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Numerical Simulation of the Action of Distant Tsunamis on the Russian Far East Coast

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Abstract—Results of a numerical simulation of the action of distant tsunamis on the coast of the Russian Far East are presented. It is shown that waves generated by focuses of the strongest M9 earthquakes in the region of South Chilean coast, as well as in the region of Papua New Guinea and Solomon Islands, are most dangerous for this coast. Other tsunamigenic zones of the Pacific Ocean, by virtue of their geographical position, orientation of focuses, and absence of pronounced channels (submarine ridges) along paths of tsunami propagation are not dangerous for it even at a limit magnitude of submarine subduction earthquakes. The simulation results are compared with historical data about manifestations of distant tsunamis on the Russian Far East coast.

Keywords: tsunami, submarine earthquakes, tsunami danger, tsunami zoning, numerical simulation

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INTRODUCTION

The main threat for the Far East coast of Russia emanates from the nearest submarine earthquake focuses positioned in the Kuril–Kamchatka seismogenic area and in the eastern part of the Sea of Japan. Since the 20th century, 95% of dangerous (with heights above 1 m) tsunamis, as well as tsunamis with human losses, were observed just from regional focuses. Nevertheless, the main part of this coast is subjected to the action of tsunamis from other tsunamigenic zones of the Pacific Ocean, first and foremost, from the Aleutian and South American zones.

In the 20th century, only one distant tsunami was really dangerous for the Far East coast. It was generated by the Great Chilean Earthquake of May 22, 1960, with a magnitude of $M_w = 9.5$, the largest ever recorded instrumentally. Waves from this tsunami crossed the whole Pacific Ocean for 22 h and reached the Russian coast with heights of up to 5–6 m in some bays open to the ocean side. In many places oscillations of the ocean level and currents caused by them resulted in extensive material damage. What is even more important, considerably high level oscillations with a range of 2–3 m were observed almost everywhere over the Far East coastline, including parts (western coast of the Sea of Okhotsk and Koryak coast in the Bering Sea) that are usually not affected even in cases of strongest regional tsunamis.

The magnitude threshold established by the Russian tsunami service (RTS) for emergency alerts in the case of distant tsunamis is at the level $M_w = 8.5$. According to this threshold, nine alerts connected with distant tsunamis were issued during the period from 1958 to 2010; seven of them turned out to be false. This statistics demonstrates that the problem of distant tsunamis requires special consideration based on numerical simulation and with the involvement of all available materials of historical observations.

The processing procedure for distant earthquakes significantly differs from that for regional events and takes into account the significantly larger time allowance before the arrive of waves, as well as the possibility of information interaction with the Pacific Tsunami Warning Center (Honolulu), which at present has a wide area network of level observations based on both coastal and bottom stations. Therefore, dangerous tsunamis from distant origins practically cannot pass unnoticed at present. However, the problem of forecasting maximum heights of waves on the shore and the time of reaching maximum oscillations at specific points of the coast, as well as the duration of the alert (determining the time for safe alert-status recall) remains topical for such tsunamis. With allowance for the large inhomogeneity of the tsunami wave field upon the transoceanic propagation, this is not a simple or trivial problem even with the available telemetric records of waves at intermediate island and bottom stations.

Part of the same problem is correctly establishing the eastern (in the region of Commander Islands) and southern (in the region of Hokkaido Island) boundaries of the geographical area in which the event is classified as regional (Fig. 1). This must be done both based on studying historical data and based on results of numerical simulation of the tsunami propagation from origins in these boundary regions.

ANALYSIS OF HISTORICAL DATA

The data available in Russian catalogs [1–3] and included into the database [4] on manifestations of distant tsunamis at the Far East coast of Russia are very scarce. Foreign databases, in particular the most important [5], supported by the NOAA's National Geophysical Data Center in Boulder, United States, are even less informative in this respect.

The strongest transoceanic tsunami of the 20th century, caused by the Great Chilean Earthquake of May 22, 1960, with $M_w = 9.5$, was observed throughout the whole coast of the Pacific Ocean. On the eastern coast of Japan, mean run-up heights amounted to 3–4 m with maximums of up 7–8 m; 114 people were killed and 90 unaccounted-for, 1233 houses were completely destroyed, and more than 3500 buildings were badly damaged [6]. On the Pacific side of the Kuril–Kamchatka coast, this tsunami was observed throughout its whole lengths with heights of 2–4 m. Maximum run-up heights reaching 7 m were measured at the eastern coast of Kamchatka in Morzhovaya and Russkaya bays [3]. Data on material damage and victims are absent in Russian catalogs. In [3], information about the manifestation of this tsunami on the Bering Sea coast of Kamchatka are presented; they indicate strong currents and flooding in off-loading territories of some fish factories, ejections of ice blocks to the shore, and damages of terminals and bridges at small rivers.

The tsunami passed through Kuril straits to the Sea of Okhotsk and caused considerable oscillations for more than 2 days. The mareograph in the Nagaev bay detected five waves with heights of up to 2.2 m [7]. The wave height on the coast of Sakhalin turned out to be significantly less and amounted to 1.2 m in Korsakov, 0.8 m in Poronaysk, 0.6 m in Katangli, 0.4 m at the Cape Crillon, and 0.1 m in Kholmsk [2].

The second strongest transoceanic tsunami of Alaska in 1964 ($M_w = 9.3$) weakly manifested itself in the Far East coast of Russia. The maximum height of the level elevation was 1 m (in Podgornyi village at the eastern coast of Paramushir Island); the mareograph recorded waves with a height of 0.8 m in Severo-Kurilsk and 0.7 at Shumshu Island (Babushkino village) [2]. At Sakhalin, maximum oscillations were detected in Korsakov (0.4 m). Data on manifestations of this tsunami over the coast of Okhotsk are absent.

The third strongest Pacific tsunami of the 20th century (Aleutian of 1946), which appeared after a moderate earthquake (its originally determined magnitude was only 7.4), did not manifest itself anywhere on the Far East coast of the Russian Federation. The possible cause of this is the pronounced directionality of energy radiation of this tsunami: a narrow energy maximum went to Hawaii and the Marquesas Islands [8]. Data on the manifestation of another transoceanic tsunami (Aleutian of 1957, $M_w = 9.1$) for this coast are also absent.

The last strongest Pacific tsunami (Tohoku, March 11, 2011) caused dangerous level oscillations lasting more than one day at some places on the eastern coast of Kuril Islands and Kamchatka. Maximum wave heights (up to 3 m) were observed in Krabovaya bay at the western shore of Shikotan Island; at its eastern coast, run-up heights did not exceed 1.5 m. In Malo-Kurilsk the mareograph recorded oscillations with a range of up to 2.3 m [9]. The maximum run-up in Severo-Kurilsk (Paramushir Island) reached 2.5 m; in Burevestnik (Iturup Island) it was 2 m. In the basin of the Sea of Okhotsk, only background-level oscillations were observed: the maximum heights of waves, according to mareograph records, were 0.53 m (Kurilsk), 0.42 m (Korsakov), and 0.44 m (Poronaysk). The mareograph in the Nagaev bay on March 12–14 recorded several waves with a maximum amplitude of 1.1 m [10]. The cause of small level oscillations in the Sea of Okhotsk is the position of its basin very much out of the way of the principal maximum of energy propagation oriented to the southeast.

As was mentioned above, South American tsunamis are a real threat for the Far East coast of the Russian Federation. The global databases [4, 5] contain information about 17 destructive tsunamis that occurred near the South American coast during the whole time of historical observations (1500–2013). Among them, at least eight events are mentioned in [11] as causing dangerous (with a height of more than 1 m) tsunami waves on shores of Japan. Unfortunately, corresponding historical data on the Kuril–Kamchatka coast are absent. However, based on model representations of the propagation of transoceanic tsunamis and on observations of the tsunami of 1960, one can suppose that average heights of waves of South American tsunamis at the Japan and Kuril–Kamchatka coasts are approximately the same.

Using the available data, one can estimate the average period of repeatability in observations of South American tsunamis with heights of 2 m and higher near Japanese coasts. Over a period of 400 years (from 1586 to 1995), this turns out to be 58 years, which is less than the expected period of repeatability for strong (with a magnitude of 7.5 and higher) submarine earthquakes in an individual seismotectonic block of the Kuril–Kamchatka seismogenic area, 140 ± 50 years

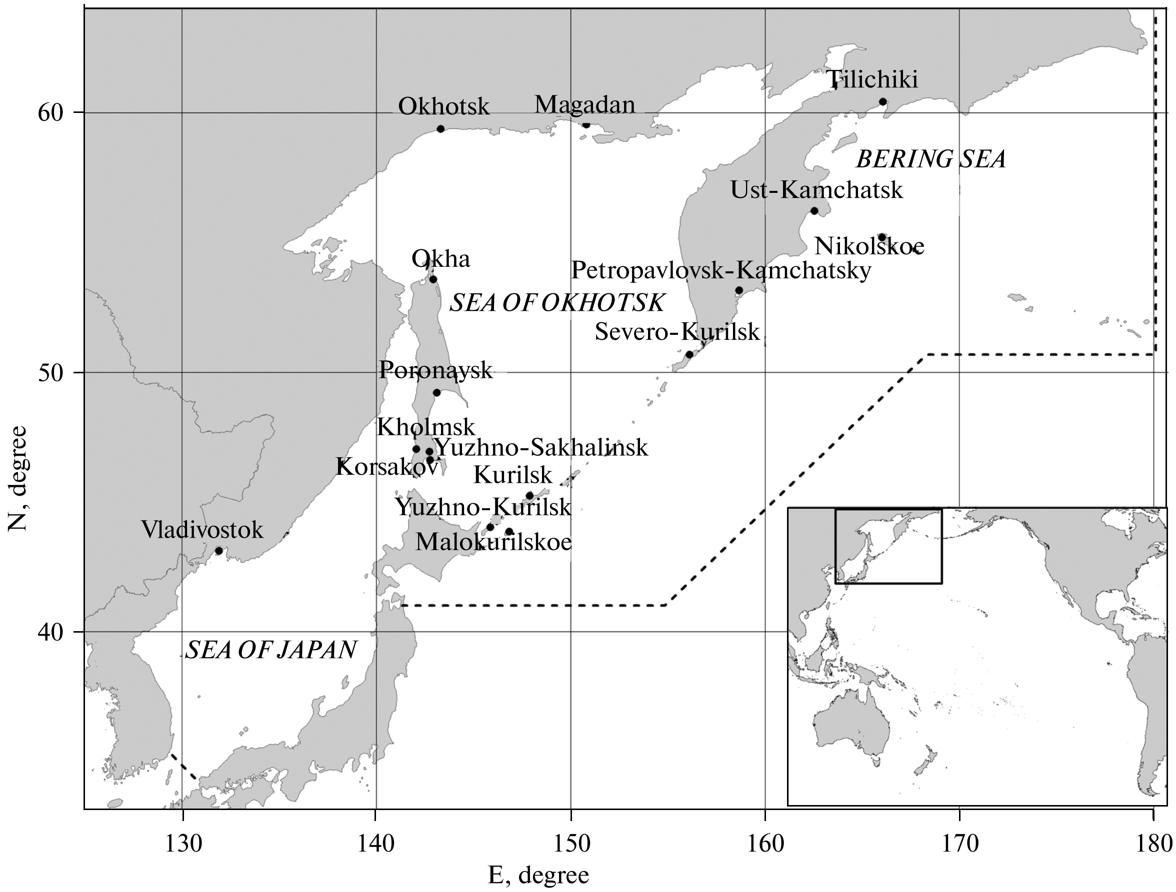


Fig. 1. Schematic map of the Russian Far East coast and contiguous waters with an indication of settlements mentioned in the text. The dashed line shows the boundary of the region within which a tsunamigenic event is considered "regional." The insertion at the bottom to the right shows the position of the depicted region in the schematic map of the Pacific.

[12]. It follows that the threat of distant tsunamis for the Far East coast of Russia is at least comparable with that from neighboring regional earthquakes. The maximum possible heights of waves from such distant earthquakes are unlikely to exceed 9–10 m; however, in contrast to regional tsunamis, which have dangerous action on a restricted part of the shore (the first hundreds of kilometers), distant tsunamis can manifest themselves almost along the entire Far East coast of Russia, including coasts of the Okhotsk and Bering seas. For peripheral seas not having active seismogenic areas inside them, distant tsunamis make a considerable (if not the main) contribution to the total tsunami hazard for the coast.

SEISMOGENIC TSUNAMI SIMULATION TECHNIQUE

Traditionally, the tsunami dynamics is described using approximate shallow-water models based on the hypothesis that the characteristic vertical scale is smaller than the horizontal scale. The specific form of the representation of the used system of equations and allowance for additional factors (Coriolis and bottom friction forces) is determined mainly by the aim, character, and spatial scale of the solved problem. A correct numerical implementation of equations of the mathematical model and boundary conditions at free (marine) and reflecting (shore) boundaries permits one (in the presence of adequate bathymetric data) to perform calculations of the tsunami propagation in calculation domains that are rather complex in the coastline configuration and depth distribution for simulating real basins of the World Ocean. According to results of test calculations and comparisons of numerical results with materials of field observations, these models quite reliably reproduce the characteristics of tsunami waves travelling over the ocean and parameters of their manifestation in the coastal area.

The so-called "piston model" is used for the model of tsunami excitation in such calculations. This model is based on introducing vertical motions of the basin bottom into the continuity equation. They are identified with residual coseismic displacements of the ocean bottom in the region of origin of the submarine earthquake. Such displacements are usually calculated by formulas derived in [13] and representing residual (static) displacements of the surface of a homogeneous elastic half-space under the action of an internal spatial dislocation-type source. In this work we used similar formulas obtained by V.K. Gusiakov in [14] 7 years earlier than Y. Okada. In spite of differences in the representation of final expressions for displacement components in [13, 14], numerous tests showed a complete correspondence in values of calculated displacements at any sets of parameters of the model origins.

Displacements calculated for a plane boundary of a homogeneous half-space are superimposed on the real bottom relief in the region of the origin; the appearing additional perturbations (e.g., violation of the stability of continental slopes) and the contribution of the horizontal component of bottom displacements are as a rule neglected. Bottom displacements are considered to appear instantaneously (more exactly, during one time step of the numerical scheme) because the real duration of motions in origins of submarine earthquakes (50–100 s, with the exception of maximally strong events that have a significantly longer process in sources) is still smaller than typical periods of tsunami waves (5–15 min for regional tsunamis and up to 30–40 min in the case of strongest transoceanic tsunamis). This approach to simulating tsunamis is at present commonly accepted and is applied in the overwhelming majority of works carried out in Russia and abroad on tsunami calculations at specific parts of the World Ocean basin.

Results of tsunami calculations presented in this work were obtained based on the STATIC program, which implements the algorithm for calculating residual displacements and MGC software package implementing MacCormack type computational schemes approximating classical equations of a nonlinear shallow water system written in the spherical coordinate system [15, 16].

As an example of results obtained in this approach, Fig. 2 presents energy maps for model origins with magnitudes M_w = 7.8, 8.4, and 9.0 positioned in the region of the Krusenstern strait (the largest strait of the Kuril Ridge) separating the Raikoke and Shiashkotan islands. For each point of the calculation domain, such diagrams show the spatial distribution of tsunami amplitude maximums reached during the whole computation time and yield an easy-to-interpret picture of tsunami energy radiation by the earthquake origin and its further evolution during propagation in the ocean. The energy maps presented in Fig. 2 illustrate the aforementioned capability of tsunami that are generated by M9 megaearthquakes to penetrate basins of peripheral seas and cause dangerous oscillations on their coasts, which are usually not of concern in cases of tsunamigenic earthquakes with a lesser magnitude.

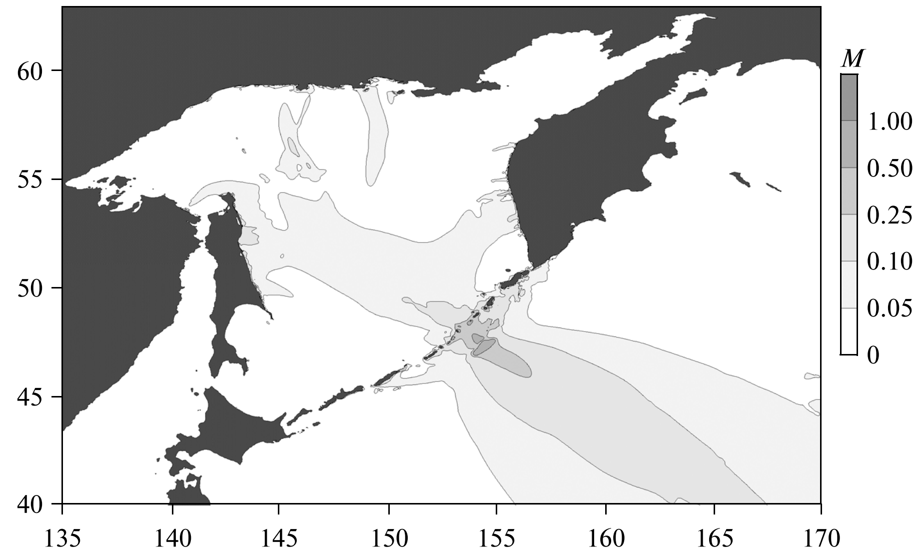
CHOOSING TSUNAMIGENIC ZONES AND PARAMETERS OF MODEL EARTHQUAKES

An analysis of the ITDB/WLD database content [4] for the Pacific Ocean shows that, during the period from 1900 to the present day, when the historical catalog can be considered complete, even with regard to weak tsunamis, submarine earthquakes are responsible for 84% of all tsunamis occurring in this period. Other tsunamis are divided between earthquakes due to collapse (landslides) (5%), volcanogenic (4%) and meteorological (2%) tsunamis; the source of up to 5% of tsunami observations is still unidentified. Among transoceanic events, the overwhelming majority of them was caused by very strong subduction earthquakes with magnitudes of 9.0 or higher [17]. The experience of studying the aftermath of the tsunami after the explosion of the Krakatau volcano in 1883 shows that strongest volcanogenic tsunamis have a devastating effect on the coast only in close proximity to the source (at a distance of no more than 200–300 km) and cannot create dangerous level oscillations in the far zone. It follows that one can restrict oneself only to cases of seismogenic tsunamis when considering the threat of distant tsunamis for the Far East coast of the Russian Federation.

By virtue of the aforementioned prevalence of such tsunamis in the Pacific Ocean, the main tsunamigenic zones here always coincide with the position of seismically active zones forming the so-called circum-Pacific Belt, within which 99% of Pacific earthquakes occur. As follows from the analysis of historical data on manifestations of distant tsunamis at the Far East coast of Russia, only earthquakes with a magnitude of 9.0 and higher seem to be really dangerous for it. Proceeding from these considerations, seismogenic zones of the Pacific Ocean were approximated by a system of model origins of submarine earthquakes with a magnitude M_w = 9.0. Every origin was a rupture area with a length L = 430 km and width W = 150 km with a movement magnitude over it D_0 = 11.6 m. The seismic moment is $M_0 = 3.6 \times 10^{29}$ n m, which corresponds to a magnitude of M_w = 9.0 according to H. Kanamori's correlation relationship $M_w = (\log M_0 - 16.1)/1.5$ [18].

Parameters of model sources were chosen proceeding from fundamental understandings of subduction earthquake mechanisms following from the concept of oceanic platform subduction under continental platforms in the region of active continental margins. In most cases, the trend azimuth of the rupture plane was determined by the coastal (island) indentation and the angle of incidence of the rupture area was chosen to coincide with the main lithospheric interface between the prograding continental platform and downgoing oceanic crust; this angle varied in a range from 10° to 45°. The movement direction over the rupture plane in all cases with the exception of origins in the region of the westernmost tip of the Alaska–Aleutian zone was

(a)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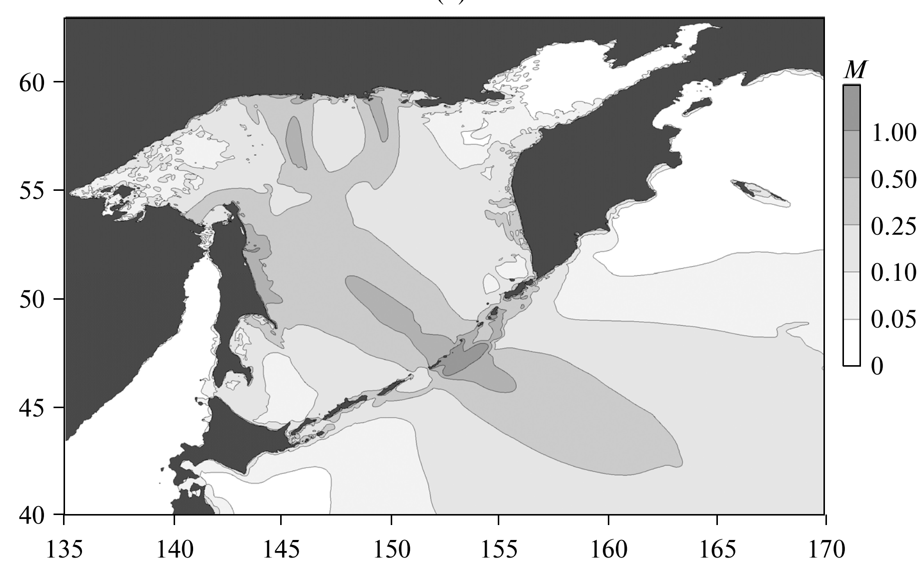
(b)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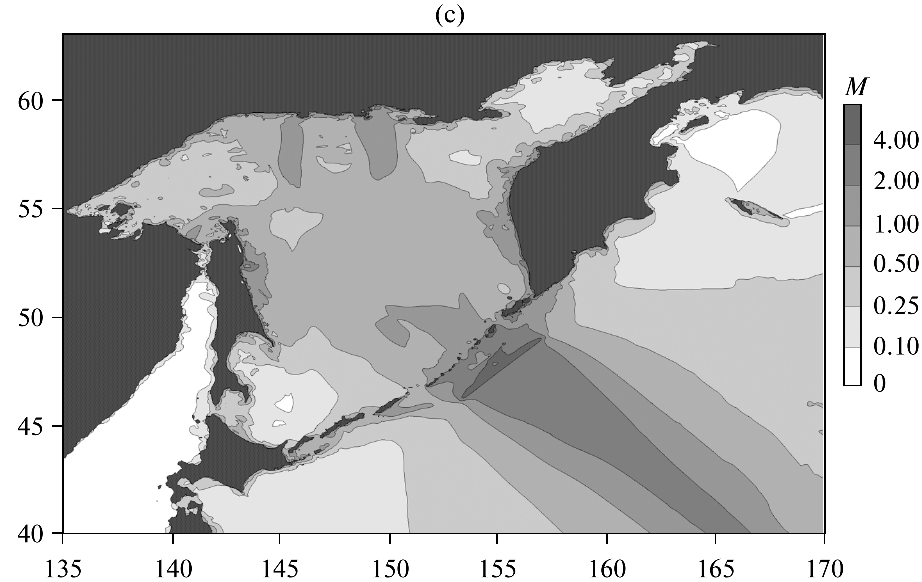
(c)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170

Fig. 2. Distributions of maximum positive wave amplitudes calculated for model origins with magnitudes M_w = (a) 7.8, (b) 8.4, and (c) 9.0 in the region of the Krusenstern Strait.

taken to be equal to 90°, which corresponds to the most tsunami-dangerous version of the origin mechanism: thrust or upthrust (for west Aleutian origins it was taken to be 15°). The depth of occurrence of the upper edge of the rupture was assigned in a range of 10–20 km. The used set of model earthquakes corresponds to local seismotectonic particularities not in all tsunamigenic zones; however, in the considered case, the differences seem to be insignificant when compared to the influence of the orientation of origins and tsunami propagation paths.

The constructed set of 94 model sources is shown in Fig. 3. Origins 1, 2, and 86–90 are "boundary" and "close" for the Russian Far East coast. They are included into the constructed system of origins for the total covering of all seismically active zones of the Pacific Ocean, which allows one to obtain a comparative quantitative estimate for expected wave heights from distant and near origins at any point of the protected coast.

To perform a quantitative analysis of the relative tsunami threat from different origins, 693 virtual mareographs were arranged along the entire Far East coast of Russia. The mareographs stored total calculated marigrams in the process of calculations. Among them, 82 mareographs were positioned at grid points nearest to the "protected" points (including seaside towns and villages of Primorye, Kolyma, western and eastern coasts of Sakhalin, Kuril Islands, and Kamchatka). Additionally, 611 mareographs were arranged in boundary "sea" points distributed along the shore at a distance of 20–30 km from each other.

The propagation of tsunami from distant origins was simulated in a computational "Pacific" basin that extends from 100° E to 60° W and from 60° S to 65° N on a computational grid with a step of 2 angular minutes. The grid was constructed based on the well-known 1-min GEBCO bathymetric array [19]. All calculations on simulating the propagation of tsunami generated by distant origins were performed in 48 h of physical time of wave propagation.

As a result of a series of scenario calculations intended for estimating the relative tsunami threat for the Russian Far East coast from different tsunamigenic zones of the Pacific Ocean, a large amount of computational material was obtained. It included the following groups of data:

(1) Calculated marigrams at locations of virtual mareographs;

(2) Distributions of extreme (maximum positive and minimum negative) wave amplitudes at locations of virtual mareographs;

(3) Energy charts: distributions of maximum positive and minimum negative wave amplitudes at all points of the calculated basin;

(4) Distributions of detection times of first arrivals (expected tsunami arrival, ETA) at location points of virtual mareographs and at all grid points;

(5) Distributions of detection times of maximum positive and minimum negative wave amplitudes (expected tsunami maximum, ETM) at location points of virtual mareographs.

The last two characteristics are as important as calculated dynamical parameters of the tsunami (maximum amplitudes and wave heights and maximum range of level deviations). The simulation result shows that the difference between ETA and ETM for distant tsunamis at some points of the Okhotsk and Bering Seas (and, to a lesser extent, the Sea of Japan) can reach tens of hours, which is very significant for constructing correct algorithms of RTS actions. An analysis of complete calculated marigrams is also important for determining the time of alert recall, because the monotonic descent of oscillation amplitudes even for several hours does not guarantee the impossibility of their new rise with reaching dangerous values in the case of distant events. Such a rise can appear as a result of the interaction between edge waves generated by tsunami and intrinsic oscillations that are also initiated in closed and semiclosed basins of peripheral seas by tsunami waves arriving from the open ocean.

ESTIMATE OF THE TSUNAMI THREAT FOR THE FAR EAST COAST OF RUSSIA BY RESULTS OF NUMERICAL SIMULATION

An analysis of calculated wave heights in coastal points of the Far East coast shows that origins from different zones cause significantly different level oscillations at the same points even at a similar magnitude of model earthquakes. For an integral energy characteristic of the dangerous affect of a specific origin on the entire Far East coast on the whole, a quantity E defined by the formula

$$E = \sum_{i=1}^{N} A_i^2,$$

was introduced. Here, A_i is the sum of absolute values of the maximum and minimum level values generated by the model origin at the i-th computational point during the whole computation time and N is the number of virtual mareographs. The quantity E calculated over all 693 virtual mareographs positioned along the entire Russian Far East coast can serve as an analog of the tsunami energy fraction arriving at this region from

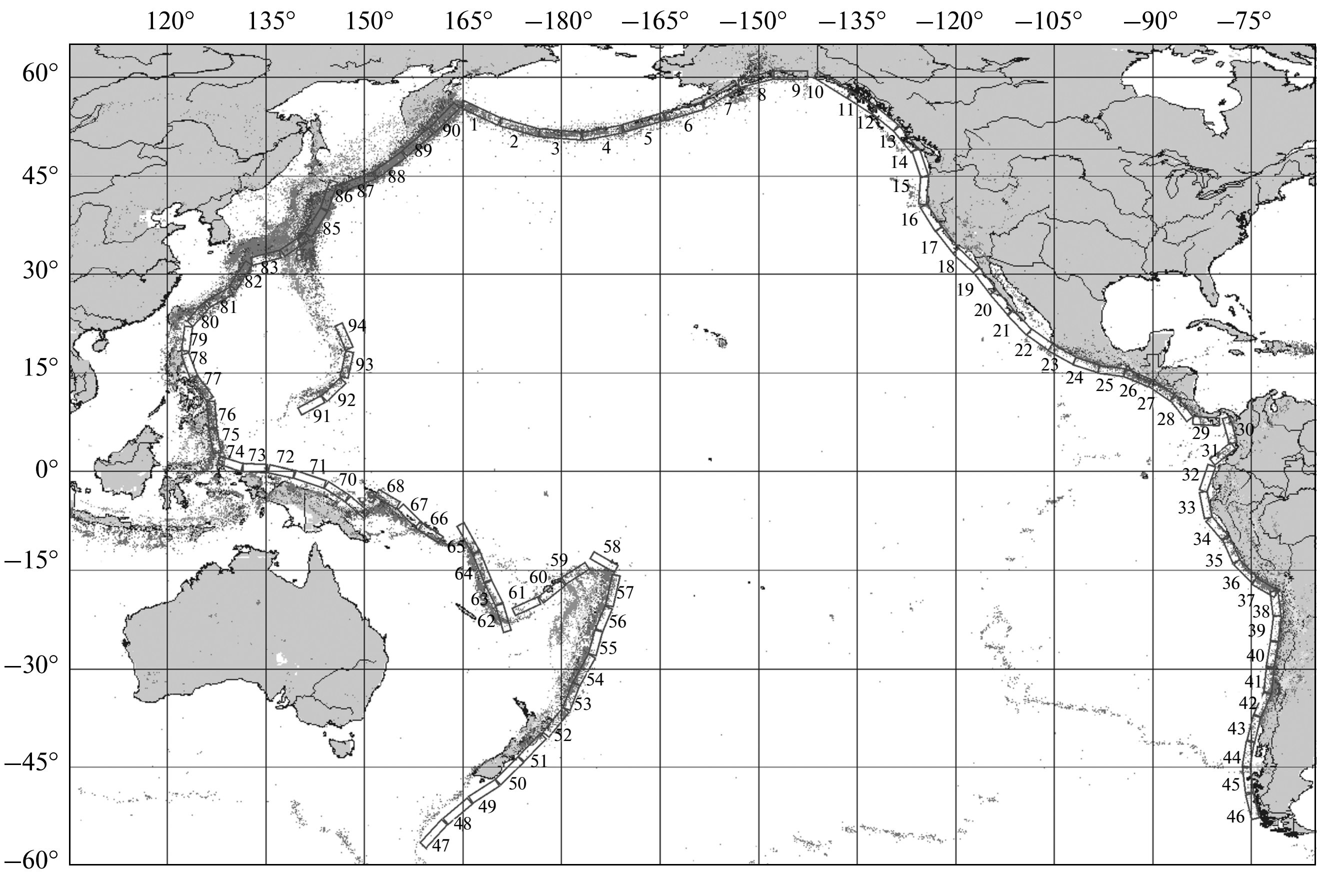

Fig. 3. Pacific Ocean seismicity map constructed by data of global seismic catalog for 1900–2013 [4] with projections of rupture areas of model origins of submarine earthquakes with magnitudes $M_w = 9.0$. The labels near areas are numbers of model origins mentioned in the text.

a specific source; based on this fraction, one can compare the relative tsunami threat from different origins. Figure 4 presents the distribution of this characteristic; it was calculated for all model sources shown in Fig. 3.

As is seen from the behavior of the quantity E, the action of origins of strongest tsunamis on the Russian Far East coast is extremely irregular. As was mentioned above, the highest priority hazard for the coast is earthquakes located directly in the Kuril–Kamchatka seismogenic zone (origins 87–90), as well as Aleutian origins 1–3. The height of waves from them exceed maximum heights created by origins from distant zones by a factor of 4–5.

As the origins shift to the East (along the Aleutian island arc), the calculated quantity E rapidly decreases (origins 4 and 5) and then remains approximately at the same level up to the northern coast of Chile with minimum values for Mexican origins 23–25, for which the main radiation maximum is directed to Antarctica. With a transition from one origin to another, the energy characteristic E behaves rather monotonically; this permits one to interpolate data from neighboring origins in the case when a real earthquake occurs in the interval between them. The exception here is the Canadian origin 12, the minimum tsunami threat from which can be explained by the fact that most of its wave energy is blocked in the Hecate Strait between the continent and Haida Gwaii archipelago.

The calculated heights begin to increase for Chilean sources approximately from 30° S when the principal maximum of energy radiation is directed to the northwestern part of the Pacific Ocean. An example of an energy map for one of these sources (no. 45) is presented in Fig. 5. The largest wave heights at the Russian coast appear from origins 44 and 45 located near the southern coast of Chile. Here it should be recalled that the catastrophic Chilean earthquake of 1960 with a magnitude of 9.5, which caused dangerous waves throughout the entire Russian Far East coast, occurred in region of origin 42, which is behind its southern neighbors (origins 44 and 45) in the relative tsunami threat approximately by a factor of 2.

Thus, based on the analysis of quantity E used as an integral energy characteristic of the relative tsunami threat of different origins, one can state that the South Chilean earthquake origins constitute a menace for the Far East coast quite comparable to that carried by much closer earthquakes in the western part of the

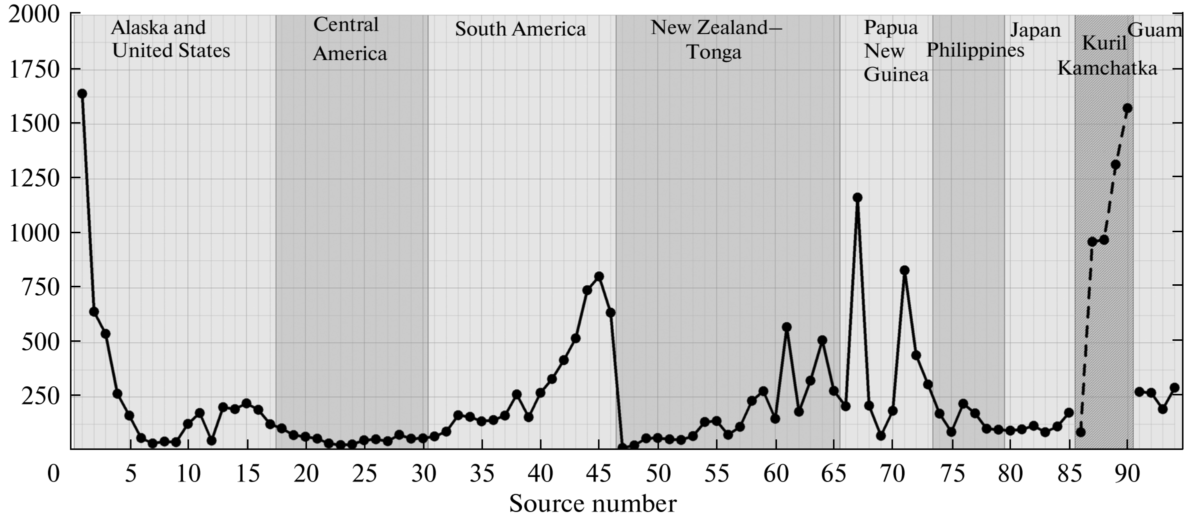

Fig. 4. Integral energy characteristic of the action of different tsunamigenic earthquakes origins on the Far East coast of Russia. On the horizontal axis, the number of the model origin (in correspondence with that in Fig. 3) is plotted; on the left vertical axis is the quantity E. On the right axis the same quantity is plotted in another, five-fold decreased, scale related to origins 86–90 (the Kuril–Kamchatka group).

Aleutian ridge. Here, however, it should be recalled that the discussed characteristic is an integral value calculated over all coastal points of the protected coast and its small value does not exclude the possibility for the existence of dangerous heights at a certain bounded part of the coast. Aleutian origins constitute the highest menace for the eastern coast of Kamchatka and northern part of Kuril Islands, which protect other parts of the Russian Far East from the action of these origins to a considerable extent. At the same time, waves from South Chilean origins rather freely pass through Kuril straits to the Sea of Okhotsk, where they cause dangerous (with an amplitude of up to 2 m) oscillations on the eastern coast of Sakhalin, on the coast of Kolyma, and in western Kamchatka. For the western coast of Sakhalin Island and all of Primorye, these origins are not dangerous.

In passing to the western coast of the Pacific Ocean, the tsunami threat sharply decreases (origins 47–57 in the New Zealand–Tonga region). The increase in the threat begins from origin 58, the radiation diagram of which is oriented to the northern part of the ocean. With a further consideration of origins along seismogenic zones in the western part of the Pacific Ocean, the tsunami threat begins to increase, but the characteristic E behaves nonmonotonically with significant jumps when passing from one origin to another. This can be explained by the presence of a large number of islands and island archipelagos in this part of the ocean; they accumulate the wave energy in the contiguous waters. The quantity E takes its maximum value for origins 67 (Solomon Islands) and 71 (New Guinea). Their tsunami threat for the Russian Far East coast exceeds the threat from South Chilean origins 44–46 in their "integral" action. The energy map for origin 67 is presented in Fig. 6.

The further movement of model origins to the North along the Philippine and Japanese seismogenic zones again leads to a decrease in their tsunami threat until they directly approach the southern boundary of the Far East region. For origins 85–86 (the Tohoku–Hokkaido region), the sharpest jump of the integral characteristic E occurs; it marks the transition of origins from the far impact area to the near impact area.

Analysis of the obtained calculated mareograms and kinematic characteristic of tsunami verifies the fact known from observations: for distant tsunamis, maximum level oscillations in many points occur much later, sometimes after tens of hours after the arrival of not only the head wave (ETA time), but also of the energy maximum (ETM time) expected with allowance for the frequency dispersion inside the wave packet.

The results correspond to known ideas about several physically different processes taking place in the case of transoceanic tsunamis. The first is the process of the dynamic propagation of the initial wave packet radiated by the origin. The second is the process of shaking the entire Pacific Ocean as a unified but configurationally very complicated basin; the process can last for several days after the injection of considerable energy into this oscillatory system. The third process is connected with the appearance of edge waves and intrinsic oscillations of peripheral sea basins; the oscillations are excited by tsunami waves arriving from the open ocean.

In the case of South Chilean origins 45 and 46, the radiation maximum of which is oriented to Japan,

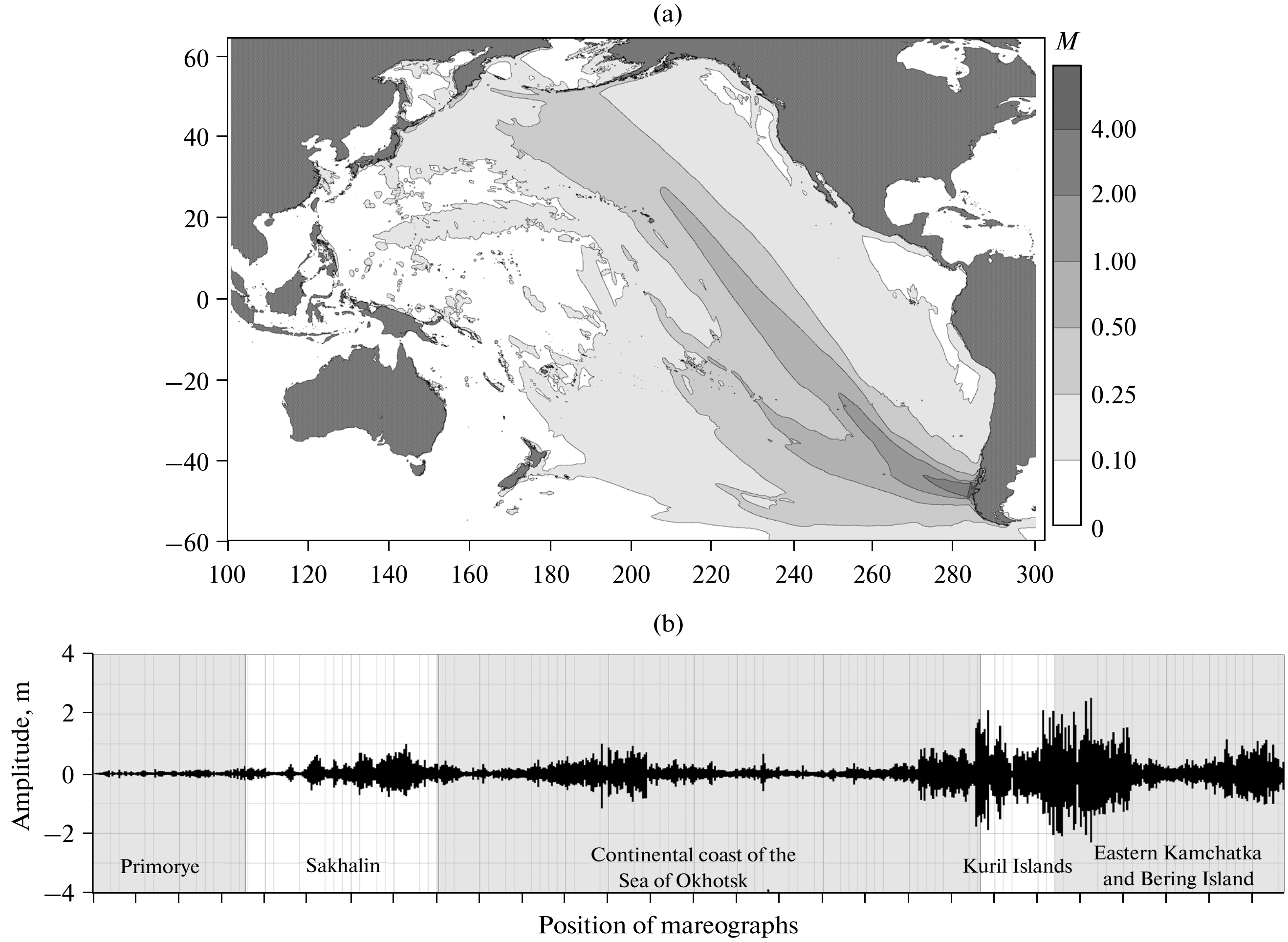

Fig. 5. Distribution of maximum positive wave amplitudes for South Chilean origin 45 and corresponding histogram of maximum positive and maximum negative wave amplitudes along the Far East coast of the Russian Federation.

Kuril Islands, and Kamchatka, the instant of the maximum wave arrival approximately corresponds to calculated ETA times plus 2–3 h. Maximum oscillations on the Sakhalin and Koryakia coasts occur 1 day after the arrival of the head wave. This indicates the fact that resonance oscillations of peripheral seas (Okhotsk and Bering) are involved in the process.

In the case of Central American origins oriented to the southeastern part of the Pacific Ocean, maximum oscillations at almost all points of the Russian Far East are provided by the aforementioned shaking of the entire ocean basin and occur much later than ETA (by 24–48 h). The instants of maximum positive and maximum negative displacements of the level do not correspond in time and can be also separated by tens of hours.

Origins in the regions of the Aleutian Islands and New Guinea are a somewhat intermediate situation. In this case, part of the protected coast appears to be in the zone affected by lateral leafs of the energy map of the sources. Correspondingly, the maximum amplitude at such points occurs shortly after ETA; at other coastal points, maximums are provided by the following shaking of the basins of peripheral seas.

Estimating the lower boundary for magnitudes of model earthquakes that are most dangerous for the Russian Far East coast (with origins in the region of South Chile and New Guinea) is also an important problem. To solve it, an additional series of calculations was performed for the most dangerous origins with lesser magnitudes, the epicenters of which coincided with those of sources 45, 67, and 71 with a magnitude of 9.0. In addition to epicenter coordinates, the determining angles of the earthquake mechanism were preserved; the values of the size of the area and movement along it varied in correspondence with the value taken of the magnitude M_w.

The calculation results verify that a magnitude of 9.0 is a kind of a threshold value for the appearance of a real threat to the Far East coast in the case of distant origins. Even when it decreases by 0.2 (up to a magni-

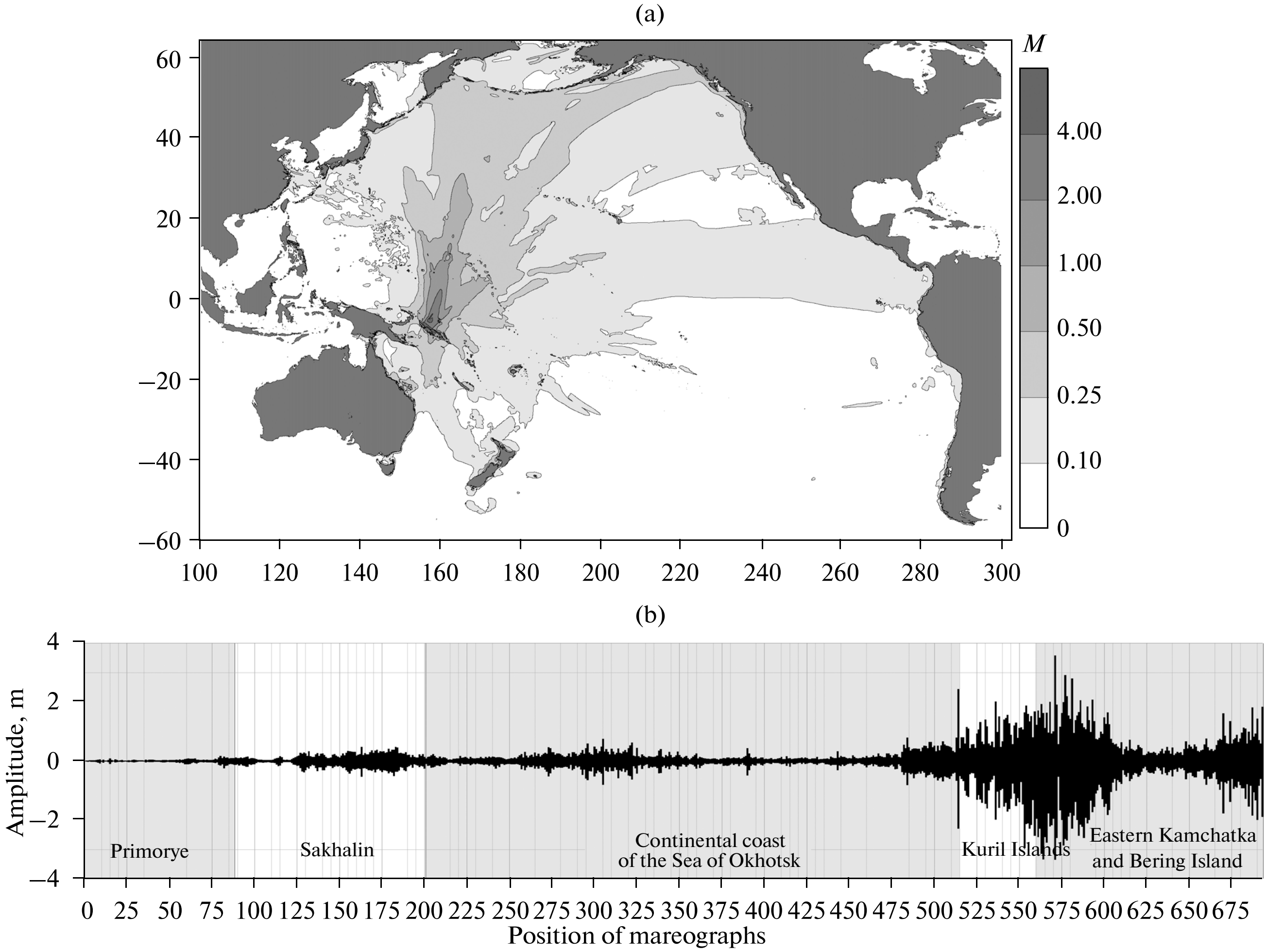

Fig. 6. Distribution of maximum positive wave amplitudes calculated for origin 67 (the region of Solomon Islands) and corresponding histogram of maximum positive and maximum negative amplitudes along the Far East coast of the Russian Federation.

tude of 8.8), the calculated wave heights become less than 2 m and drop to several tens of centimeters with a further decrease in magnitude (on average, by two times as the magnitude decreases by 0.2).

This series of calculations verifies the conclusion that, even in most dangerous Pacific tsunamigenic zones (South American and New Guinean) with regard to the geographical position, the real threat for the Russian Far East coast comes from only ultimately strong submarine earthquakes with a magnitude of 9.0 or higher; at the same time, there must be an origin mechanism corresponding to the underthrust along the main lithospheric interface in subduction zones. All other possible origin mechanisms (e.g., in the presence of a significant shear component), as well as deep-focus earthquakes (with depths of more than 100 km), cannot create a dangerous tsunami even at ultimately possible magnitudes.

CONCLUSIONS

According to the analysis of historical data and numerical simulation of the distant tsunami action on the Russian Far East coast, one can state the following conclusions.

(1) The action of tsunamis from distant origins on the Far East coast of Russia is highly irregular and is determined both by the position of the origins and their orientation with respect to this coast and by elements of the submarine ocean relief along the propagation path of the main energy maximum. In addition to this, wave heights strongly vary along the coast itself, depending on its type (open oceanic coast, western coast of the island arc, and coasts of interior seas).

(2) The most dangerous origins for the Far East coast of Russia are those positioned in the South Chilean zone (to the south of 30° S). By virtue of the specificity of the mutual position of the source and affected area (a distance of almost 180°, which leads to a noticeable convergence of the tsunami front when

propagating on the sphere), the strongest South Chilean tsunamis have the strongest action on the coast of Japan, Kuril Islands, and Kamchatka. An additional amplifying factor, when compared to all other tsunamigenic zones of the Pacific Ocean, is also the presence of an abrupt coast and steep continental slope near South American shores, which are very efficient reflectors of tsunami energy.

(3) Another potentially dangerous tsunamigenic region is the Solomon Islands–Papua New Guinea region. The orientation of some submarine earthquakes in this region is such that the Kuril–Kamchatka coast turns out to be in the range of the origin energy radiation maximum; then the radiation can be amplified by the focusing action of submarine relief elements. The absence of historical data on the strongest M9 earthquakes in this zone does not mean (according to the latest knowledge about the seismotechnique of subduction zones [20, 21]) that they will not appear.

(4) In open ocean side regions of the Far East coast of Russia, the arrival of maximum tsunami amplitudes as a rule coincides with calculated ETA times, i.e., with the arrival time of the main wave packet directly from the origin region. However, for a much more extended coast of peripheral and interior seas (Japan, Okhotsk, and Bering), maximum level oscillations can begin 10 h after the expected time of the head wave arrival. This fact complicates the regimentation of the alerting and alert-recall procedures in the case of distant events.

(5) An analysis of the statistics on alerts for distant tsunamis and results of the performed simulation shows that the threshold value of the magnitude $M_w = 8.5$ accepted now for alerting seems underestimated. The real danger for our coast appears only upon earthquakes with a magnitude of $M_w = 9.0$ and higher in some tsunamigenic zones. Taking into account the possible error in rapid determination of the magnitude (which can reach 0.3–0.5), one can recommend a magnitude of $M_w = 8.5$ as the threshold value for alerting when processing distant earthquakes. The direct tsunami alerting and execution of protective measures, in particular, evacuating the population from the near-shore zone, must be performed when receiving data about really dangerous wave heights detected at the intermediate island and bottom stations.

(6) The risk of missing a strong tsunami from a distant source is at present minimized owing to developed communication tools and international data exchange implemented in the scope of the International Coordination Group for the Tsunami Warning System in the Pacific of the Intergovernmental Oceanographic Commission of UNESCO. For such events, however, the problem of forecasting maximum wave heights, times at which these maximums are reached at specific coast points, and the duration of the alert status (determination of the time of safe alert recall) still remains.

(7) The presence and real-time availability of data from deepwater tsunami detectors of the DART system does not remove the problem of false alerts, because there is no direct dependence between tsunami amplitudes on deep water and maximum run-up heights overwashes in specific coast points. Here, special works should be carried out on determining most informative detectors and establishing such a dependence on specific “source–protected coast” paths.

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REFERENCES

1. S. L. Solov’ev and M. D. Ferchev, “Summary data on tsunamis in the USSR,” Bull. Sov. Seismol. Akad. Nauk SSSR, No. 9, 23–55 (1961).
2. S. L. Solov’ev, “Basic data on tsunamis on the Far East coast of the USSR (1937–1976),” in *Tsunami Research in the Open Ocean* (Nauka, Moscow, 1978), pp. 61–136 [in Russian].
3. Yu. A. Zayakin, *Tsunamis on the Far East Coast of Russia* (Kamshat, Petropavlovsk-Kamchatsky, 1996) [in Russian].
4. CD-ROM Integrated Tsunami Database for the World Ocean (ITDB/WLD), 2000 BC to Present (Tsunami Laboratory, ICMMG SD RAS, Novosibirsk, 2014). http://tsun.sscc.ru/nh/tsunami.php.
5. NOAA/WDS Global Historical Tsunami Database (National Geophysical Data Center, Boulder, USA, 2014). http://www.ngdc.noaa.gov/hazard/tsu_db.shtml.
6. *The Chilean Tsunami of May 24, 1960, as Observed along the Coast of Japan (December 1961),* Committee for Field Investigation of the Chilean Tsunami of 1960.
7. B. P. Vazhenin, “Problems of tsunami research for the northern Sea of Okhotsk,” in *Problems of Integrated Geophysical Monitoring of the Russian Far East. Proceedings of the Second Regional Scientific and Technical Conference* (Petropavlovsk-Kamchatsky, 2010), pp. 312–317 [in Russian].
8. E. A. Okal, C. E. Synolakis, G. J. Fryer, P. Heinrich, et al., “A field survey of the 1946 Aleutian tsunami in the far field,” Seismol. Res. Lett. **73**, 490–503 (2002).
9. V. M. Kaistrenko, G. V. Shevchenko, and T. N. Ivel’skaya, “Manifestations of the March 11, 2011 Tokhoku tsunami on the Russian Far East coast,” Seism. Prib. **38** (1), 41–64 (2011).
10. V. B. Tyurnin, Tsunamis in the northern part of the Sea of Okhotsk. http://www.meteo.magadan.ru/Meteo/tsunami.htm.

11. K. Iida, *Catalog of Tsunamis in Japan and Neighboring Countries, Special Report* (Aichi Institute of Technology, Yashigasa, 1984).
12. S. A. Fedotov, "On the seismic cycle, possibility of quantitative zoning, and long-term seismic forecast," in *Seismic Zoning of the SSSR* (Nauka, Moscow, 1968), pp. 121–150 [in Russian].
13. Y. Okada, "Surface deformation due to shear and tensile faults in the half-space," Bull. Seismol. Soc. Am. **75**, 1135–1154 (1985).
14. V. K. Gusiakov, "Residual displacements on the surface of an elastic half-space," in *Conditionally Well-Posed Problems of Mathematical Physics in the Interpretation of Geophysical Observations* (VTs SO RAN, Novosibirsk, 1978), pp. 23–51 [in Russian].
15. Yu. I. Shokin, V. V. Babailov, S. A. Beisel, L. B. Chubarov, S. V. Eletsky, Z. I. Fedotova, and V. K. Gusyakov, "Mathematical modeling in application to regional tsunami warning systems operations," in *Computational Science and High Performance Computing III, Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Ed. by E. Krause, Yu. Shokin, M. Resch, and N. Shokina (Springer, Berlin–Heidelberg, 2008), pp. 52–68.
16. V. S. Kosykh, L. B. Chubarov, V. K. Gusiakov, D. A. Kamaev, V. M. Grigor'eva, and S. A. Beisel, "A technique for computing maximum heights of tsunami waves at protected Far Eastern coastal points of the Russian Federation," in *Results from Testing of New and Improved Technologies, Models, and Methods of Hydrometeorological Forecasts* (IG-SOTsIN, Moscow–Obninsk, 2013), No. 40, pp. 115–134.
17. V. K. Gusiakov, "Strongest tsunamis in the World Ocean and the problem of marine coastal security," Izv., Atmos. Ocean. Phys. **50** (5), 435–444 (2014).
18. H. Kanamori, "The energy released in great earthquakes," J. Geophys. Res. **82**, 2981–2987 (1977).
19. GEBCO General Bathymetric Chart of the Oceans. http://www.gebco.net/data_and_products/gridded_bathymetry_data/.
20. S. Stein and E. A. Okal, "The size of the 2011 Tohoku earthquake needn't have been a surprise," Eos Trans. AGU **92**, 227–228 (2011).
21. S. Stein, R. Geller, and M. Liu, "Why earthquake hazard maps often fail and what to do about it," Tectonophysics **562–563**, 1–25 (2012).

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