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Tsunamis on the Russian Pacific coast: history and current situation

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Abstract

The Pacific coast, including the Kamchatka Peninsula, the Kuriles, the Sea of Japan, the Sea of Okhotsk, and the Bering Sea, is the main tsunami-prone area in Russia. The Far East tsunamis are much more frequent, extensive, and devastating than those in the Black, Caspian, Baltic, and White Sea coasts, as well as in major inland lakes of Baikal, Ladoga, etc. The tsunami catalog of the Russian Far East from 1737 to present lists 110 events with mainly near-field and few far-field sources (105 and 5 events, respectively). Most of the catalogued tsunamis (95 cases) were induced by earthquakes, and few events had volcanic (3), landsliding (2), meteorological (3), and unknown (2) triggers. Altogether there were eleven devastating tsunamis for the period of observations, with >10 m heights, out of which two great events in 1737 and 1952 when the waves exceeded 20 m. The wave heights were in the range 2.5–10 m in fifteen hazardous tsunami events and within the tidal range (~1–2 m) in thirteen cases; the other events were small and detectable only instrumentally. Thus, the average recurrence times for tsunamis of different magnitudes in the Russian Pacific coast are 25 years for devastating events and 10–15 years for hazardous tsunamis; small tsunamis occur almost every year, according to statistics for the last sixty years collected at the regional network of tide stations. The topics discussed in the paper concern the completeness and reliability of the Far East catalog; distribution of tsunami events in space and time; correlation between the intensity of tsunami and the magnitude of the causative undersea earthquake; tsunami recurrence; tsunami warning and long-term hazard assessment and mapping.

Keywords: natural disaster; earthquake; seismotectonics; tsunami; tsunami hazard; tsunami risk mapping

Introduction

Assessment of tsunami hazard is a key seismological problem in the Russian Far East where submarine earthquakes generated within the island-arc slope of the Kuriles–Kamchatka seismic belt can reach $M = 9.0$ and often trigger tsunami waves. Tsunami is the fourth major hazard by life and infrastructure losses after earthquakes, floods, and typhoons. Tsunamis were responsible for about 1% of fatalities from natural disasters in the 20th century having killed more than four million people (Topics 2000, 2001), but became the deadliest hazard in the 21st century after the Indian ocean Sumatra event of 2004, with a death toll of 227,000 (NGDC/WDS GHTDB, 2015).

Sudden, brief, and sweeping tsunamis can inflict great damage and pose fatal risks to people within the attack zone. Efficient protection from this hazard is problematic because of large recurrence times at each specific part of the coast: deadly tsunamis occur every 30–50 years even in most active areas of the Pacific coast (Japan, Chili or Burma), and the recurrence of great devastating events is as large as 100–150 years. This is far greater than the recurrence of floods or typhoons and commensurate with that of earthquakes or volcanic eruptions. Tsunamis become hazardous above some natural threshold of wave height while the waves below this value can pass unnoticed or confused with wind, storm, or tide surge. This is, among others, a reason why people may be fatally unprepared to meet the tsunami emergency.

The Pacific coast, including the Kamchatka Peninsula, the Kuriles, the Sea of Japan, the Sea of Okhotsk, and the Bering Sea, is the main tsunami-prone area in Russia. The Far East tsunamis are far more frequent, extensive, and powerful than those known in the Black, Caspian, Baltic, and White Sea coasts, as well as in major inland lakes of Baikal, Ladoga, etc. The first exhaustive synthesis of tsunami data, mainly in the Kuriles and Kamchatka coasts, belongs to Soloviev (1968) who discussed the physical causes of tsunami events and the

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significance of the problem to Russia. Soloviev (1968) tabulated the basic parameters of thirty nine historic tsunamis in the area between 1737 and 1965, explained their possible mechanisms, and suggested models for estimating their seaward and inland spread. The final section of the paper (Soloviev, 1968) is devoted to brief forecast and risk mapping, two principal objectives of theoretical and applied tsunami research.

According to Soloviev (1968), reliable prediction is possible with the use of tide gauges placed on the ocean bottom along the shelf margin at key protected sites; such cable or buoy stations are currently used in Japan, India, Chili, and other countries (Rabinovich and Eble, 2015). As for short-term prediction, the probabilistic seismotectonic approach outlined by Soloviev (1968) has never been implemented in Russia. Similar ideas made basis for the method of probabilistic tsunami hazard assessment (PTHA) developed about forty years later and used broadly for tsunami risk mapping of different scales in the US, Canada, Australia, and New Zealand (Gonzales et al., 2009; Knighton and Bastidas, 2015; Leonard et al., 2014; Power and Downes, 2009; Power et al., 2011).

The paper of Soloviev (1968) concerns currently live issues and has been largely cited in all Russian publications on the subject. However, 430 new tsunami events have occurred since it was written, and a large progress has been made in ways of their characterization and interpretation. The Far East catalog has been extended with forty five tsunamis postdating 1968, as well as with some historic events of the 18th and 19th centuries reported in historic accounts and in recently discovered old publications. Along with a wealth of new evidence on tsunami occurrence in the Pacific coast of Russia, more insights have been gained on the generation and propagation of tsunami waves. The new data call for synthesis and analysis, with implications for prediction and assessment of tsunami hazard.

There is no exact scientific definition of tsunami yet. In the 1960s, tsunami was interpreted as long-period (2 to 200 min) waves induced by sudden processes, mainly of tectonic origin, on the sea bottom or surface: submarine earthquakes, volcanic eruptions, as well as onshore or offshore landslides (Soloviev, 1968). Geographically, the Pacific coast was considered to be the most vulnerable while only minor waves coming occasionally from far-field sources (e.g., the Lisbon earthquake of 1755 or the Krakatau eruption of 1883) were expected in other coasts. The most faithful model defined tsunami as long waves in shallow water. However, the waves like those in the 1958 Lituya Bay megatsunami hardly have long wavelengths, though being obviously anomalous and disastrous. The Lituya Bay tsunami followed an earthquake with a of 7.9 (Miller, 1960) which triggered an enormous . The wave that traveled across the bay during the event had a crest reaching 30 m in height, and the sudden displacement of water destroyed vegetation up to 525 m above the bay level.

As far as these phenomena were further studied and ever more data were collected, it became clear that huge water displacement hazardous to population and engineering structures was possible in marine as well as in continental settings: natural or manmade lakes or even large rivers (Didenkulova and Pelinovsky, 2009; Nikonov, 2004, 2007; etc.). The periods of such waves may vary from 1–2 min to one hour, which corresponds to the frequency range between wind and tidal waves. Some tsunamis have atmospheric (air pressure) triggers: meteotsunamis arise more often than others in the eastern US and Adriatic coast, the Bengal Bay, the Bolear islands, etc. (Vilibiæ et al., 2014).

Therefore, the modern tsunami catalogs include classical earthquake-induced marine tsunamis, as well as tsunami-like events that result from external impacts in any water body and consist in sudden water displacement near the shore hazardous for people and structures.

Whichever be its trigger, the tsunami wave involves the whole water column and displaces enormous water masses. They are thus disastrous events basically different from wind waves which likewise can reach heights of 8–10 m but cause far lesser losses.

Available tsunami data from the Russian Pacific coast

The knowledge of historic tsunami events observed in the Russian Far East has been summarized in earthquake catalogs (Kondorskaya and Shebalin, 1977; Mushketov and Orlov, 1893), special tsunami catalogs (Soloviev and Ferchev, 1961; Soloviev and Go, 1974, 1975; Soloviev, 1978; Soloviev et al., 1986; Zayakin, 1996), scientific publications and reports of specific events, as well as in global parametric databases supported by the National Geophysical Data Center in Boulder, USA (NGDC/WDS GHTDB, 2015) and the Tsunami laboratory at the Institute of Computational Mathematics and Mathematical Geophysics (ICMMG) in Novosibirsk (HTDB/WLD, 2015). The databases are generally consistent in amount and content of data, with some difference in estimates of tsunami size, confidence level, classification of triggers, etc. The tsunami data (tables and plots) from the Russian Far East region reported in this paper are mainly selected from the global database supported by ICMMG with the *WinITDB* graphical shell (WinITDB, 2007).

To be included into the regional Far East tsunami catalog, a near-field event has to fall within the responsibility zone of the Far East tsunami warning service (TWS) and a far-field one has to be felt at least once within the Russian Pacific coast. The first regional catalogs of Soloviev (1978), Zayakin (1996), and others *de facto* used this formal criterion and included far-field tsunamis that caused damage or hazardous flood at the coasts of Russia. However, the approach needs update nowadays.

As the instrumental facilities have progressed, the tide stations of the Far East regional network detect ever more events of minor sea level change detectable only in station readings. Advanced digital stations deployed at some sites of the Russian Pacific coast record almost all significant events within and outside the region. For instance, the Sumatra event of 26 December 2004 was recorded as a 29 cm wave height at the Severo-Kurilsk tide station (Rabinovich et al., 2006).

The regional stations record large far-field tsunamis that inflict major damage near their sources, such as the Samoa event of 29 September 2009 with a 22.3 m maximum runup on the nearest shore or the Chili tsunami of 27 February 2010 (runup reaching 29 m), as well as those that have no serious consequences at the origin and appear as 5–10 cm sea level change at the Far East stations, like the Papua-New Guinea tsunami of 03 January 2009 or that in Vanuatu of 07 October 2009 (Shevchenko et al., 2013). Therefore, it is reasonable to choose some minimum wave height measured or observed in the Russian Far East (for example, 0.5 m) as a criterion for including an event into the regional catalog. The threshold of 0.5 m high waves is used, specifically, to appraise brief tsunami warning (Gusiakov, 2010; Vorobieva et al., 1983). The chosen threshold value will constrain the share of near- and far-field events in the regional catalogs.

The Far East tsunami catalog

The historic tsunami catalog of the Russian Far East, like many other regional catalogs, begins with a devastating event: a tsunami triggered by the Kamchatka earthquake of 6 October 1737. Early historic events are commonly poorly documented, but reports on the Kamchatka tsunami of 1737 are available due to the Second Kamchatka Expedition, which worked in the region from 1735 to 1740. Stepan Krasheninnikov, a Russian explorer, naturalist and geographer, a member of the Expedition, disembarked on the Kamchatka western coast near Bolsheretsk two weeks after the earthquake, when the aftershock activity still continued ("it was hard to keep feet" as he wrote). He promptly understood the importance of the event, and spent most of his time during the first trips to Kamchatka on collecting evidence of tsunami and earthquake effects. The tsunami of 1737 was possibly the greatest regional event for the whole history of observations, judging by its parameters cited in the book of Krasheninnikov (1755): 63 m and 31 maximum surge heights (Paramushir Island and Avacha Gulf, respectively); more than 700 km of heavily damaged coast; prolonged and intense aftershock activity; volcanism; prominent tsunami-related effects such as emergent sea bottom in bays or changes to the coastal topography. The event must have caused many fatalities among the Koryak and Kamchadal natives, but the number of victims is impossible to estimate, even approximately. Very likely it crossed the ocean and, like the Kamchatka tsunami of 1952, may have affected the nearby Aleutian and Japan islands, or reached as far as the Hawaii or, perhaps, even South America, where the event of 1952 excited 2–3 m high waves (The tsunami, 1952; The Chilean tsunami, 1953).

The devastating Kamchatka tsunami of 4 November 1952, another great event of this kind in the region, demonstrated the destructive power of such a natural disaster. The surge height reached 18–20 m in the eastern shore of Paramushir Island (Savarensky et al., 1958) and actually swept off the city of Severo-Kurilsk. People in the islands of Paramushir and Shumshu suffered an especially strong impact as many moved there from continental Russia just a few years before, when the islands became part of the Soviet Union in 1945, and were unaware of tsunami hazard. That was one of causes of so many deaths, of which the exact number was possibly calculated but hidden from the public. The open-source estimate was 2336 civilian fatalities (Shevchenko et al., 2012), but times more military people were killed as they made the greatest part of the population at that time. The most exhaustive report and expertise of the consequences can be found in the book of Smyshlyaev (2003) who talked to people and studied local historic accounts and eye-witness reports. As he estimated, from 10,000 to 14,000 people were killed, mostly the tsunami victims (Smyshlyaev, 2003). In the current version of the database (HTDB/WLD, 2015), the event is quoted as having caused 10,000 fatalities, which rather shows the size of the disaster and the available order of accuracy.

Note that there have been no documented tsunami death cases over the entire Russian Far East coast since 1952, but it does not mean that fatalities would never happen in the future. Large tsunami events have long recurrence times (low occurrence probability per year) but threaten with severe losses, including high life risks. In this respect, they are similar to bolid impacts which are hardly probable but, if happen, may cause a global catastrophe and kill a great part of the human population (Bobrowsky and Rickman, 2007). For example, there were no life losses over the 2500 km long eastern coast of Japan for 51 years between the Chilean tsunami of 27 May 1960 when 204 people were killed (The Chilean Tsunami, 1961) and the Tohoku event of 11 March 2011 when the number of victims reached 18,465 (National Police, 2015). At the same time, sixty six tsunamis of different sizes had occurred in the area, most of them following regional earthquakes.

Altogether regional earthquakes triggered 105 tsunami events in the Russian Far East (Japan and Okhotsk Sea coasts) for the period from 1737 to 2015. In five cases, waves higher than 0.5 m were caused by far-field sources (Chili in 1960, 2010, and 2015; Alaska in 1964; and Tohoku in 2011), though instrumentally recorded remote events have been far more numerous, and their number is growing progressively with the advance of instruments. The Far East regional tsunami catalog spans 278 years, a half of events before 1963 and the other half after this median date. This distribution reflects the contrast in the past and present data completeness (see below).

The geography of tsunamis and their causative earthquakes in the Russian Far East (by 31 December 2015) is quite uneven (Fig. 1): ninety one events in the Kurile–Kamchatka zone; four in the Sea of Okhotsk; and ten tsunamis in the Japan Sea, including the Tatar strait (thirty two events occurred altogether but only ten were reliably documented in the Russian Pacific coast). Most of the Kurile–Kamchatka earthquakes fall within a band between the trench axis and the shelf edge, where the oceanic plate is subducting beneath the island-arc zone of continental lithosphere (Lobkovsky and Sorokhtin, 1979). Therefore, the earthquake mechanisms should correspond to a low-angle thrust (Lobkovsky and Sorokhtin, 1980), which generally agrees with the statistics of CMT mechanisms (Global CMT Catalog, 2015) available since 1976. The

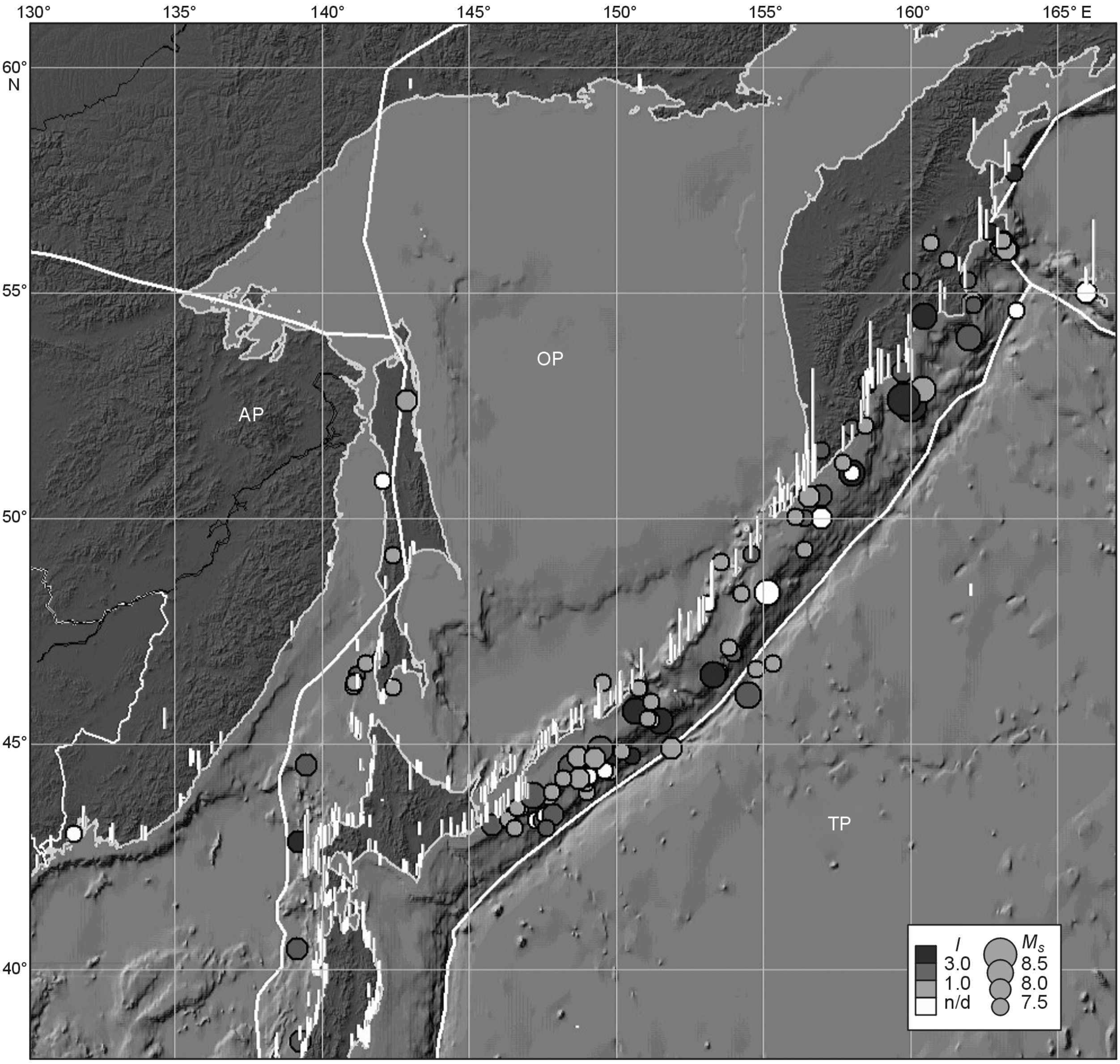

Fig. 1. Location map of 105 regional tsunamigenic earthquakes in the Russian Pacific coast from 1737 to 2015. The size of circles is proportional to earthquake magnitudes; gray shades record tsunami intensities (Soloviev–Imamura scale). White bars mark observed respective tsunami heights. Solid white lines are plate boundaries, after the digital model of Bird (2003). Abbreviations stand for plate names: PP, Pacific plate; OP, Okhotsk plate; AP, Amur plate. Hereafter n/d means no data.

tsunamigenic earthquakes in the Japan Sea originate along the Okhotsk–Amur plate junction, possibly also with the Japan microplate south of the Okhotsk plate inferred in the model of Bird (2003). Most events have steep reverse slip mechanisms.

The distribution of tsunami intensities in time (Fig. 2) illustrates the contrast in data completeness between the early and late parts of the regional catalog. The intensities (I) are according to the Soloviev–Imamura scale (Soloviev, 1972) based on average wave heights along the nearest coast, while the I accuracy is proportional to the number of measurements.

The Far East tsunami catalog (Fig. 2) is more or less complete after mid-1950s when a network of tide stations was setup in the region, while the data for the 18th and 19th centuries are restricted to large and great events of $I > 1$, and even some of such events may be missing. The 278-year total length of the record hardly exceeds one seismic cycle of 200 ± 50 yr (Vikulin, 1990, 2003) corresponding to the recurrence of $M \geq 7.7 \pm 0.2$ earthquakes within the northwestern Pacific margin, and is obviously insufficient for reliable prediction of tsunami recurrence and maximum possible size.

Tsunami intensity I histograms (Fig. 3a) include two megatsunami events of $I > 4$, with waves higher than 20 m (in 1737 and 1952); nine devastating tsunamis of $3 \leq I < 4$ and >10 m wave heights; hazardous tsunamis of $1 \leq I < 3$ and >2–3 m waves in 27 cases; wave heights within tide values (1–2 m) in 15 cases; and 36 small tsunamis detectable only instrumentally. Thus, the average recurrence times for tsunamis of different sizes in the Russian Pacific coast are 25 years for devastating events and 10–15 years for hazardous tsunamis; small tsunamis occur almost every year, according to statistics for the last 60 years collected at the regional network of tide stations.

Note that it is impossible to estimate the intensity of quite many tsunamis (15%), especially the preinstrumental events with unknown wave heights. To fill the gap, careful search of additional evidence is needed from all possible data sources, which can be as successful as historic seismology (Nikonov, 1997; Nikonov and Fleifel, 2014).

The greatest part of the catalogued tsunamis (95 events, or 90%) were induced by earthquakes, and few events had volcanic (3), landsliding (2), meteorological (3), and unknown (2) triggers. Thus, it is reasonable to use the earthquake prediction methods for tsunami warning.

The most significant tsunamis (fifteen regional events listed in Table 1 and marked in Fig. 4) pose the greatest risks to people living in the coastal areas and make the greatest part of hazard.

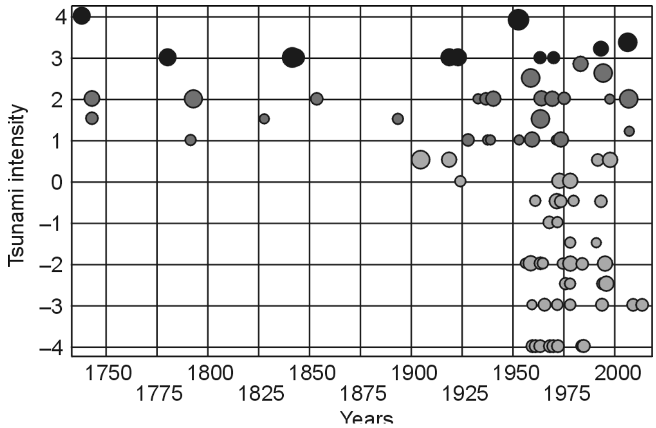

Fig. 2. Variations of tsunami intensity (I) in time from 1737 to 2015. The size of circles is proportional to earthquake magnitudes; gray shades record tsunami intensities. Legend same as in Fig. 1.

Tsunami intensity vs. earthquake magnitude

Correlation between the intensity of tsunamis and the magnitude of the causative undersea earthquakes is the key point in tsunami hazard assessment and risk mapping. The data in the historic catalog and the tools built into the *WinITDB* graphic shell allow investigating this correlation, both for the magnitude M_s estimated from surface waves with 20 s periods and the moment magnitude M_w. It is especially important for the warning service that predicting the tsunami intensity from earthquake magnitudes is hard or impossible. This is evident in the $I(M_s)$ and $I(M_w)$ plots (Fig. 5) showing only a general trend of greater tsunami intensity at larger earthquake magnitudes, while the scatter of data exceeds six points of the intensity scale for $M = 7–8$ earthquakes, which most frequently excite tsunamis, corresponding to 64-fold difference in average wave heights on the nearest coast.

The large scatter (for both short-period M_s and longer-period M_w) is due to difference in the water depth, mechanisms, and origin depth of earthquakes, and to coseismic gravity effects. The influence of water depths at submarine seismic sources on tsunami intensity was first noted by Iida (1970) in earthquakes of Japan. Earthquakes in deep ocean mobilize greater amounts of water and thus excite tsunamis of greater initial energy. Earthquakes with high-angle reverse and normal slip mechanisms pose the greatest tsunami hazard, while motions on low-angle thrusts are less hazardous, as predicted by simulations (Alekseev and Gusiakov, 1984; Comer, 1984). The reason may be that low-angle thrusts generate deeper-focus earthquakes, while the presence of a large strike-slip component in earthquake mechanisms makes the ensuing tsunamis times smaller. The earthquakes with origin depths about 60 km induce twice smaller tsunamis than the 30 km deep ones (Gusiakov, 1976). Seismicity deeper than 80 km almost never causes large tsunamis.

Secondary processes triggered by seismic shocks, such as land- or rock-sliding, may strongly increase the tsunami size. Coseismic landsliding contributed a lot to tsunami generation in 30% of earthquakes within the Pacific seismic belt and was even the main tsunami trigger in some cases, e.g., for the Papua New Guinea tsunami of 17 July 1998 (Gusiakov, 2001).

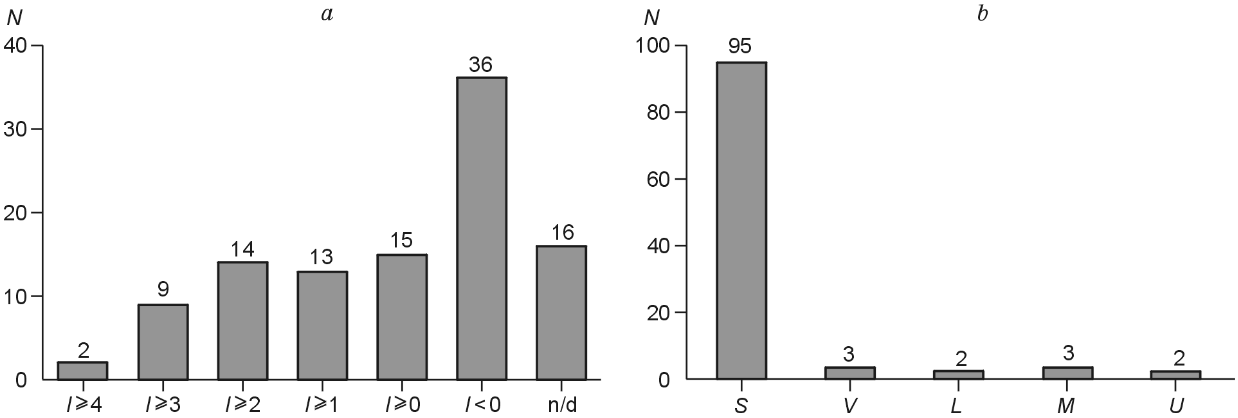

Fig.3. Histograms of tsunamigenic events in the Far East region: intensity I (*a*) and triggers (*b*). *S*, seismic; *V*, volcanic; *L*, landslides; *M*, meteorological; *U*, unknown sources. Numerals above bars are number of events within the respective range of parameter values.

Table 1. Significant* regional tsunamis observed in the Russian Pacific coast from 1737 to 2015

Date	*M*	*I*	H_{max}, *M*	N_G	N_R	*F*	Location
17.10.1737	8.3	>4	63	4	4	n/d	Kamchatka
29.06.1780	7.5	3	12	5	5	12	Central Kuriles
17.05.1841	8.4	3	15	7	3	1	Kamchatka
25.04.1843	8.4	3	>5	8	1	n/d	Iturup Island
07.09.1918	8.2M_s	3	8	26	12	24	Central Kuriles
03.02.1923	8.3M_s	3	14	17	3	2	Kamchatka
13.04.1923	7.2M_s	3	14	10	3	35	Kamchatka
04.11.19520	8.5M_w	4.1	18.6	343	22	~10,000	Kamchatka
6.11.1958	8.4M_w	2.5	5.0	56	12	0	Iturup Island
20.10.1963	7.2M_w	3.0	15.0	47	31	0	Urup Island
22.11.1969	7.3M_w	3.0	15.0	19	10	0	Kamchatka
27.05.1983	7.7M_w	2.8	5.0	138	48	1?	Japan Sea
12.07.1993	7.7M_w	3.2	5.5	190	15	0	Japan Sea
04.10.1994	8.1M_w	2.6	10.4	116	30	0	Shikotan Island
15.11.2006	8.1M_w	3.5	22.4	254	120	0	Simushir Island

Note. *M* is earthquake magnitude, from surface waves (M_s) and seismic moment (M_w) or inferred from shaking intensity; I is tsunami intensity, Soloviev-Imamura scale; H_{max} is maximum runup on Russian Pacific coast; N_G is total number of observed wave heights; N_R is number of observed heights on Russian Pacific coast; *F* is number of fatalities on Russian Pacific coast (n/d means no data).
* Significant events in NGDC/WDS earthquake and tsunami databases are defined as those that cause large financial (>$1,000,000) or life (>10) losses; are induced by $M > 7.5$ earthquakes; or have intensity $I > 2.5$.

Tsunami earthquakes

The problem of tsunami earthquakes is essential for evaluating the location and size of pending tsunami events. The term *tsunami earthquake* was introduced by (1972) for events that trigger s very much larger than expected according to the shorter-period surface-wave earthquake magnitudes. For instance, theof 1 April 1946 with the waves higher than 40 m followed an $M_S = 7.4$ earthquake, a magnitude mentioned in earlier and later earthquake catalogs. The earthquake that triggered the devastating Sanriku tsunami of 15 June 1896 with a maximum wave height of 38.2 m, which caused more than 27,000 deaths, had a magnitude of = 7.4–7.6 inferred from shaking intensity. (1972) defined a tsunami earthquake as that for which the calculated from surface waves with a period of about 20 seconds differs markedly from the M_W. Source deformation in these earthquakes has a time constant of about 100 s or more, which reduces the energy of surface waves but is a stronger tsunami trigger (, 1972).

There were four tsunami earthquakes in the Kurile–Kamchatka zone: on 13 April 1923 in the Gulf of Kamchatka; 20 October 1963, near Urup island; 22 November 1969, at the Ozernoi Cape (Northeastern Kamchatka), and on 10 June 1975 near Shikotan Island (Table 2).

The model of Fukao (1979) for two tsunami earthquakes of October 20, 1963 and June 10, 1975 that occurred off the coasts of the Kurile Islands and eastern Hokkaido, respectively, explained their extremely strong tsunamigenic effect proceeding from the spatiotemporal characteristics of the sources as well as from the amplitude and phase spectra of long-period surface waves and the long-period *P* waveforms. As he found out, the rupture extension branched upward from the lithospheric interface emerging as a trench axis, in a complex way through the wedge consisting largely of thick deformable sediments. Thus, a great sea depth, a large vertical component of rupture, and large loads of thick poorly consolidated sediments deforming the seafloor can result in extensive tsunamis though attenuate the energy of short-period waves used in M_S estimates.

Unlike other tsunamigenic shocks, the four mentioned earthquakes and other such events generated tsunamis that exceeded the expected intensity (see the $I(M_W)$ curve in Fig. 5, *b*). Each case of the lack of correlation between tsunami size and earthquake magnitude (both M_S and M_W) has to be carefully studied, because it may have such causes as an additional landsliding effect at the source.

Brief tsunami warning in the Russian Pacific coast

The tsunami warning service (TWS) is supposed to warn about the arrival time of a pending tsunami and its possible wave heights. This is feasible because seismic waves in the crust travel much faster than tsunami waves in the ocean (4–7 km/s against 0.1–0.2 km/s), and tsunamis lag 15–20 min behind the arrival of seismic signals to the station.

The Far East TWS was founded in 1958 and first came into action during the $M_S = 8.1$ Urup earthquake of 6 November 1958. The service was set up taking into account that the Kurile–Kamchatka islands are quite far apart while the sources of undersea earthquakes are closely spaced, which rules out the use of onshore tide stations for tsunami detection. Prediction was based on recording seismic waves which arrive 15–20 min before tsunamis. At that time no instant communication was available between three TWS seismic stations (in Yuzhno-Sakhalinsk, Kurilsk, and Petropavlovsk-Kamchatsky) and each had to issue warning independently, from its own records (Soloviev, 1968). For local events, warning was issued

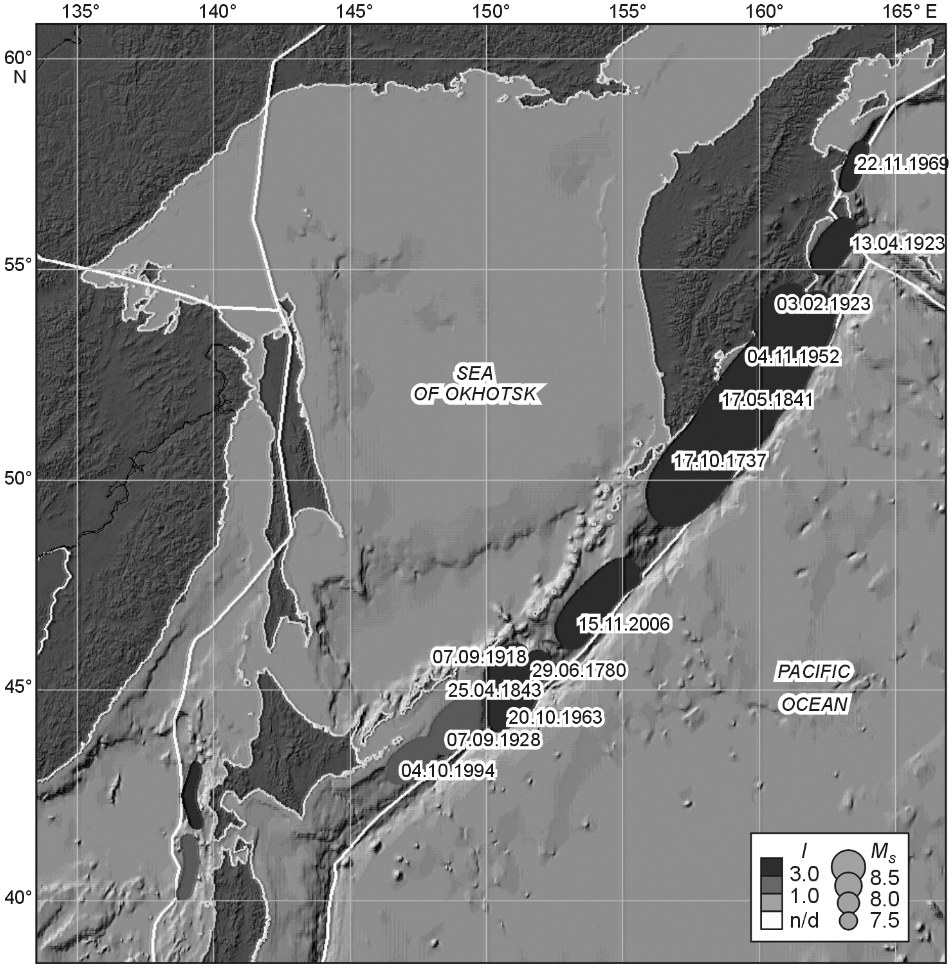

Fig. 4. Location map of significant tsunamis (Table 1).

when the epicenter fell into the zone of TWS responsibility and the magnitude exceeded $M_S = 7.0$, while warning for far-field Pacific events came from the Pacific Tsunami Warning System based in Honolulu (Hawaii).

However, the seismic method is insufficient for prediction of tsunamis given that their sizes may exceed those expected from the magnitudes of undersea earthquakes (Fig. 5). It is inevitably probabilistic, and the shares of false alert and missed tsunamis depend on chosen threshold magnitude of earthquakes. According to the theoretical estimate of Soloviev (1972), the true, false, and missed alerts must be related as 150:500:1, respectively, at the threshold magnitude $M = 7.0$. This estimate is consistent with the 50-year experience of regional tsunami prediction with the magnitude-geographic method (Gusiakov, 2010). With the criterion of wave height exceeding 0.5 m, fifty out of sixty seven warnings (75%) issued by TWS were false.

Generally, the Far East tsunami warning service has operated quite successfully, never missing hazardous events, and has gained much experience in prediction of near- and far-field tsunamis. The only fault is a high percentage of false alert, which brings people's discredit to the warning system and increases life risks in the case of hazardous tsunamis. Thus, the warning service should improve by reducing the number of false alert cases.

Another way of achieving better warning quality was mentioned in the early work by Soloviev (1968). The Pacific coast is unevenly populated, and ever more people are moving to a few cities from small villages along the coast. The tsunami hazard is the greatest in the villages of Ust'-Kamchatsk, Nikolskoye in Bering Island, Severo-Kurilsk in Paramushir Island, Yuzhno-Kurilsk in Kunashir Island, and Malokurilsk and Krabozavodsk in Shikotan Island, which are sheltered by quite a long shelf from the ocean side taking about 15 min of tsunami wave travel. Thus, it is reasonable to set up a reliable advanced warning system which would receive cable or radio signals from ocean bottom sensors deployed at the shelf edge or slightly farther offshore. The lead time in this case will be the same as in the seismic method.

Furthermore, it is necessary to estimate possible tsunami heights at specific points of the coast instead of the binary yes/no approach (hazard/no hazard). To begin, three levels can be distinguished (large tsunami/tsunami/possible or small tsunami) with respective countermeasures recommended for the rescue service and municipal authorities. The division can base on evaluating expected wave heights using the existing simulation techniques and the algorithms of prediction updat-

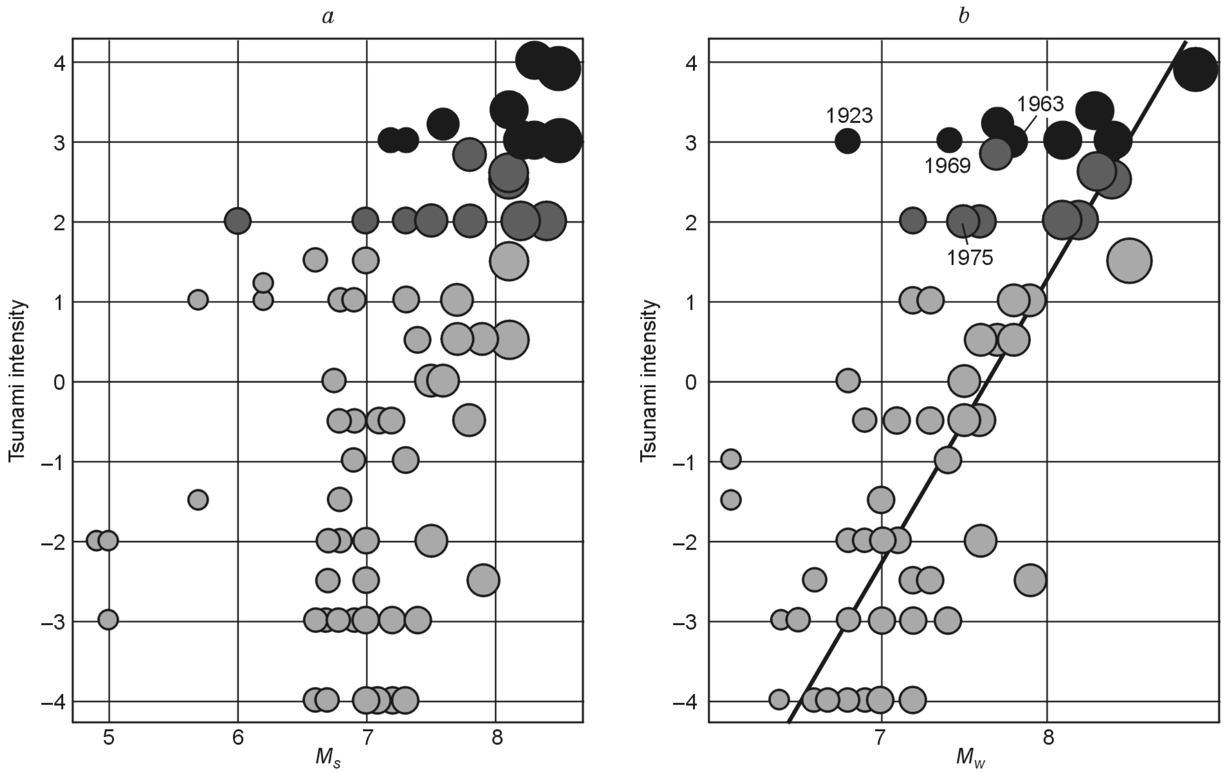

Fig. 5. Tsunami intensity (Soloviev–Imamura scale) vs. M_s (*a*) and M_W (*b*) earthquake magnitudes, for events in the Far East region from 1737 to 2015. Solid line in panel (*b*) is theoretical curve $I = -27.1 + 3.6M_w$ (Gusiakov and Chubarov, 1987). Dates are quoted for tsunami earthquakes listed in Table 2.

ing as far as data from progressively improving tide stations become available.

As for the prediction of far-field tsunamis, real hazard comes mostly from transoceanic teletsunami events triggered by great ($M = 9$) earthquakes. The Tohoku tsunami of 2011 induced up to 3.5 m waves (Shevchenko et al., 2012) in the western coast of Shikotan (Krabovaia Bay). In the 20th century, only two far-field events caused notable waves in the Russian Pacific coast: 3–4 m high throughout the Okhotsk coast and 5–6 m in the Kuriles and in eastern Kamchatka from the Chilean tsunami of 1960 and up to 1 m high in Paramushir Island from the Alaska event of 1964. However, two other devastating tsunamis in the Aleutian islands (in 1946 and 1957) had no impact. Note that seven out of nine teletsunami warnings between 1958 and 2000 were false. Therefore, the problem of far-field tsunamis requires special research using historic data and simulations, like the first attempt undertaken by Beizel et al. (2014). First, precise geographic constraints (Commander Islands in the east and Hokkaido in the south) should be placed on the tsunami sources to be assigned to the Kurile–Kamchatka catalog. In this respect, the decay of wave heights with distance of the tsunami source from the Russian Pacific coast has to be estimated proceeding from historic evidence and modeling of tsunami generation and propagation.

Tsunami risk mapping

In conclusion it is pertinent to discuss tsunami risk mapping based on preliminary assessment of long-term tsunami hazard expressed as expected wave heights and recurrence. Appropriate hazard assessment can ensure safe and sustainable life on vulnerable territories; choose proper strategies of their long-range development; and optimize protection countermeasures in the case of emergency, including choice of secure shelters and evacuation routes.

Long-term tsunami risk evaluation is similar to the assessment of seismic hazard, which currently follows the Prob-

Table 2. Parameters of tsunami earthquakes in Russian Pacific coast

Date and location	M_s	M_w	I	H_{max}, *M*	N_G	N_R
13.04.1923, Kamchatka	7.2	6.8	3.0	20.0	17	3
20.10.1963, Urup Island	7.2	7.8	3.0	15.0	47	31
22.11.1969, Ozernoi Cape	7.3	7.4	3.0	15.0	19	10
10.06.1975, Shikotan Island	7.0	7.5	2.0	5.5	116	30

Note. M_s is surface-waves magnitude; M_w is moment magnitude.

abilistic Seismic Hazard Assessment (PSHA) approach. This approach is used worldwide and makes basis for the project of overall seismic risk mapping (OSRM-2012) of the Russian territory (Ulomov, 2013). The project does not include tsunamis as a consequence of undersea earthquakes, though they pose major hazard to the Russian Far East, which is the most highly seismic region of the country, with 90% of all large earthquakes. However, the project results such as updated catalogs of historic earthquakes, data on source structure, and maps of earthquake nucleation zones for the tsunami-prone areas can and should be used for the assessment of tsunami hazard in the Pacific and other coasts of Russia.

There exists an elaborate advanced method of probabilistic tsunami hazard assessment (PTHA) (Gonzales et al., 2009) used broadly in the US, Canada, Australia, New Zealand, and Europe (Knighton and Bastidas, 2015; Leonard et al., 2014; Power and Downes, 2009; Power et al., 2011). PTHA is applied to map tsunami and inundation risks on different scales: the coast of a country as a whole, a city or a village, a harbor or a port. With all its natural and engineering pitfalls, the method is efficient and can be adapted to tsunami risk mapping of the Russian coasts.

PTHA includes probabilistic seismotectonic modeling of main tsunamigenic zones that pose hazard to the coast along with tsunami generation and propagation modeling aiming at estimating expected wave heights at specific sites on the coast (Gonzales et al., 2009). To account for high geographic variability of wave heights, especially along dissected coasts, the tsunami risk maps should be of 1:10,000–1:100,000 scales but such maps cover limited areas of 1–10 km. Thus, a generalized 1:2,000,000 to 1:4,000,000 map of large coastal areas based on seismotectonic modeling is indispensable to compare different coasts in terms of tsunami hazard and to make basis for more detailed mapping. Compiling such a map should be the first step in a large package of work on mapping expected inundation for specific cities and villages required for emergency mitigation measures and development strategies.

Conclusions

Tsunamis pose real hazard to many coastal areas of the Russian Far East, especially in the Kamchatka Peninsula and the Kurile Islands where runups reaching 15–20 m or higher have been repeatedly observed for the past 250 years. In Primoriye, hazardous 5–7 m waves can follow submarine earthquakes in the eastern Japan Sea. The Sea of Okhotsk is less hazardous but can experience 4–5 m waves induced by great Pacific teletsunami, including those at the Chilean coast.

The Far East regional catalog that includes 110 tsunamis for a period since 1737 is quite complete as to devastating and large events and can make basis for estimating the recurrence of large and small tsunamis in the region. Its improvement may lie mainly with updating the locations and energy estimates of tsunami sources, as well as with search for unknown historic tsunami evidence.

The catalog of wave heights in the Russian Pacific coast, with about 580 observations, is much less complete. Only 10% of events have been characterized by ten or more measurements sufficient for reliable evaluation of tsunami size; wave heights are unknown in 35 events, and their intensity can only be inferred from implicit data. This part of the catalog needs update based on all possible sources.

The division of the Far East region into three zones (Kurile–Kamchatka, Japan Sea, and Okhotsk Sea) is quite reasonable for the tsunami warning system: hazardous tsunamis have never transcended their generation zones over the whole period of observations.

The greatest problem in brief tsunami warning is that 75% of alerts are false. This percentage can be reduced due to additional hydrographic information from undersea cable and buoy stations which should protect at least large settlements of the Russian Pacific coast.

Prediction can be better if more rigorous geographic constraints are placed on the warning areas within tsunamigenic zones. These constraints should stem from analysis of observed wave heights within their limits and simulated tsunami propagation from sources of different locations and sizes.

Any development work in coasts vulnerable to tsunami requires assessment of long-term risks using detailed maps, with estimates of expected wave heights and inundation, for specific coastal areas, cities, harbors, and bays. This assessment can be more successful with a generalized 1:2,000,000 to 1:4,000,000 map of large coastal areas. It has not been complied yet, though there are earthquake and tsunami databases, as well as processing techniques and facilities available for this work.

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