extra earthquake sources considered here. The model earthquake sources that are mentioned in the text are marked with indices.

earthquakes (with an earthquake fault 108 km long) and 500 km) for Mw = 9.0 earthquakes an earthquake fault 430 km long). The rupture plane at sources of simulated earthquakes was chosen to be along the trend of the seismogenic zone.

We tried to clarify the effects of small variations in the source position along the seismogenic zone on the wave amplitude along the Sea-of-Okhotsk coast by also considering "extra" model tsunamigenic earthquakes with magnitude Mw = 9.0 whose epicenters were shifted southwest and northeast of the "basic" source (*c*) at intervals of approximately 45 km (see Fig. 2).

We simulated tsunami propagation in a rectangular region that extends from 127° to 180° E and from 32° to 63° N on a constant-step mesh of 1 minute of arc based on the well-known 1-minute bathymetric array (GEBCO, 2008). The results were presented as distributions of the extreme (the maximum positive and minimum negative) wave amplitudes along the Sea-of-Okhotsk coast as recorded by virtual tide gauges (see Fig. 2) that are installed at marine grid points of the computation mesh. "Glow diagrams" proved to be as valuable; these are distributions of maximum (for the entire time of computation) tsunami amplitudes at each point of the region of interest. These diagrams furnish a graphic way of presenting the directions and paths of tsunami-energy propagation; they help to identify the coastal segments where the most intensive oscillations occur.

As was to be expected, the leading parameter that controls the degree of tsunami hazard for an undersea earthquake in the Kuril–Kamchatka zone for the Sea-of-Okhotsk coast is its magnitude (Fig. 3). Earthquakes of magnitude Mw = 7.8 or less pose practically no serious hazard of sea-level changes on this coast, whatever the epicenter location is along the seismogenic zone. The associated amplitudes do not exceed 0.45 m for the eastern coast of Sakhalin and 0.35 m for the Kolyma coast. Dangerous (with amplitudes greater than 0.5 m) waves on these coasts are produced by Mw > 8.0 earthquakes. For an Mw 8.4 earthquake (see Fig. 3b) in the continental slope against Matua Island, the waves that come to the eastern coast of Sakhalin reach heights of 2.5–3.0 m, while those on the Kolyma coast are 1.5–2.0 m. However, really dangerous tsunami waves are produced by earthquakes whose magnitude approaches the value Mw = 9.0. The resulting mean positive amplitudes can then reach 3–4 m both on the eastern coast of Sakhalin and on the continental coast of the Sea of Okhotsk; the maximum amplitudes reach 5–6 m (see Figs. 3c, 4).

As was noted above, the presence of numerous deep and wide Kuril straits allows tsunami waves to pass rather freely into the Sea-of-Okhotsk basin. A numerical study of the relationship of tsunami hazard on the Sea-of-Okhotsk coast to the locations of model tsunamigenic earthquakes earthquakes relative to the Kuril islands showed that even large islands like Paramushir, Simushir, or Iturup cannot be an insuperable barrier for waves that

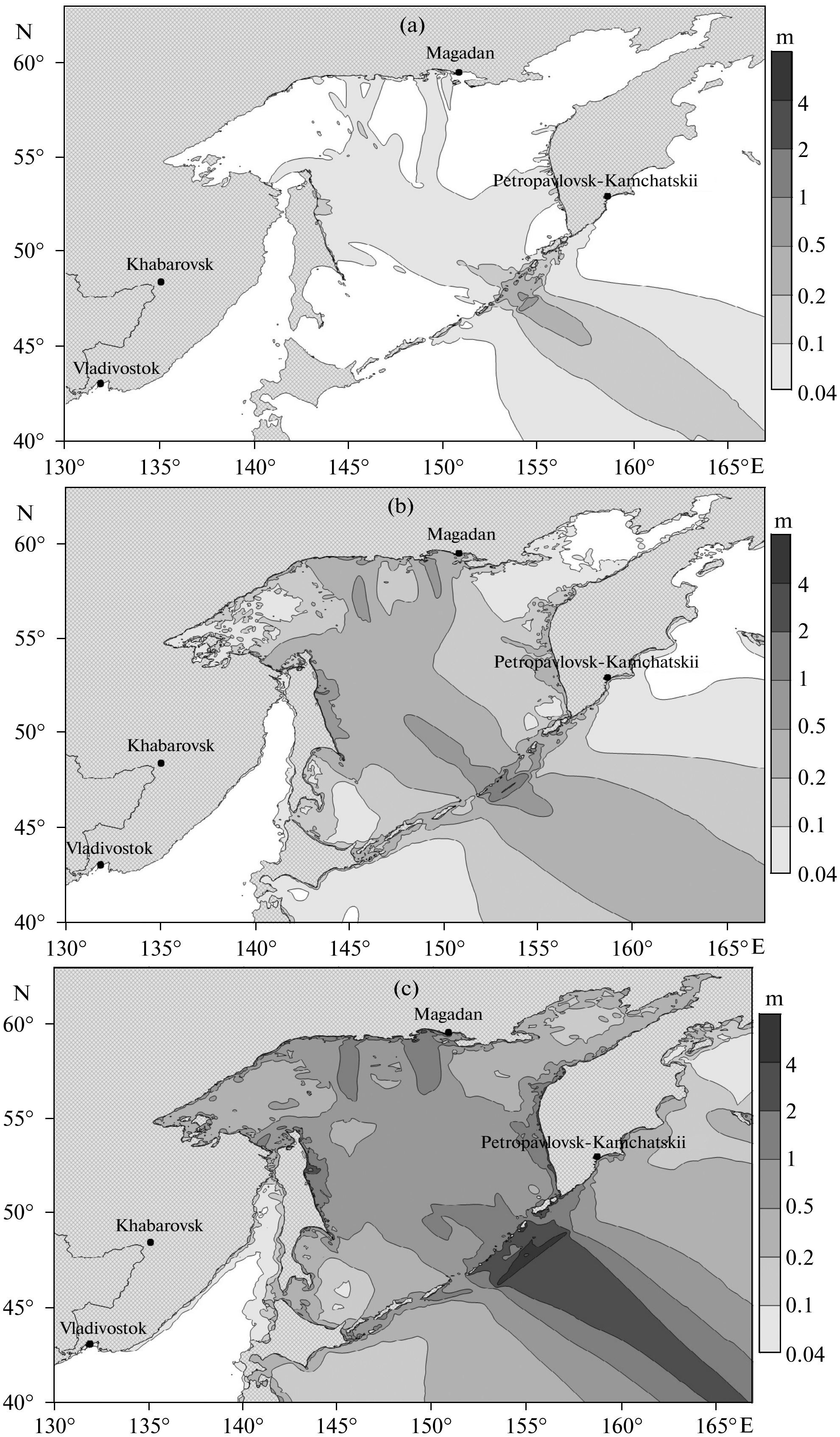

Fig. 3. The glow diagrams for model earthquakes with magnitudes $M_W = 7.8$ (a), $M_W = 8.4$ (b), and $M_W = 9.0$ (c), all in the Kuril–Kamchatka zone.

are excited by sufficiently long (for Mw > 8) earthquake sources. Wave energy penetrates through the straits into the Sea of Okhotsk and then is distributed over all of its area; sea-level variations at specific sites along the coast were controlled almost exclusively by local conditions.

It follows from the calculated glow diagrams that the greatest hazard for Sakhalin is posed by earthquakes that are situated between basic rsources (*b*) and (*c*) (see Fig. 2). As an earthquake is shifted toward source (*c*), the amplitudes in the north of this island become higher.

There are two well-defined tsunami-prone zones along the continental coast of the Sea of Okhotsk (see Fig. 3); one of these includes Okhotsk and Inya and the other Magadan and the neighborhoods of Balagannoe and Tauisk. The existence of two dominant zones of energy concentration is felt already for the "southern" option (rupture zone *b* in Fig. 2). As one moves north the zones become ever more pronounced and reach a maximum in a scenario based on rupture zone ($c-3$) (here and below we are using the rupture zone designations that are shown in Fig. 2). The greatest effect on the western coast of Kamchatka is due to the tsunami waves that are generated by sources ($c+3$) and ($c+4$).

Local variations in height at shoreline sites under shifts of earthquake source location were evaluated for three virtual tide gauges near the Ayan, Okhotsk, and Magadan. It turned out that the greatest hazard for Ayan can emanate from rupture zone ($c-3$), which excites waves with amplitudes of approximately 2 m and a double amplitude of approximately 4 m. The adjacent tide gauges situated on the opposite (northern) side of the cape record waves of lower amplitudes.

The coast line near the town of Okhotsk is comparatively smooth; this leads to practically identical amplitude distributions for each of the nearest virtual tide gauges. Here, the maxima of positive amplitudes are reached by the wave due to source ($c-2$), but there are two negative extrema; one was related to source ($c-3$) and the other to ($c+3$).

The most complex picture is observed around Magadan; this is due to the coastline configuration, which is rather complex in this case. For example, the tide gauge that was installed deep inside the Nagaev Bay records the maximum values for source (*d*) (the positive amplitude is 3.9 m and the double amplitude is 8.3 m). When a source is shielded by the Kamchatka Peninsula, practically a third of it, the wave energy is captured by the western (Kamchatkan) shelf and is again radiated toward Magadan (Fig. 5).

Summing up, an analysis of glow diagrams shows that the distribution of wave energy along the Sea-of-Okhotsk coastline is extremely non-uniform and is controlled, not only by the orientation and location of the source, but also by resonance properties of the shelf areas adjacent to the coast.

The results suggest that tsunamigenic earthquakes with magnitudes, Mw, below 8.5 that occur in the continental slope of the Kuril arc actually pose no serious hazard for the Sea-of-Okhotsk shores, although they can cause appreciable sea-level oscillations. An analysis of glow diagrams shows that a tsunami that is generated in the landward slope of the Kuril–Kamchatka trench can penetrate into the Sea of Okhotsk through the straits, but the energy that arrives is sufficiently rapidly scattered in this extensive sea body.

A different situation occurs for extremely large (of the M9 class) earthquakes like those that occurred off Kamchatka in 1737 and 1952 and off Japan in 2011. The energy of the associated tsunamis is so great that it can cause resonance in the entire basin of this marginal sea that lasts for several days. These can in turn cause resonance with the modes of free oscillations in the adjacent shelf areas, some bays and gulfs. This may cause strong currents and coastal floods to heights of a few meters. The

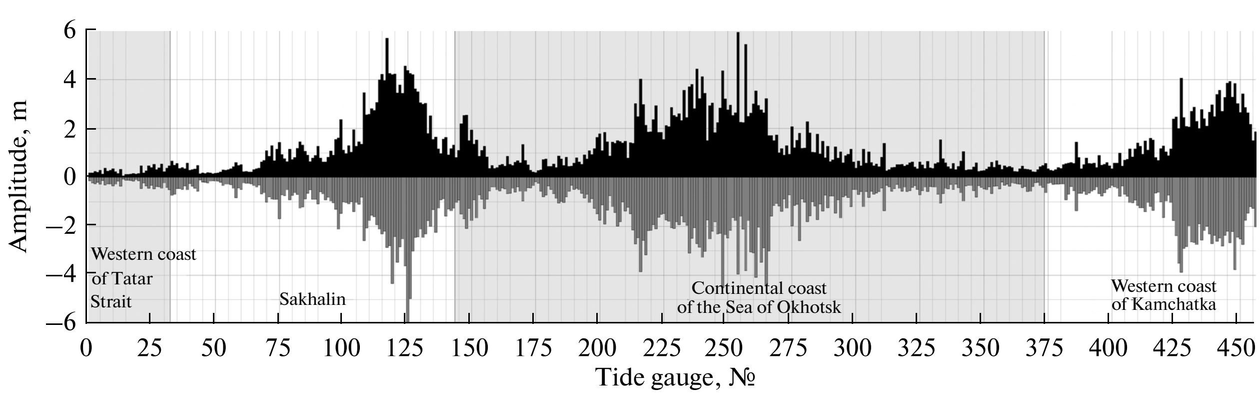

Fig. 4. The distributions of the maximum positive and minimum negative wave amplitudes (vertical black and grey bars, respectively) that are generated by the basic model source (*c*) with magnitude Mw = 9.0.

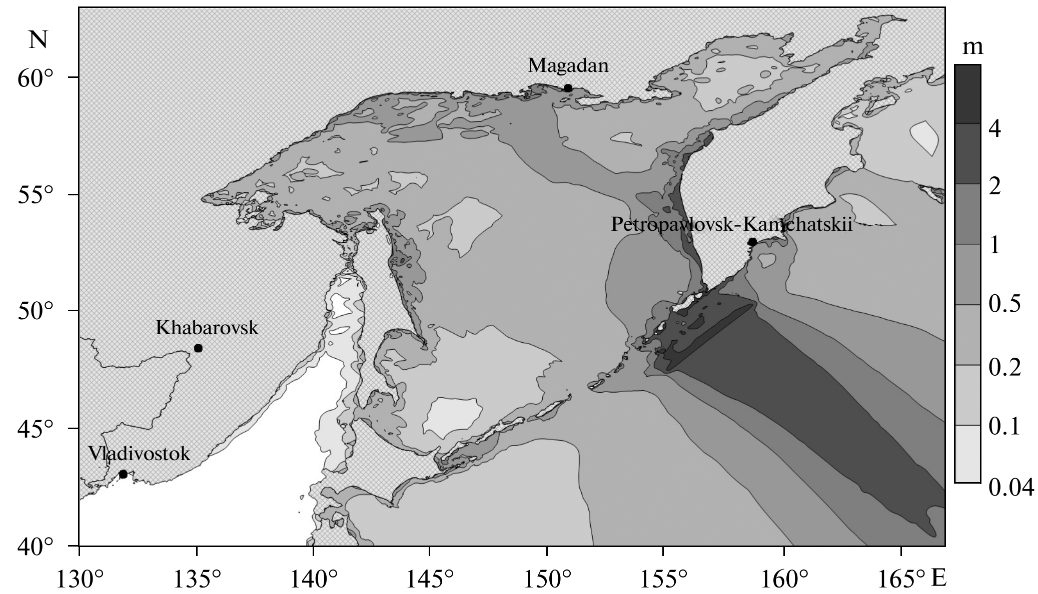

Fig. 5. The glow diagram for a simulated earthquake with magnitude Mw = 9.0, which is near the southernmost tip of Kamchatka and generates a tsunami that poses the greatest hazard to the coast adjacent to Magadan (maximum amplitude 3.9 m, the associated double wave amplitude 8.3 m).

times of maxima for such oscillations depend on many factors, in particular, weather and tide phases, consequently, they are hardly predictable and can occur many hours (and even days) from the arrival of the first disturbance.

A HAZARD ANALYSIS OF DISTANT TSUNAMIS: NUMERICAL SIMULATION

An analysis of historical observations shows that the Sea-of-Okhotsk coast is more vulnerable to the impact of transoceanic tsunamis traveling from remote tsunamigenic zones in the Pacific than to the effects of regional tsunamis. At least, it was transoceanic tsunamis, viz., the 1960 Chilean and the 2011 Tohoku events, that caused the maximum sea-level variations at Magadan.

A special study was carried out in order to more accurately evaluate the potential of remote tsunamigenic zones that pose a hazard to the Russian Far East coast. The results of this study were published in (Beisel et al., 2014). Numerical simulation of tsunami propagation from the major tsunamigenic zones in the Pacific, as carried out in this publication on a constant 2 arcmin grid in a rectangular region extending from 100° E to 60° W and from 60° S to 65° N demonstrates that the real hazard is posed only by extremely large (Mw = 9.0 or greater) undersea earthquakes. The magnitude of that hazard largely depends on the location of the remote source zone relative to the Russian Far East coast. Apart from the well-known southern Chile zone whose maximum radiation is directly toward the Russian Far East coast, there is also a dangerous zone around New Guinea and the Solomon Islands. The sources in these zones can also cause dangerous sea level variations at the Russian Far East coast (Fig. 6).

An analysis of marigrams from southern Chile earthquakes with magnitude Mw = 9.0 as computed for the continental coast of the Sea of Okhotsk shows that the maximum wave heights can exceed 2 m on the coast. Similar figures are obtained for the eastern coast of Sakhalin and the western coast of Kamchatka (Fig. 7). The heights due to earthquakes from the Papua–New Guinea region are slightly lower, but these too (Fig. 8) substantially exceed the hazard threshold (0.5 m).

The special character of remote tsunamis consists, first, in the fact that considerable amplitudes of sea-level oscillation are observed along long sections of the Sea-of-Okhotsk coast and, secondly, in that the time of arrival of maximum wave can be in a considerable (occasionally by some tens of hours) delay relative to the time of arrival of the first (head) tsunami wave due to the existence of alternative paths for the propagation of tsunami waves with dominant amplitudes (see, e.g., Kowalik, 2008).

This feature is the leading distinction of these tsunamis compared to those that are due to local earthquakes. The zone of the maximum impact due to these local tsunamis is confined to the coastal segments nearest to the

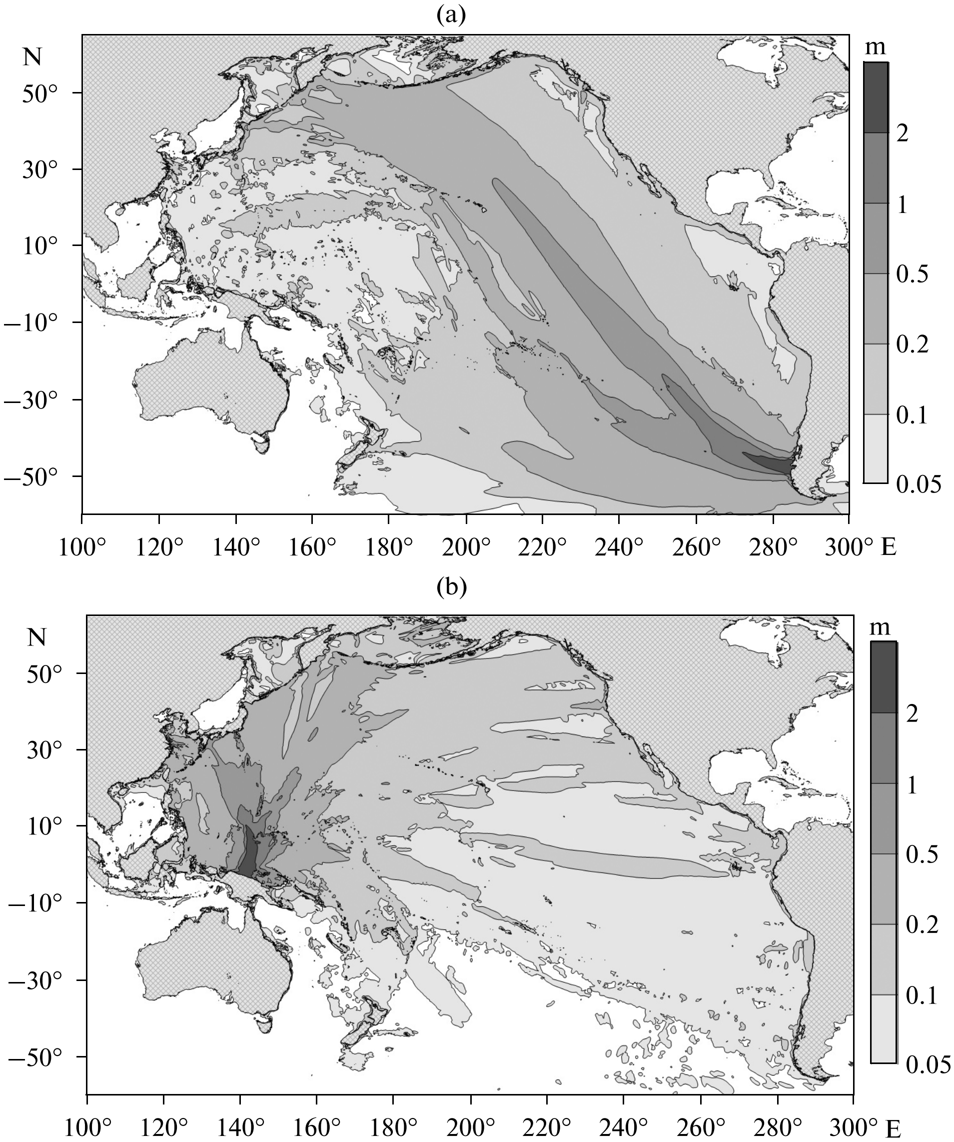

Fig. 6. The glow diagrams for simulated earthquakes with magnitude Mw = 9.0, which are off the Chile coast (a) and off the Papua–New Guinea (b).

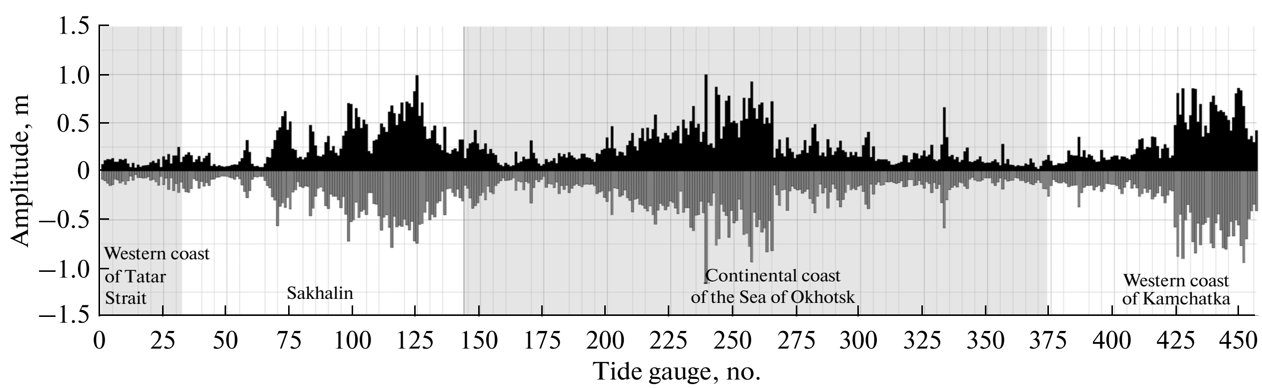

Fig. 7. The distributions of the maximum positive and minimum negative wave amplitudes along the Sea of Okhotsk coast (vertical black and grey bars, respectively) generated by a model Mw = 9.0 earthquake in southern Chile.

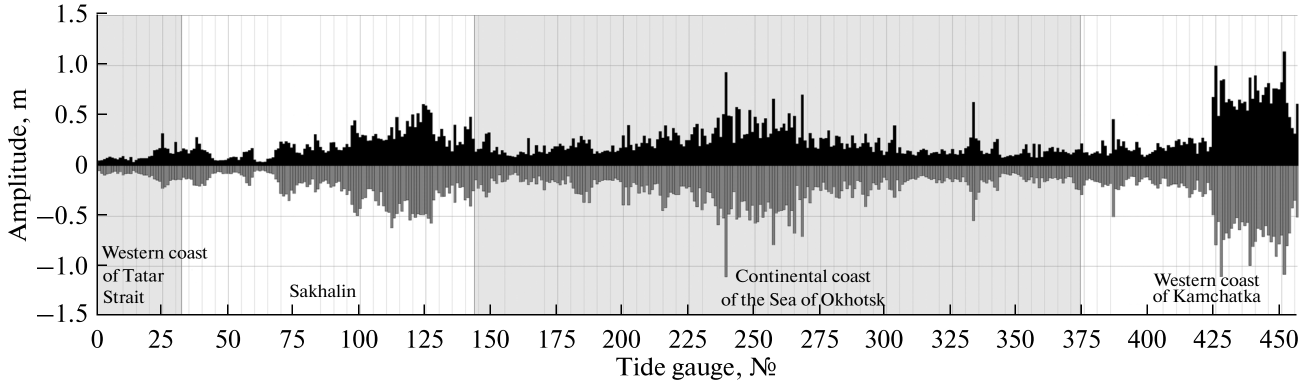

Fig. 8. The distributions of the maximum positive and minimum negative wave amplitudes along the Sea of Okhotsk coast (vertical black and grey bars, respectively) generated by a simulated Mw 9.0 earthquake in the Papua–New Guinea area.

source, while the maximum wave arrives soon after the first head wave.

CONCLUSIONS

We examined the available materials from actual observations of tsunamis at the Sea-of-Okhotsk coast and from simulation results to come at the following conclusions:

The Sea of Okhotsk does not contain any tsunamigenic zones of its own within itself that could cause strong earthquake-induced tsunamis. However, the sea is prone to regional tsunamis due to large ($M > 8$) undersea earthquakes that are generated by the Kuril–Kamchatka zone, as well as to the penetration of great transoceanic tsunamis that can be generated by mega-earthquakes ($M \geq 9$) that occur in other tsunamigenic zones in the Pacific, primarily in the South American zone.

The results of the numerical simulation show that dangerous (with heights above 0.5 m) sea-level oscillations in the western coast of the Sea of Okhotsk that are caused by Kuril–Kamchatka earthquakes could be generated by earthquakes of magnitude Mw = 8.0. For magnitudes of Mw = 8.4 the double amplitudes of sea-level oscillations can reach 2 m in the Magadan area, the figure rises to reach 8 m for Mw = 9.0. Tsunamis of this kind are certain to produce a disastrous impact along the Kolyma coast.

The study of the variations of sea level oscillations in the Sea of Okhotsk depeding on the source location relative to the Kuril Islands chain shows that even larger islands, such as Paramushir, Simushir, or Iturup cannot be a serious barrier for sufficiently long (for $M > 8$) earthquake rupture zones. Wave energy penetrates through straits into the Sea of Okhotsk and is then redistributed over the entire sea basin; sea-level oscillations at particular sites were almost exclusively controlled by local conditions (the bathymetry of the adjacent shelf areas and the resonance properties of bays and gulfs).

If the source is near the southernmost tip of Kamchatka, the wave energy would be captured by the western Kamchatka shelf and be radiated again toward Magadan; the amplitudes of sea-level oscillations in the Magadan area reach the maximum for this source location, a third of which is shielded by the Kamchatka Peninsula.

The presence of an ice cover can magnify the impact of a tsunami (longer run-up distance, the heavy ice transport onto the shore). Another hazard can arise when the coastal fast ice is broken and people are on the ice fishing. The effect can take place with very low tsunamis (a few tens of centimeters).

Tsunamigenic events are relatively rare in the Sea of Okhotsk compared with the adjacent Kuril–Kamchatka zone, hence the real tsunami hazard in the region is somewhat underestimated. The result is that the residents are negligent about being in the coastal zone, the local authorities underestimate the hazard, and no preventive measures are taken against tsunamis. Realistic evaluation of tsunami hazards for the Sea-of-Okhotsk coast requires purposeful effort in the search for and systematization of historical evidence relating to tsunami occurrences, expeditionary field work looking for traces of older tsunamis on the Sea-of-Okhotsk coast, identification and evaluation of the tsunamigenic potential of active faults in the coastal zone, as well as a study of the potential volcanogenic and slide tsunamis by numerical simulation.

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REFERENCES

Beisel, S.A., Gusiakov, V.K., Chubarov, L.B., et al., Numerical simulation of the impact of remote tsunamis on the Far East coast of Russia, *Izvestiya RAN, Fizika Atmosfery i Okeana*, 2014, vol. 50, no. 5, pp. 578–590.

Chubarov, L.B., Babailov, V.V., and Beisel, S.A., *The MGC Program for Calculating Tsunami Waves Due to Earthquakes*, Inventor's certificate for registration of programs for computers by the Federal Service of Intellectual Property, Patents and Trade Marks no. 2011614598. Registered at the Computer Program Register June 9, 2011.

GEBCO General Bathymetric Chart of the Oceans, 2008. http://www.gebco.net/data_and_products/gridded_bathymetry_data/

Gidrometeorologiya i gidrokhimiya morei (Hydrometeorology and Hydrochemistry of the Seas), vol. IX, Sea of Okhotsk, issue 1, *Gidrometeorologicheskie usloviya* (Hydrometeorological Conditions), St. Petersburg: Gidrometeoizdat, 1998.

Gusiakov, V.K., Residual displacements at the surface of an elastic half-space, in *Uslovno-korrektnye zadachi matematicheskoi fiziki v interpretatsii geofizicheskikh nablyudenii* (Constrained Well-Posed Problems of Mathematical Physics in Interpretation of Geophysical Observations), Novosibirsk: VTs SO RAN, 1978, pp. 23–51.

Historical evidence on tsunamis in the Sea of Okhotsk, in *Monograficheskii spravochnik. Proekt "Morya" Gidrometeorologiya i gidrokhimiya morei* (Monographic Handbook, Project "Seas", Hydrometeorology and Hydrochemistry of the Seas) vol. IX, Sea of Okhotsk, issue 1, *Gidrometeorologicheskie usloviya* (Hydrometeorological Conditions), St. Petersburg: Gidrometeoizdat, 1998, pp. 225–226.

Iida, K., *Catalog of Tsunamis in Japan and Neighboring Countries*, Special Report, Yashigasa, Aichi Institute of Technology, 1984.

Integrated Tsunami Database for the World Ocean (ITDB/WLD), 2000 BC to Present, CD-ROM, Tsunami Laboratory, ICMMG SD RAS, Novosibirsk. 2014. Web-version: http://tsun.sscc.ru/nh/tsunami.php

Kaistrenko, V.M., Shevchenko, G.V., and Ivel'skaya, T.N., Events due to the March 11, 2011 Tohoku tsunami on the Pacific coast of Russia, *Seismicheskie Pribory*, 2011, vol. 38, no. 1, pp. 41–64.

Kanamori, H., The energy release in great earthquakes, *J. Geophys. Res.*, 1977, vol. 82, pp. 2981–2987.

Kim, Kh.S. and Rabinovich, A.B., Tsunamis on the northwestern coast of the Sea of Okhotsk, in *Prirodnye katastrofy i stikhiinye bedstviya v Dal'nevostochnom regione* (Natural Disasters in the Russian Far East), Vladivostok: DVNTs AN SSSR, 1990, vol. 1, pp. 206–218.

Kowalik, Z., Energy flux as a tool in locating tsunami secondary sources, *Science of Tsunami Hazards*, 2008, vol. 27, no. 3, pp. 1–29.

Krasheninnikov, S.P., *Opisanie zemli Kamchatki* (A Description of Kamchatka Land), vol. 1, St. Petersburg: Nauka, 1994.

Levin, B.V., Kaistrenko, V.M., Rybin, A.V., et al., The impact of the November 15, 2006 tsunami on the central Kuril Islands and simulation of run-up heights, *Dokl. Akad. Nauk*, 2008, vol. 419, no. 1, pp. 118–122.

Lobkovskii, L.I. and Baranov, B.V., On the excitation of tsunamis at subduction zones, in *Protsessy vozbuzhdeniya i rasprostraneniya tsunami* (Tsunami Excitation and Propagation), Moscow: IO AN SSSR, 1982, pp. 7–17.

Lobkovskii, L.I., Rabinovich, A.B., Kulikov, E.A., et al., The Kuril earthquakes and tsunamis of November 15, 2006 and January 13, 2007: Observations, analysis, and numerical modeling, *Okeanologiya*, 2009, vol. 49, no. 1, pp. 1–16.

Novyi katalog sil'nykh zemletryasenii na territorii SSSR s drevneishikh vremen do 1975 g. (A New Catalog of Large Earthquakes in the USSR Area from Earliest Times Until 1975), Moscow: Nauka, 1977. [Available as *New Catalog of Strong Earthquakes in the USSR from Ancient Times through 1977*, Report SE-31, N.V. Kondorskaya and N. V. Shebalin, Editors-in-Chief, Translated and Published by World Data Center A for Solid Earth Geophysics, EDIS, Boulder, Colorado, 1982.]

Okada, Y., Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am.*, 1985, vol. 75, no. 4, pp. 1135–1154.

Savarenskii, E.F., Tishchenko, V.G., Svyatlovskii, A.E., et al., The November 4–5, 1952 tsunami, *Byulleten' Soveta po Seismologii AN SSSR*, 1958, no. 4, pp. 36–37.

Shevchenko, G.V. and Ivel'skaya, T.N., Tsunami i drugie opasnye morskie yavleniya v portakh Dal'nevostochnogo regiona Rossii (po instrumental'nym izmereniyam) (Tsunamis and Other Hazardous Sea Occurrences in the Ports of the Russian Far East: Instrumental Measurements), Yuzhno-Sakhalinsk: FGBUN IMGiG DVO RAN, 2013.

Shevchenko, G.V., Ivel'skaya, T.N., and Kaistrenko, V.M., *Tsunami na Kuril'skikh ostrovakh. Osobennosti proyavleniya i mery po snizheniyu riska* (Tsunamis on the Kuril Islands: The Impact and Mitigation Measures), Yuzhno-Sakhalinsk: FGBUN IMGiG DVO RAN, 2012.

Shokin, Yu.I., Babailov, V.V., Beisel, S.A., et al., Mathematical modeling in application to regional tsunami warning systems operations, *Comp. Science and High Perf. Computing III, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Krause, E., et al., Eds., 2008, vol. 101, pp. 52–68.

Solov'ev, S.L., Basic data on tsunamis on the USSR Pacific coast, 1937–1976, in *Izuchenie tsunami v otkrytom okeane* (Tsunami Studies in the Open Ocean), Moscow: Nauka, 1978, pp. 61–136.

The Chilean Tsunami of May 24, 1960. The Committee for Field Investigation of the Chilean Tsunami of 1960, The Committee, 1961.

Tikhii okean. Atlas okeanov (The Pacific Ocean. Atlas of the Oceans), Moscow: GUNiO MO SSSR, 1974.

Tyurnin, V.B., *Tsunami v severnoi chasti Okhotskogo morya* (Tsunamis in the Northern Sea of Okhotsk), FGBU Kolymskoe Upravlenie po Gidrometeorologii i Monitoringu Okruzhayushchei Sredy, 2014. http://www.meteo.magadan.ru/Meteo/tsunami.htm

Vazhenin, B.P., *Printsipy, metody i rezul'taty paleoseismogeologicheskikh issledovanii na Severo-Vostoke Rossii* (The Principles, Methods, and Results of Paleoseismogeological Studies in the Russian Northeast), Magadan: SVKNII DVO RAN, 2000.

Vazhenin, B.P., On the evaluation of tsunami hazards for the northern coast of the Sea of Okhotsk, in *Nauka Severo-Vostoka Rossii—nachalo veka: Materialy Vserossiiskoi nauchnoi konferentsii, posvyashchennoi pamyati akademika K.V. Simakova i v chest' ego 70-letiya* (The Science of the Russian Northeast—the Beginning of a Century: Proc. All-Russia Conference Devoted to the Memory of Academician K.V. Simakov and His 70th Anniversary), Magadan, April 26–28, 2005, Magadan: SVKNII DVO RAN, 2005, pp. 245–249.

Vazhenin, B.P., The Kuril volcanoes as sources of tsunamis in the northern Sea of Okhotsk, in *Vulkanizm i geodinamika: Materialy III Vserossiiskogo simpoziuma po vulkanologii i paleovulkanologii* (Volcanism and Geodynamics: Proc. III All-Russia symposium on Volcanology and Paleovolcanology), vol. 3, Ulan-Ude: Buryatskii Nauchnyi Tsentr SO RAN, 2006, pp. 659–663.

Vazhenin, B.P., Problems in the study of tsunamis in the northern Sea of Okhotsk, in *Problemy kompleksnogo geofizicheskogo monitoringa Dal'nego Vostoka Rossii. Trudy vtoroi regional'noi nauchno-tekhnicheskoi konferentsii* (Problems in Multidisciplinary Geophysical Monitoring in the Russian Far East. Proceedings of the Second Regional Scientific Conference), October 11–17, 2009, Petropavlovsk-Kamchatskii, Petropavlovsk-Kamchatskii: GS RAN, 2010, pp. 312–317.

Vazhenin, B.P. and Lebedintsev, A.I., Offshore coastal landslides and their significance for earlier colonization of the northern Sea-of-Okhotsk coasts, in *Neolit i paleometall severa Dal'nego Vostoka* (The Neolith and Metals in the Northern Far East), Magadan: SVKNII DVO RAN, 2006, pp. 164–175.

Zayakin, Yu.A., *Tsunami na Dal'nem Vostoke Rossii* (Tsunamis in the Russian Far East), Petropavlovsk-Kamchatskii: KAMSHAT, 1996.

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