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Original article

Manifestation of the 2025 Kamchatka Tsunami on the Shumshu Island Coast (Northern Kuriles): Field Surveys and Numerical Simulations

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Abstract
Purpose. The purpose of this study is to investigate the parameters of the Kamchatka tsunami induced by the earthquake of July 29 (30), 2025, off the Kamchatka Peninsula, and its manifestations on the northern coast of Shumshu Island (Northern Kuril Islands), based on field survey results and numerical simulations.
Methods and Results. The results of field surveys of tsunami deposits in the northern part of Shumshu Island made it possible to determine the boundaries of maximum penetration of tsunami waves into the island interior and to measure the run-up heights at eight points. The coordinates of the maximum inundation line were recorded by GPS, and the run-up heights were determined using the Gebco_2019 Grid topographic maps. Wave generation, propagation, and run-up were numerically simulated within the framework of shallow water theory using the NAMI DANCE software package and nested grids with a minimum grid size of 8 m in the coastal zone. It was established that on the northern (Sea of Okhotsk) coast of Shumshu Island, the average run-up heights were 3–4 m and the maximum reached 6 m, whereas on the eastern (Pacific Ocean) coast of the island, they were 6–8 m, and the maximum in the Cape Pochtarev area reached 12 m (with wave penetration inland up to 110 m). It was shown that significant tsunami-induced fluctuations in sea level occurred not only off the Pacific coast of Shumshu Island on the side of the tsunami source, but also in the narrow shallow straits (First and Second Kuril Straits) separating the island from the Kamchatka Peninsula and Paramushir Island.
Conclusions. The results of numerical simulations are in good agreement with the field survey data, which confirms the reliability of the performed simulations and the possibility of applying the approach used to assess the tsunami hazard in the region. The resulting run-up heights (up to 12 m) indicate the extreme nature of the tsunami.

Keywords: earthquake, Kamchatka, Kuril Islands, tsunami, field survey, numerical simulation

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Introduction

A catastrophic earthquake with a magnitude of 8.8 took place on July 30, 2025, at 11:24:52 Kamchatka time (July 29, 2025, at 23:24:52 GMT). The earthquake parameters were promptly determined by the Unified Geophysical Service of the Russian Academy of Sciences and the U.S. Geological Survey, and were refined during the first 24 hours. The most complete characterization of the earthquake, named the Kamchatka earthquake, is given in [1]. The epicenter was located at 52.5°N, 160.3°E at a depth of 30 km, and the source itself extended southwestward for up to 500 km. This earthquake ranks sixth in the list of the strongest earthquakes in the history of observations. It generated a tsunami, for which a warning was issued by the tsunami warning service. As a result of timely measures, the population was evacuated, and human casualties were avoided.

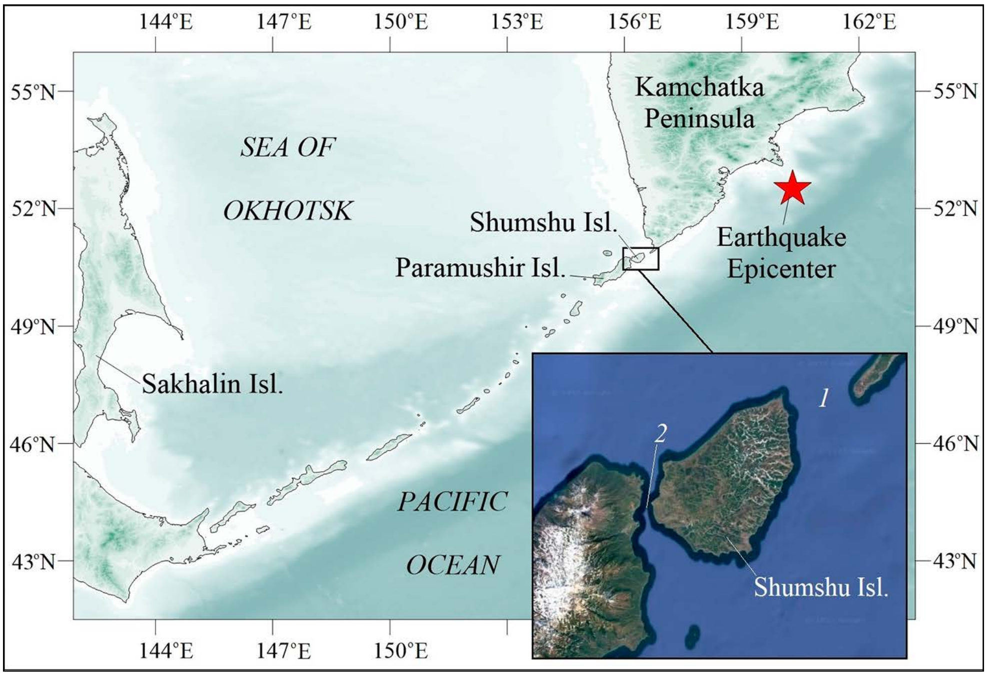
Results of numerical modeling of the generation, propagation across the study area, and coastal impact of tsunami waves allow the assessment of wave height distribution and the level of coastal impact. Calculations can be performed both operationally by the tsunami warning service and retrospectively to analyze tsunami manifestations in a specific study area. The authors have repeatedly performed numerical analyses of tsunami impacts on coastal areas [2–4], where numerical results were compared with actual sea level data from deep-water DART stations and coastal tide gauges, as well as with field survey materials of tsunami traces and eyewitness accounts.

This work is intended to analyze field observations and numerical modeling results of the tsunami propagation that occurred on July 30, 2025, local time (July 29 GMT), and its manifestations on Shumshu Island (Kuril Islands), located near the source. Numerical calculations allowed the identification of features of tsunami wave propagation across the study area, and their comparison with coastal change data provided an assessment of the correctness of the selected tsunami source parameters [5].

Study area

The epicenter of the 2025 Kamchatka earthquake was located southeast of the Kamchatka Peninsula. The generated tsunami waves propagated over the Pacific Ocean and also penetrated into the Sea of Okhotsk through the straits of the Kuril Islands. Shumshu is the northernmost island of the Greater Kuril Chain (Fig. 1). Its length is 30 km, and its width is 20 km. The proximity to the earthquake epicenter and the island's low relief (highest point 189 m, Mount Vysokaya) cause significant penetration of tsunami waves inland. The island is washed from the south by the Pacific Ocean and from the north by the Sea of Okhotsk; to the east and west it is bordered by shallow and narrow straits: the First Kuril Strait (between Shumshu Island and the Kamchatka Peninsula) and the Second Kuril Strait (between Shumshu Island and Paramushir Island). The minimum width of the First Kuril Strait is 12 km, its length is about 15 km, and its depth reaches 32 m; the minimum width of the Second Kuril Strait is 15 km, its length is about 30 km, and its depth reaches 30 m. The Vostochny Reef (near Shumshu Island) and Lopatka Reef (near the Kamchatka

Peninsula) are located in the straits, and the Kurbatovskaya Shoal lies to the north of Shumshu Island. The coast of Shumshu Island has a rocky structure, and the shores of the straits are steep. The average tide amplitude near the island coast is about 1 m.



F i g. 1. Epicenter of the 2025 Kamchatka earthquake. Inset shows the position of Shumshu Island: *1* – First Kuril Strait; *2* – Second Kuril Strait

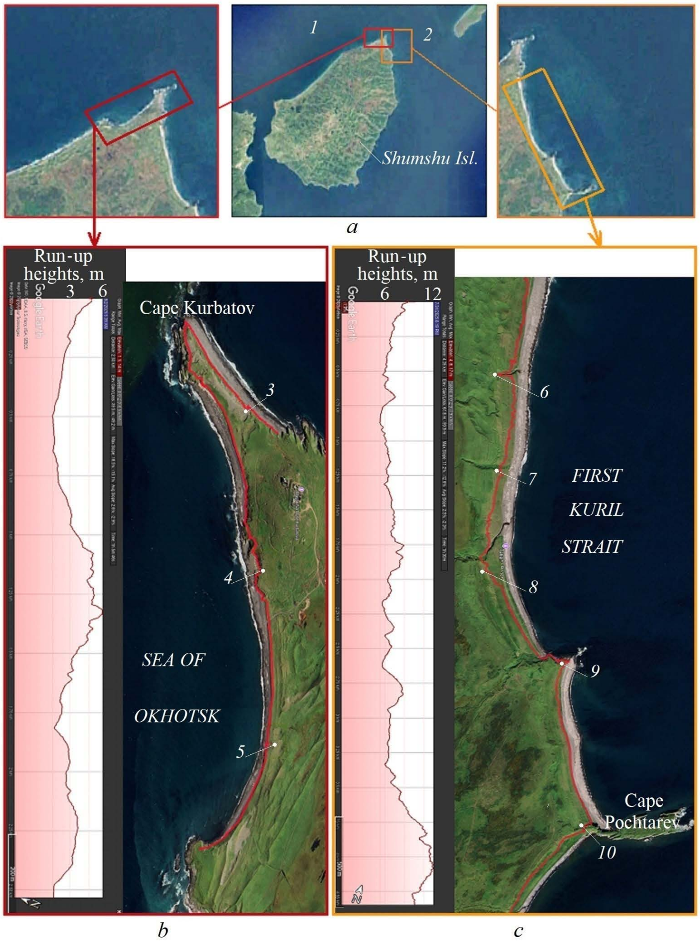
Field studies

Field surveys of tsunami traces on the Northern Kuril Islands were conducted over several days after the event, before storms destroyed these traces. The aim of the measurements was to identify the maximum coastal flooding line caused by the tsunami waves. This line was clearly identified by accumulations of floats and marine debris, as well as by trampled grass. The coordinates of points along the maximum flooding line were measured using GPS. Point elevations above sea level (zero level in the Baltic system) and the distance from the flooding line to the shoreline were determined from the General Bathymetric Chart of the Oceans (GEBCO_2019) with a resolution of 15 arc seconds, georeferenced in Google Earth.

Note that the tsunami occurred during ebb tide. According to the tide table, sea level decreased from 1.6 m at 10:00 to 1.2 m at 12:00, and then to 1 m at 14:00 Kamchatka time. Thus, point heights determined from the topographic map correspond to actual wave heights above sea level observed during the ebb phase. Since sea level was 1.0–1.2 m below the mean sea level at the time of the tsunami, absolute run-up values (relative to mean sea level) can be increased by the corresponding amount. In this paper, all given point heights are reported as recorded in the field, without tidal correction.

This method of mapping the run-up line complies with UNESCO recommendations (Post-Tsunami Field Survey Guide) [1] and has already been partially applied by the authors during a survey of the 2018 tsunami traces on Sulawesi Island (Indonesia) [2].

The results of field surveys in the area of the northern tip of Shumshu Island are given in Fig. 2. On the map of the coastal zone of this area, the red line indicates the maximum coastal flooding by tsunami waves, delineated during the survey. To the left of the map is the distribution of run-up heights (above sea level) along this line, obtained from the topographic map.



a

b *c*

F i g. 2. Study area of Shumshu Island. The red rectangle highlights Cape Kurbatov and the northwestern coast, and the yellow square indicates the northeastern coast between Cape Kurbatov and Cape Pochtarev (*a*); enlarged images of the northwestern (*b*) and northeastern (*c*) coasts: distribution of tsunami run-up heights along the Shumshu Island coast based on field surveys, the red line shows the maximum coastal flooding extent (*on the right*); distribution of run-up heights along the coastline (*on the left*). Numbers indicate: *1* – the Sea of Okhotsk; *2* – the First Kuril Strait; control measurement points on the coast: *3* – northeast of Cape Kurbatov, *4–5* – northwest of Cape Kurbatov, *6–10* – on the northeastern coast

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[1] Tsunami_BB. *ITIC Tsunami Bulletin Board.* [online] Available at: https://list.woc.noaa.gov/listinfo/tsunami_bb [Accessed: 07 August 2025].

In the area of Cape Kurbatov (Fig. 2, *b*), due to the rocky coast, it was not possible to conduct field surveys and determine the tsunami run-up height. On the northwestern coast, run-up heights did not exceed 6 m. On the northeastern coast (Fig. 2, *c*), between Capes Kurbatov and Pochtarev, wave heights ranged from 6 to 12 m, with the maximum run-up observed near Cape Pochtarev, which corresponds to theoretical concepts of wave energy concentration near capes [5].

Field survey data were used for comparison with the results of numerical calculations.

Numerical modeling of tsunami waves near Shumshu Island

The initial earthquake parameters were taken from the U.S. Geological Survey website [2] as of August 7, 2025: epicenter coordinates 52.5°N, 160.3°E, and source depth 30 km. According to the available data [2, 3], the source of the earthquake in question is located to the south along the coast of the Kamchatka Peninsula and the northern Kuril Islands. The displacement in the source is distributed unevenly: the maximum value of 10.5 m occurred in the central part of the fault, decreasing towards the periphery (Fig. 3, *a*). Therefore, for numerical calculations, the earthquake source was divided into three segments with different displacements. The initial tsunami wave was calculated using the Okada method [6] by summing contributions from the fault segments (Fig. 3, *b*). It represents an alternating sea level displacement with a depression area near the Kuril Islands, an elevation area near the Kamchatka Peninsula, and another elevated area at some distance from the Pacific coast of the northern Kuril Islands.

Numerical calculations of tsunami wave generation and propagation were performed using the NAMI DANCE computational package, which solves the nonlinear shallow water equations on a spherical Earth, taking into account bottom friction [7]. This computational package is often used in tsunami wave calculations [3, 4, 8]. Bathymetry was constructed from the Gebco Digital Atlas data (30-arc-second resolution). A free wave outflow condition was specified at the open boundaries. In all computational domains, the Manning bottom roughness parameter was taken as a constant value of 0.015 (corresponding to sandy-gravel material on the bottom in the coastal zone of the study area).

Verification of the correctness of the tsunami source selection and the testing of the numerical model were carried out using DART buoy data (21415, 21416, 21419) and the tide gauge record of Yuzhno-Kurilsk (Kunashir Island) [4].

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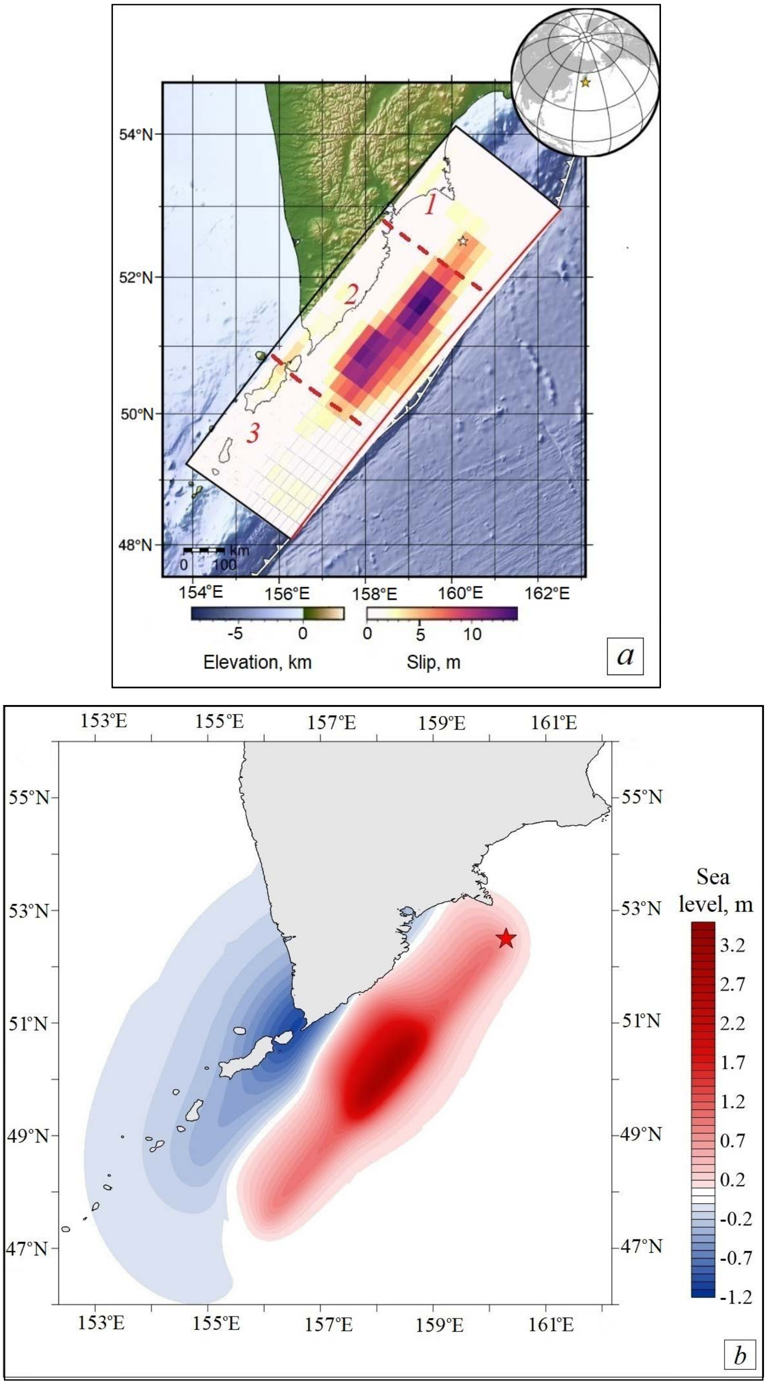
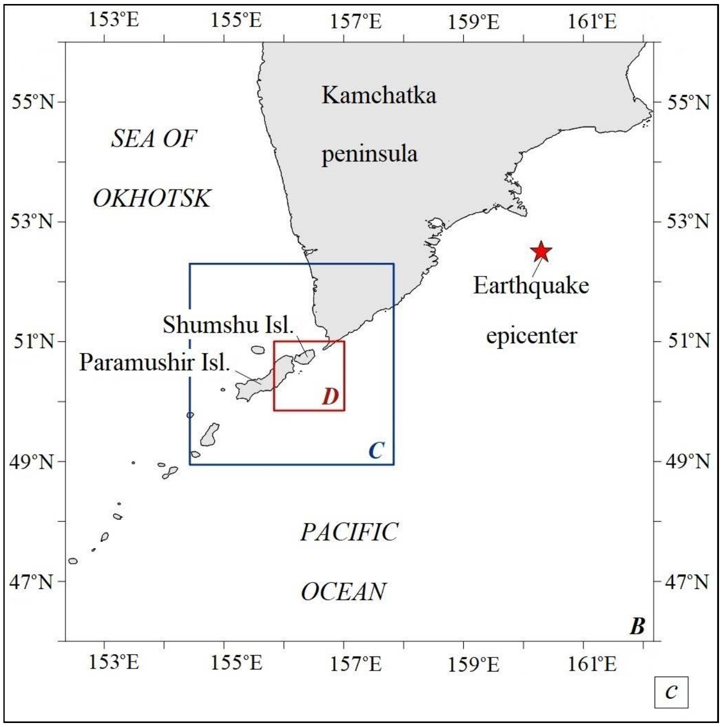
[2] USGS. *M 8.8 – 2025 Kamchatka Peninsula, Russia Earthquake.* Dataset. Available at: https://earthquake.usgs.gov/earthquakes/eventpage/us6000qw60/finite-fault [Accessed: 07 August 2025].

[3] Geophysical Survey of the Russian Academy of Sciences. *Earthquake Parameters in the Area of the East Coast of Kamchatka, Time 2025-07-29 23:24:52, Latitude 52.43, Longitude 160.46, Depth 20 km, Ms: 8.2/54.* Dataset. Available at: http://www.gsras.ru/cgi-bin/new/quake_stat.pl?sta=20253783&l=0 [Accessed: 07 August 2025].



F i g. 3. Surface projection of the displacement distribution in the earthquake source (*a*); initial displacement of the water surface (*b*); diagram of nested grids (*c*)

Continuation of the fig. 3

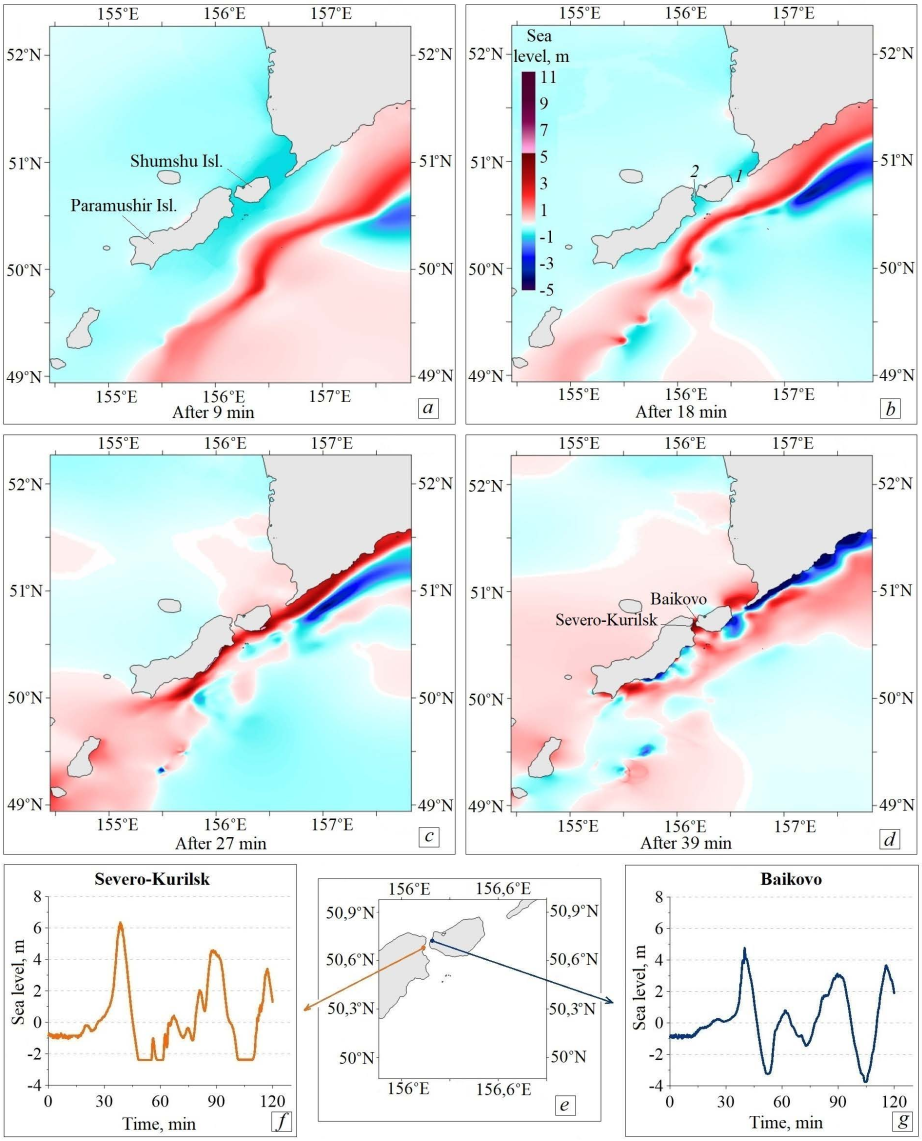


For a more detailed analysis of tsunami manifestations on the coast of the northern Kuril Islands (Paramushir and Shumshu), nested bathymetric grids with decreasing grid size were used in the numerical calculations (see Fig. 3, *c*). Grid “*B*” (grid size 177–277 m, mean 227 m) covers the tsunami source region and the adjacent water area. Nested grid “*C*” (grid size 59–92 m, mean 75 m) includes the southern part of the Kamchatka Peninsula and the northern Kuril Islands. Grid “*D*” (grid size 6–11 m, mean 8 m) covers only the southern tip of the Kamchatka Peninsula, Shumshu Island, and the northern part of Paramushir Island.

At the coast, boundary conditions accounted for wave run-up, which is necessary for analyzing run-up heights:

$$D(\lambda,\theta,t) = h(\lambda,\theta) + \eta(\lambda,\theta,t) = 0,$$

where D is the total basin depth; h is the undisturbed depth; η is the vertical displacement of the water surface; and λ and θ are the latitude and longitude of the grid points. In this case, the coastline is mobile and moves with the wave running up the shore. Numerical simulation was carried out for 2 hours. This interval was sufficient for all tsunami waves generated by the earthquake to manifest themselves along the studied coast.



F i g. 4. Tsunami wave propagation from the earthquake source (*a* – *d*) and its manifestations on the coast of Shumshu and Paramushir Islands (*e* – *g*)

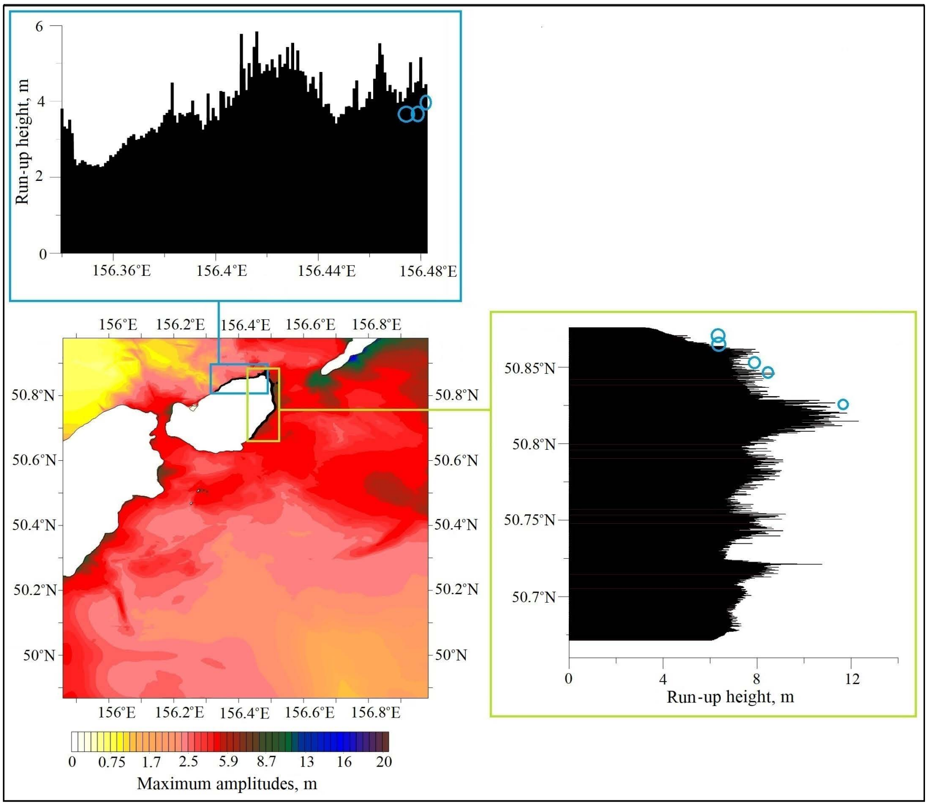
During propagation over the water area, tsunami waves encounter the coasts of the Kamchatka Peninsula and the Kuril Islands; as a result, the waves are partially reflected by the coast and partially penetrate through the straits between the islands into the Sea of Okhotsk. Analysis of available information [3] on the distribution of tsunami heights from sources located on the Pacific side of the Kuril Chain showed that wave heights on the coast of the Kuril Islands are approximately 10 times greater than those on the coast of Sakhalin Island, which is located in the Sea of Okhotsk.

The significant manifestation of tsunamis, including their run-up on the coast of the Kuril Islands, is associated with the proximity of tsunami sources, including the area off the southeastern coast of the Kamchatka Peninsula, as well as with local bottom relief features (bays, gulfs, and narrow straits) that amplify waves [9–11].

Fig. 4 demonstrates the tsunami wave propagation over the water area and its approach to the coast of Shumshu and Paramushir islands (calculated using grid *D*). After 27 minutes, the wave reaches the straits, where its oscillation amplitude increases and its propagation speed decreases due to the shallowness and narrowness of the First and Second Kuril Straits. According to calculations, the tsunami wave approached Severo-Kurilsk and Baikovo approximately 40 minutes after the earthquake (according to observations in Severo-Kurilsk, after 42 minutes). The straight segments on the model sea level graph in Severo-Kurilsk are due to the drying of the model grid node (depth 2.4 m). In Baikovo, the oscillation amplitude is smaller than in Severo-Kurilsk. Thus, the numerical simulation results are in fairly good agreement with observations.

Comparison of field survey results and numerical simulation

The distribution of maximum positive amplitudes of tsunami waves along the coast of Shumshu Island, obtained from the numerical simulation results, is shown in Fig. 5.



F i g. 5. Distribution of maximum amplitudes of tsunami waves along the Shumshu Island coast based on numerical simulation data: *above* – height profiles along the northern coast, *on the right* – those along the eastern coast, blue circles indicate the run-up heights measured at eight points during the field survey (see point locations in Fig. 2)

The highest values occur on the Pacific coast of the Kamchatka Peninsula and of Shumshu and Paramushir Islands. On the Sea of Okhotsk coast of these islands, wave heights are lower, due to the energy loss of waves when they break on the Pacific coast and pass through the narrow, shallow straits. A comparison between the numerical results for coastal tsunami heights and the observations shows good agreement. Minor discrepancies may be related to inaccuracies in the digital bottom model in the coastal zone.

Conclusion

The magnitude 8.8 earthquake near the Kamchatka Peninsula that occurred on July 29, 2025, local time, generated a tsunami that had the strongest impact on the coast of the northern Kuril Islands (Shumshu and Paramushir), causing severe destruction. Numerical modeling of wave generation, propagation, and run-up was performed within the framework of shallow water theory using the NAMI DANCE software package and nested grids with a minimum grid size of 8 m in the coastal zone.

The numerical calculations made it possible to identify features of tsunami propagation over the water area. It is shown that an increase in sea level fluctuations occurs not only on the Pacific coast on the side of the incoming tsunami wave, but also in the narrow shallow straits (the First and Second Kuril Straits) surrounding Shumshu Island. According to calculations, the average run-up heights on the northern (Sea of Okhotsk) coast of Shumshu Island are 3–4 m (maximum up to 6 m), while on the eastern coast the average values reach 6–8 m, and the maximum reaches about 12 m.

Based on field survey data of tsunami traces in the northern part of Shumshu Island, the boundary of maximum flooding was determined. On the northeastern coast, near Cape Pochtarev, the maximum run-up height reached 12 m, with wave penetration inland of up to 110 m. On the Sea of Okhotsk side of the island, wave heights did not exceed 6 m. These results are in good agreement with the numerical modeling data, confirming the model's reliability and the possibility of using the proposed approach for assessing the tsunami hazard of the region.

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Contribution of the co-authors:

Andrey I. Zaytsev – field survey coordination, analysis of the results of numerical simulations and writing of the manuscript

Efim N. Pelinovsky – analysis of the data from the field survey and numerical simulation and writing of the manuscript

Irina S. Kostenko – carrying out numerical simulations and writing of the manuscript

Anna O. Tsepkalo – carrying out field surveys, preparation of photographic materials and writing of the manuscript

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.