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NUMERICAL MODELING OF THE NEVELSK EARTHQUAKE AND TSUNAMI OF 2 AUGUST 2007

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ABSTRACT

The anomalous tsunamigenic earthquake, which occurred on August 2, 2007 at 02.37 GMT in the Tatar Strait, near the western coast of Sakhalin Island (Nevel'sk earthquake), is examined. Though the magnitude of the main shock was M=6.2, the tsunami waves generated by this earthquake were abnormally large, reaching heights of more than 3 meters at some points of the coast. Generally, earthquakes of similar magnitudes do not cause significant tsunami waves but only waves, which are very weak. Also unusual about this event was the distribution of maximum wave heights along the entire west coast of Sakhalin Island, from Chekhov to Korsakov, which were proceeded by recessions of coastal water. The present study presents the numerical simulation of this earthquake and of the tsunami it generated. Two scenarios of possible seismic sources are being considered, the dynamics of which can explain the unusual distributions of tsunami wave heights along the coast.

Key words**:** earthquake source, anomalous tsunami waves, numerical simulation

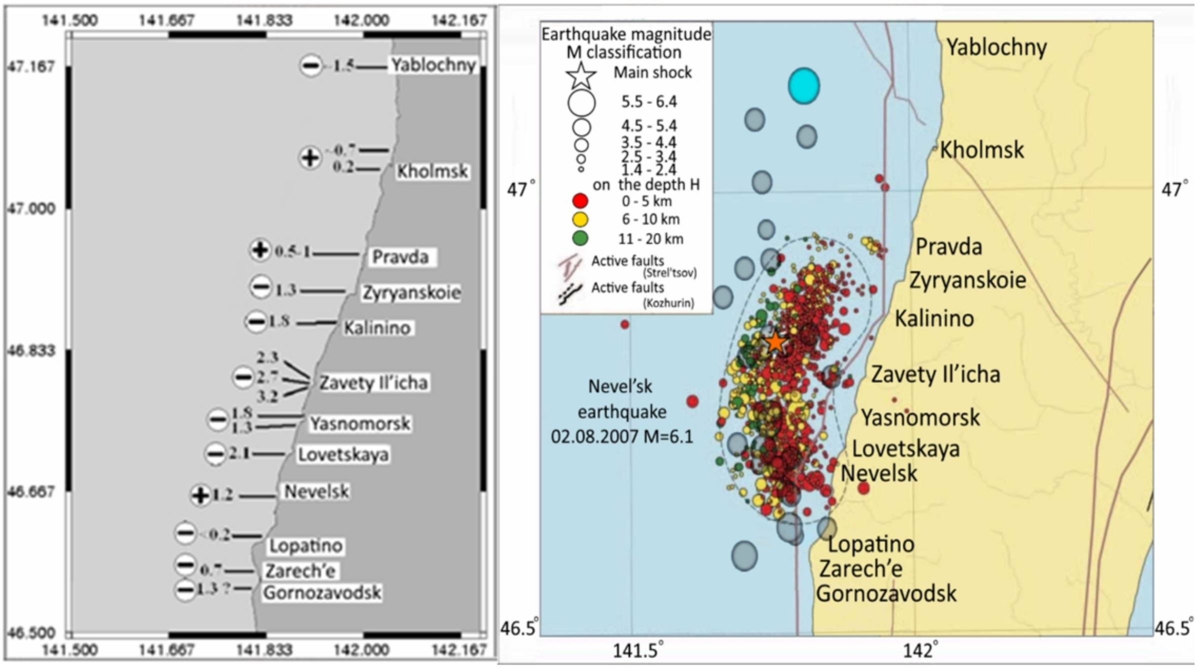
INTRODUCTION

Earthquakes occurring in the Kuril- Kamchatka zone mainly generate tsunamis in the Far Eastern region of Russia. For the period from 1737 to 1983 more than 60 tsunami events were observed or recorded on the Pacific coast of the country. According to historical and instrumental data, the coasts of Sakhalin Island are rarely struck by tsunamis [1-3]. The greatest danger for Sakhalin is tsunamis generated from seismic sources in the Sea of Japan. The most famous of these events is the Moneron tsunami of 5 September 1971, when a wave height of up to 2 m was recorded on the south coast of Sakhalin. Tsunami waves, which occur in the seismically active zone of Kuril-Kamchatka and reach the shores of Sakhalin, are usually weakened due to the attenuation effect of the Kuril ridge. An unexpected event was the generation of an “anomalous” tsunami of 2 August 2007 (at 02.37 GMT) in the area of the Tatar Strait, 60 km off Yuzhno-Sakhalinsk. This moderate earthquake with magnitude Mt = 6.2, generated tsunami waves on the west coast of Sakhalin that reached up to 3 meters in height [4,5].

1. *Features of the Nevel’sk earthquake and tsunami 02.08.2007.*

As noted in [4], the heights of tsunami waves on the coast, which were generated by the Nevel’sk earthquake on 2 August, 2007, indicate that the magnitude of this earthquake could not have been 6.2 as reported, but was significantly more. Also, in the scientific literature [4,5] it is noted that the tsunami in the Nevel’sk region followed immediately after the main shock, and began with a strong withdrawal of the water along the coast. Anomalous for this earthquake was also the rise of some parts of the coastal zone, the so-called “benches”, both in the Nevel’sk region and in other parts of the coast. A significant feature of this earthquake is the ambiguity in data in the determination of the earthquake’s epicenter, apparently due to the occurrence of several aftershocks comparable in strength to the main shock [4,5]. According to the US Geological Survey [https://earthquake.usgs.gov], the epicenter of the earthquake had coordinates 47.116 ° N 141.798 ° E (2007-08-02 02:37:42 (UTC)), and was located at a depth of 5 km, while according to the network of autonomous digital seismic stations (DAT) of the SF of the GS of RAS [http:// www.globalcmt.org] the coordinates of the epicenter were given as: 46.829 ° N, 141.756 ° E [4] (Table 6.1), with focal depth of 10.6 km.

One of the characteristic features of the Nevel’sk earthquake was that the tsunami that was generated began with a withdrawal of water in many parts of the coast (see Fig.1). It is well known that when a tsunami begins with rundown of water, the subsequent waves could have anomalously high run-up [6,7]. In addition, the character of the tsunami waves that struck the coast was very unusual: the run-up and rundown of the first waves at various points did not have any regularity, which makes it difficult to explain. The maximum heights of the waves on the coast were distributed very unevenly, not diminishing, and often, increasing, with increasing distance from the epicenter of the earthquake along the coast [8,9]. In the same case, when the seismic source was quite long, and the hypocenter was shallow the existing coastal and shelf faults (identified or not identified at the time of the earthquake) can give additional heterogeneous displacements, which in turn significantly affect the formation of tsunami waves. As known, the generation of a tsunami wave depends on the character and character and dynamics of bottom displacements in the zone of the earthquake source, or more precisely, on the initial bottom displacements. It is also known that when calculating the generation of tsunami waves, seismic data are used to determine the orientation of fractures in the source, then the model of the seismic source is refined, the energy of this earthquake is recalculated into the possible energy of tsunami and then, using various models of numerical simulation of tsunami wave propagation from source to coastal zone, an assessment is made of possible run-up of tsunami waves onto the coast [8,9]. In such computations, there is always the question of the adequacy of the seismic source model, and this is especially true for the tsunami formed by the source located in the near-field zone, i.e. at a distance of the order of the wavelength from the source to the nearest coast. At the same time, the obtained results directly depend on the choice of the model for determining the seismic source of the earthquake. Therefore, it was very important to determine the correct location of the seismic source, as well as to understand the possibility of the existence of crustal faults passing through this source. At the same time, an important characteristic of this work was the availability of data on detailed field studies of the west coast of Sakhalin Island from Yablochnoye point to Gornozavodsk one, conducted by staff members of IMGG FEB RAS. As noted in [5], of the "identified and fairly reliably mapped on land directly to the east of the city of Nevel'sk, there is a relatively long (about 40 km) sub-meridional fault of the type of thrust or uplift-thrust".



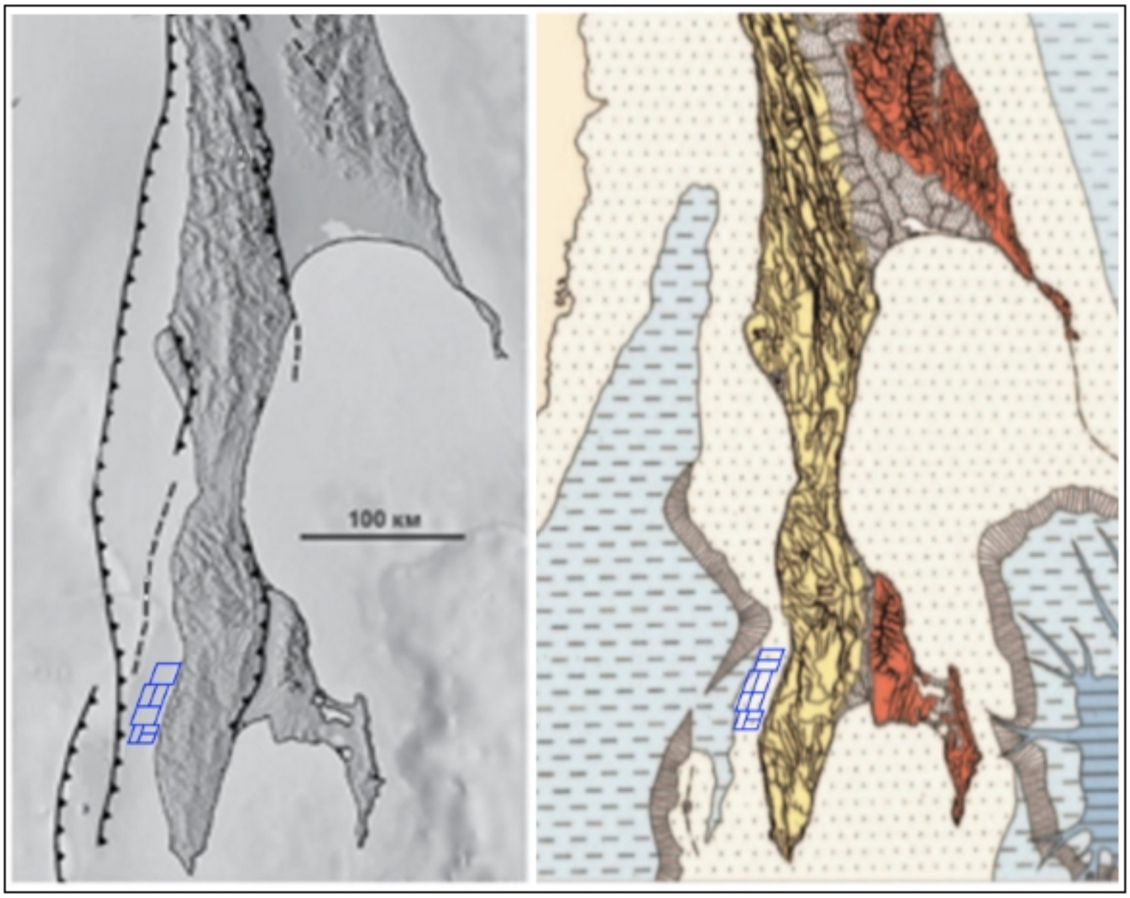
a) b)

Fig. 1. a) Character of tsunami wave run-up on the west coast of Sakhalin island at Nevel'sk earthquake (02.08.2007, M=6.2); (+) first elevation wave at run-up on the beach, (-) first depression wave at run-up on the beach [4,5]; b) earthquake main shock epicenter map (orange star) and its aftershocks (encountered by grey dashed curve) – the data are from [4]; grey circles of aftershocks and blue ring of epicenter – the data are from USA Geological Service [https://earthquake.usgs.gov].

2. *The mechanism of the Nevelsk earthquake of 02.08.2007 and the choice of scenarios for a seismic source*

In Fig.1b above, it is clearly seen that the aftershock zone covers the entire shelf zone, partially entering the dry shore, in the area surveyed by the coast. This zone has a lengthy character, which indicates the possible lengthy character of the earthquake source.

In Fig. 2 the map of active geotectonic faults [10] and the relief map of Sakhalin Island [4] are presented. The model seismic sources used for numerical modeling of the Nevel'sk earthquake and tsunami are also schematically shown here.



a) b)

Fig. 2 Model representation of computational source for Scenario 1 and Scenario 2 at maps: a) active faults of Sakhalin island [10]; b) relief of Sakhalin island [4]; blue lines – schematical representation of earthquake sources for two scenarios.

As noted in [4,5], the location of the aftershocks "coincides well with the route of the West-Sakhalin fault and almost all of the aftershocks are located on the western wing of this fault." An analysis of the factors cited in [4,5,10-12], (see Fig.2a, b) suggests that the seismic source consisted of a series of key blocks [8], the implementation of which at different times led to such an unusual distribution of run-up heights on the coast and to such a strange pattern of distribution of waves on the coast (see Fig.1a).

Also, it should be noted that a similar character of tsunami wave height distribution, in addition to the specified implementation of movements in a multi-block seismic source, can be determined by waveguide effects along the coastal zone, i.e. captured waves. In this case, the energy of the waves generated by an underwater seismic source located on the shelf is captured by the shelf and the wave, which is subsequently reflected from the coast, then from the edge of the shelf (as in a waveguide), spreads along the coast, slowly attenuating [13]. In this case, the wave process is oscillatory in character: the form of the wave field is determined by the decay of the wave into separate oscillating trains (corresponding to each mode of the captured wave) with different speeds of movement: high-frequency components propagate ahead and lower-frequency components coming only later [14]. When they are superposed, a complex pattern of interference arises, leading to a non-monotonic change in the height of the run-up along the coastline. However, in this paper, the effect of such a process on the distribution of waves along the coastal zone will not be considered.

3. Numerical simulation of the Nevel’sk earthquake and tsunami 02.08.2007.

To study the earthquake of August 2, 2007, in the Tatar Strait, we analyzed the field data obtained from the survey of the western coast of Sakhalin Island [4,5], and analyzed the possible location of the seismic source. Based on the analysis performed, the choice of optimal variants of seismic source dynamics was made, numerical simulation of tsunami wave generation and propagation up to 5-meter isobaths for the water area ($138^0 \div 146^0$ E, $45^0 \div 55^0$ N) was made, with a calculated grid, including 480x599 points.

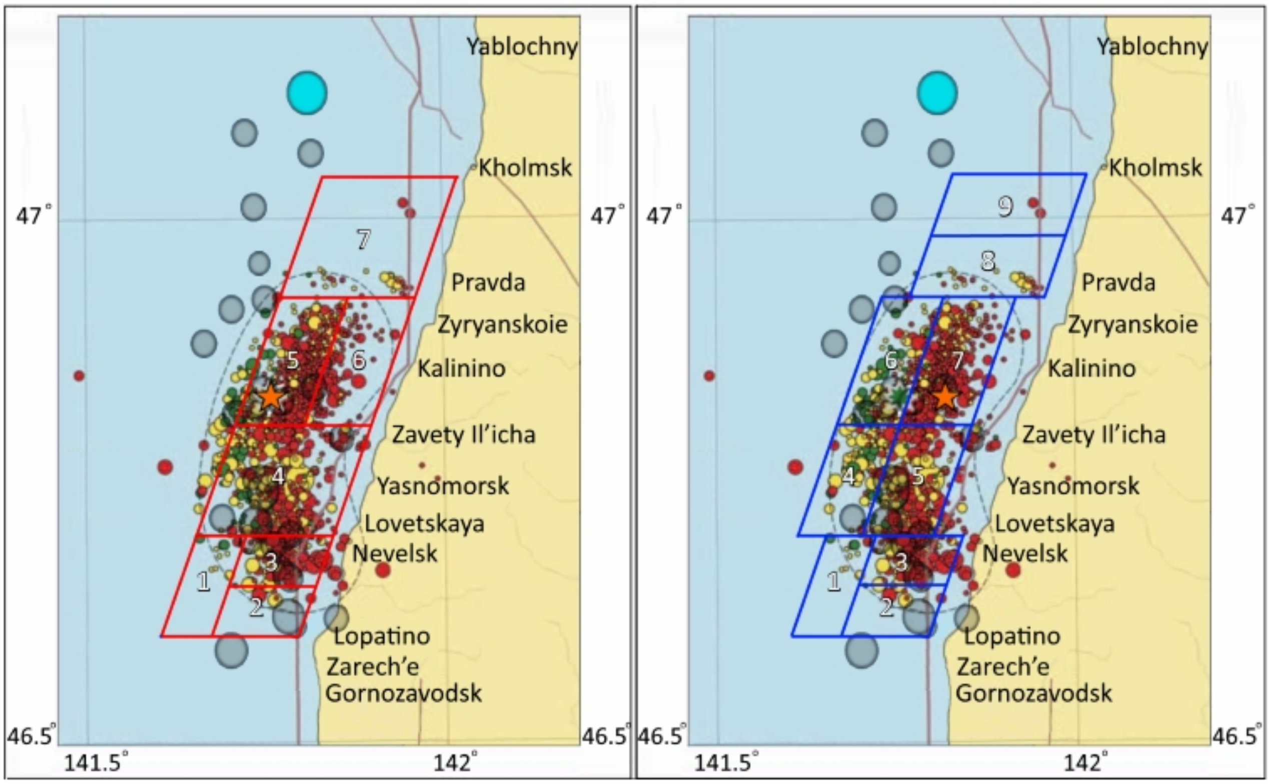
In this work, a number of calculation options with different implementation of the movements in the source were considered. The choice of options was determined by coastal survey data. It is well known (see, for example, [9]) that the sign of the displacement shift in the center determines the sign of the run-up phase for sources located in the near-field zone, i.e. at a distance of the order of the wavelength. Since we had data on the character of the run-up of tsunami waves from the coastal section from Yablochny to Gornozavodsky points, then the rundown or run-up of the waves at specific points can determine the character of movements in the part of the source that is oriented to this part of the coast. Therefore, the analysis of possible movements of blocks in the source was carried out by selecting the speeds of movement and adjusting the magnitudes of the displacements of a particular block (see, for example, [9]).

Of all the options considered, two Scenarios were selected, the results of which most correlate with the results of field studies of the coast of the western part of Sakhalin, conducted by staff of IMGIG FEB RAS [4]. For numerical simulation of a tsunami, a seismic source was chosen, located at a distance of 2 to 7 km from the coast (depending on the Scenario and on the location of the block), whose width were 19 km, and 50 km long. For the first Scenario, the source consisted of 7 blocks (see Fig.3a), for the second one - of 9 blocks (see Fig.3b). For Scenario 1, the number of blocks in the seismic source was determined primarily by the character of the bottom bathymetry, and for Scenario 2, by the co-seismic displacements from [4,16,17].

In Table 1, data on the sequence of movement of blocks in the source when implementing Scenario 1 are presented.

Table 1

Block number	1	2	3	4	5	6	7
Shift value (m)	0.6	1	-1	-1	1	-1	-0.6
Start time (sec)	0	20	20	0	0	0	20
Stop time (sec)	10	60	40	10	20	30	30



a) **b)**

Fig. 3. Schematic representation of model seismic block sources a) (red contour) for computation on Scenario 1; b) (blue contour) – on Scenario 2. Location of earthquake epicenter for Scenario 1 is determined on data of net of autonomous digital seismic stations (DAT) SF GS RAS [4,5]; for Scenario 2 location of earthquake epicenters is determined on data by Kim Ch.U. (IMGiG Far-East Branch of RAS) [4].

In the framework of nonlinear shallow water equations (see, e.g., [9,13]), numerical simulation of tsunami wave generation by this seismic source, propagation of these waves over the computational area was carried out and maximum wave values were estimated for a number of coastal points (Fig.1a). The simulation was carried out with a time step of 1s, with checking for convergence and stability of the numerical scheme [15]. The results of numerical simulation of the generation and propagation of tsunami waves for Scenario 1 are presented in Fig. 4 and Fig. 5. It is clearly seen that the wave field from such a source is substantially determined by the bottom topography. Thus, the wave front extending towards the continental slope has a well-defined elongated shape, which is caused by faster wave propagation to the underwater depression area, up to 800 m deep. At the same time, the wave front approaching Sakhalin coast is flatter. In addition, there is a predominant propagation of the wave front in the southwestern direction of the Sakhalin coast, while the wave reaches the more northern points of the coast in a longer period of time (Fig.5). This may be due to the greater width of the shelf zone to the north.

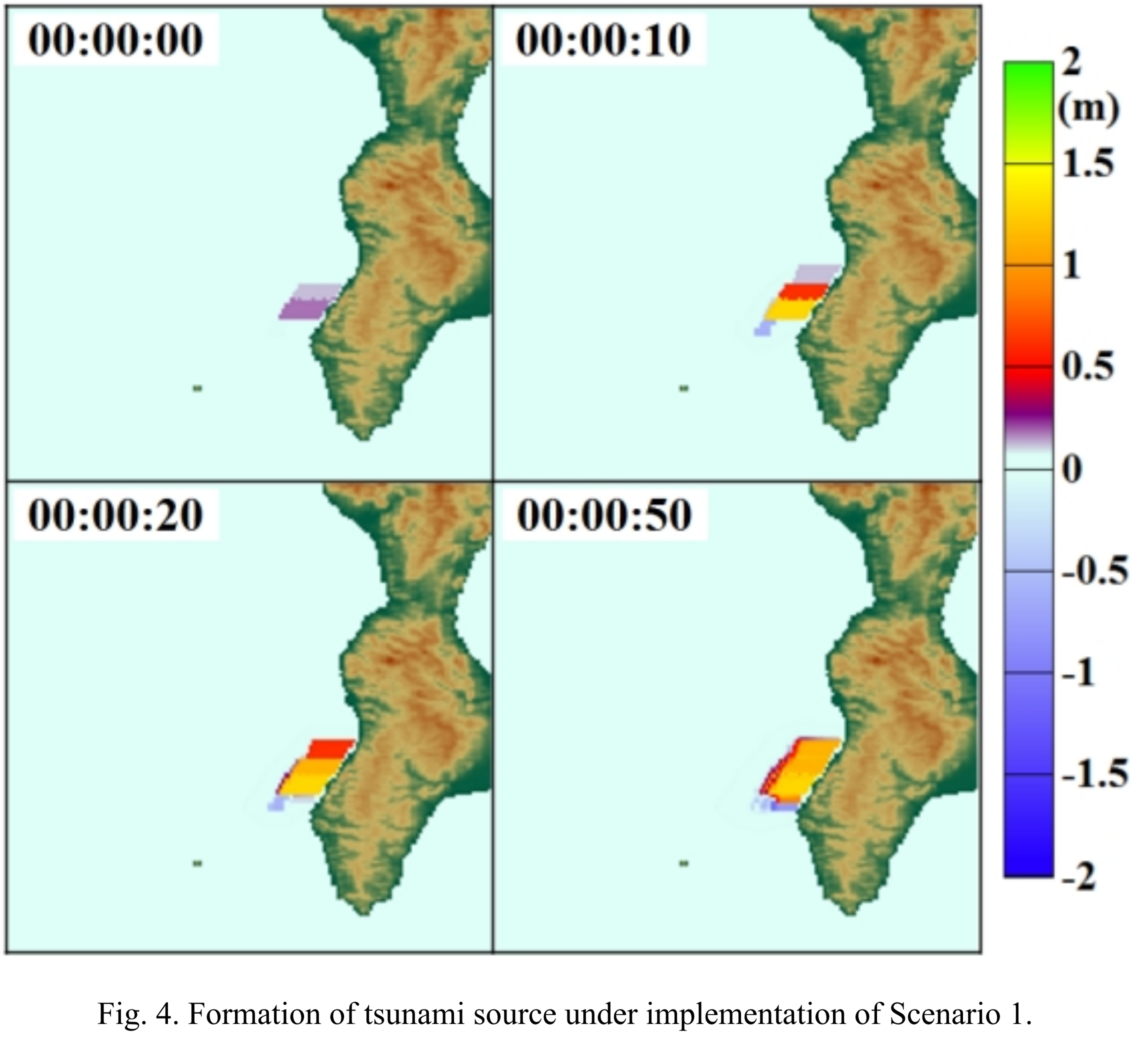


Fig. 4. Formation of tsunami source under implementation of Scenario 1.

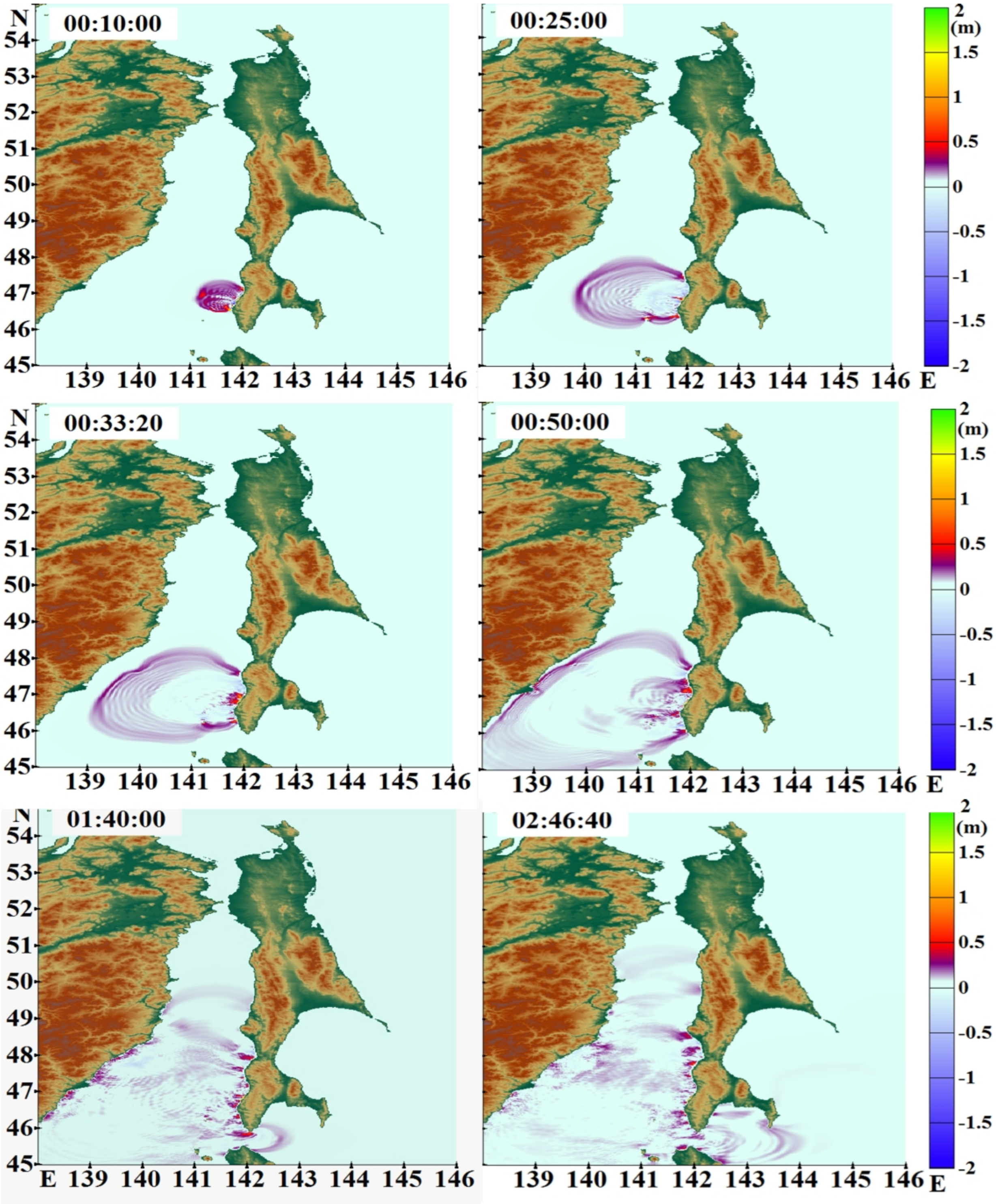


Fig. 5. Propagation of tsunami wave on computational basin at implementation of Scenario 1.

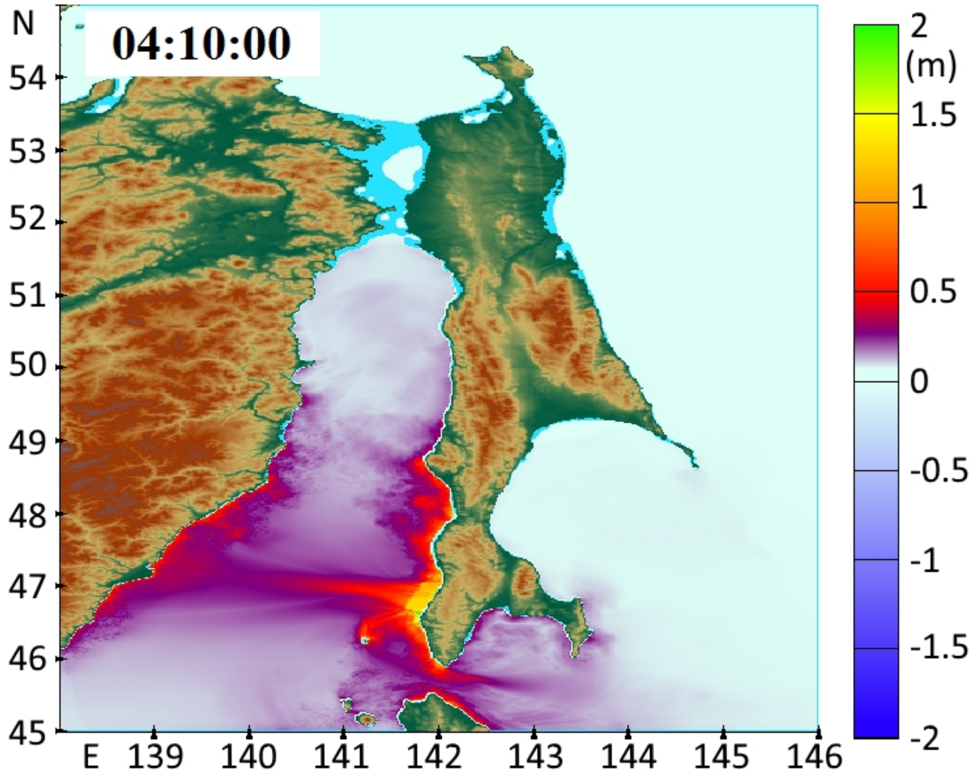


Fig. 6. Maximum wave height distribution in the computational basin (Scenario 1).

Figure 6 presents a picture of the distribution of maximum wave heights in the water area. Its detailed analysis allows us to estimate the effect of possible movements in a seismic source and justify the use of a multi-block key model for calculating the generation.

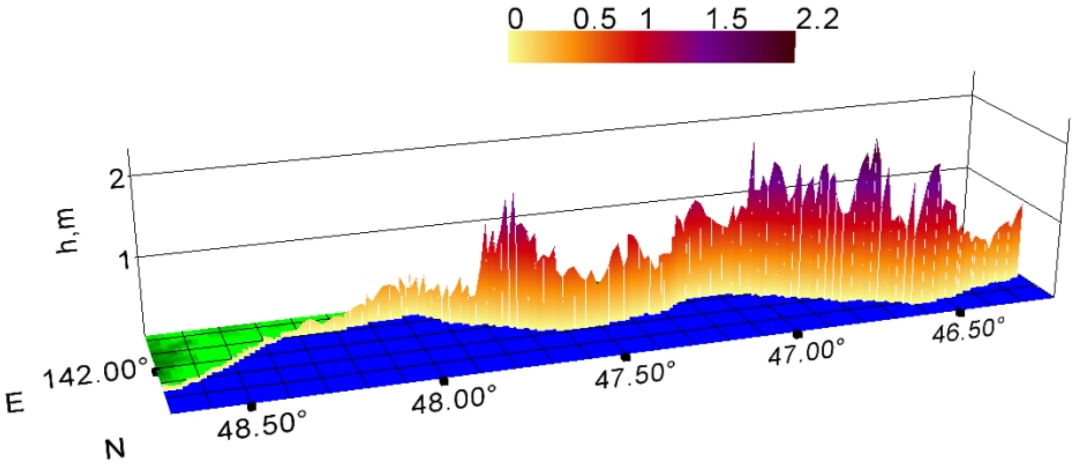


Fig. 7. 3D histogram of maximum tsunami wave height distribution (Scenario 1).

Fig. 7 shows a three-dimensional histogram of the distribution of the maximum heights of tsunamis along the western coast of Sakhalin Island, obtained by computation according to Scenario 1.

It is clearly seen that the highest heights of run-up are in the range from 46.7^0 to 47^0 N, which is consistent with the data shown in Fig.1a. It can be seen that the maximum heights reaching 2.0 m are alternated by heights ranging from 0.3-0.5 m.

For the second computation, a seismic source was used, a schematic view of which is shown in Fig. 3b. When modeling Scenario 2, data from [4,16,17] were used, where it was proposed to apply the one- dimensional distribution of the co-seismic displacements of the earth's surface, obtained using the Japanese ALOS satellite, "which were fixed in a narrow coastal zone less than 10 km wide and about 30 km from the village Lopatino to the village Kalinino" [4,16,17]. The division of the deformation zone into 2 extended sections: the northern section and the southern section, comparable to the corresponding aftershocks with M = 6.2 and M = 5.8, allowed us to present the seismic source in the following form (Fig. 8) and set the dynamics of the key blocks in the source represented in Table 2.

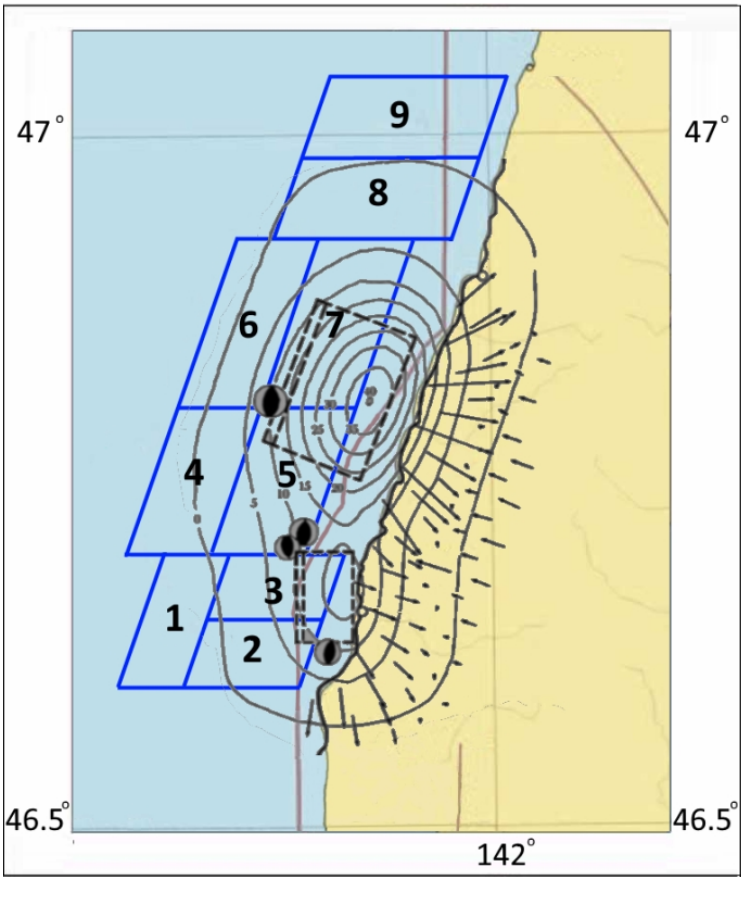


Fig. 8. Schematic representation of model seismic block source (blue contour) for Scenario 2; grey curves are the co seismic shifts from works [4,16,17].

Table 2

Number of case	Block Number	1	2	3	4	5	6	7	8	9
1	Vertical shift (m)	0.5	0.3	-0.4	1.0	-1.5	1.8	-0.8	0.15	-0.15
	Start time (s)	20	20	0	40	30	20	0	50	50
	Stop time (s)	30	40	20	50	40	50	20	70	70
2	Vertical shift (m)					1.8		1.2		0.2
	Start time (s)					40		20		70
	Stop time (s)					60		40		90

In Fig. 9, the generation process of the tsunami source during the implementation of Scenario 2 is shown. Unlike Scenario 1, the beginning of the movement of the blocks corresponding to two sections of the deformation zones (see Fig. 8) can be seen in Fig. 9 (left upper panel). Further aftershock movement to the south and north was approximated by the movement of blocks in the earthquake source (Table 2), which can be seen on the upper right panel of Fig. 9. Such a complex implementation of the dynamics of a seismic source noticeably changed the structure of the wave field in the tsunami source (see Fig. 9, bottom panels).

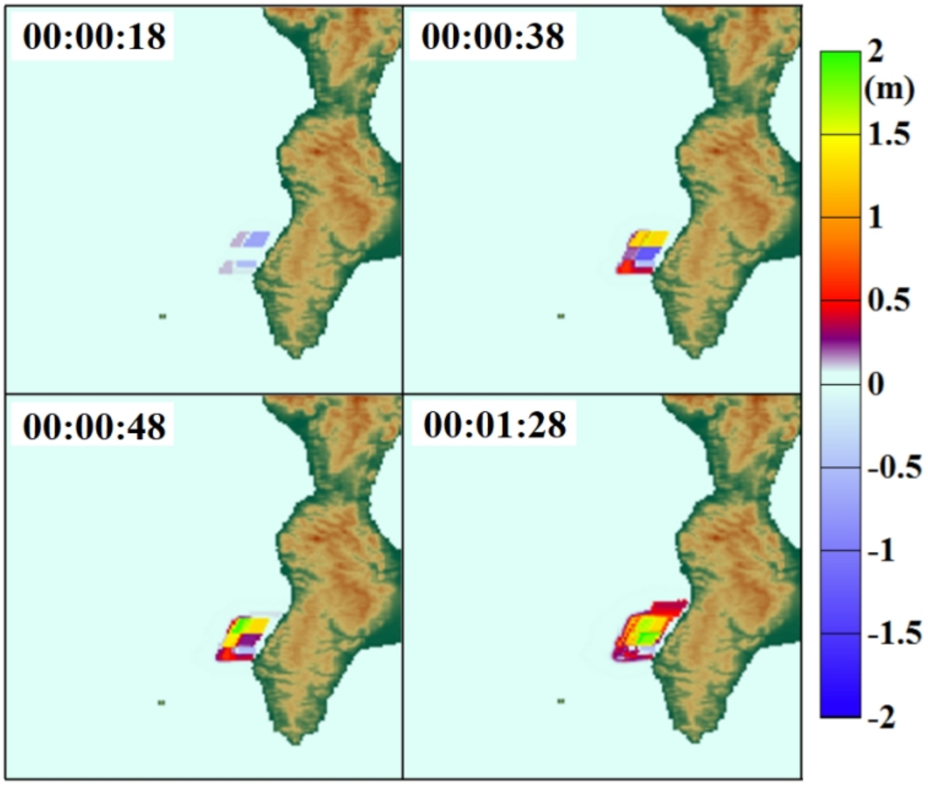


Fig. 9. Formation of tsunami source under implementation of Scenario 2.

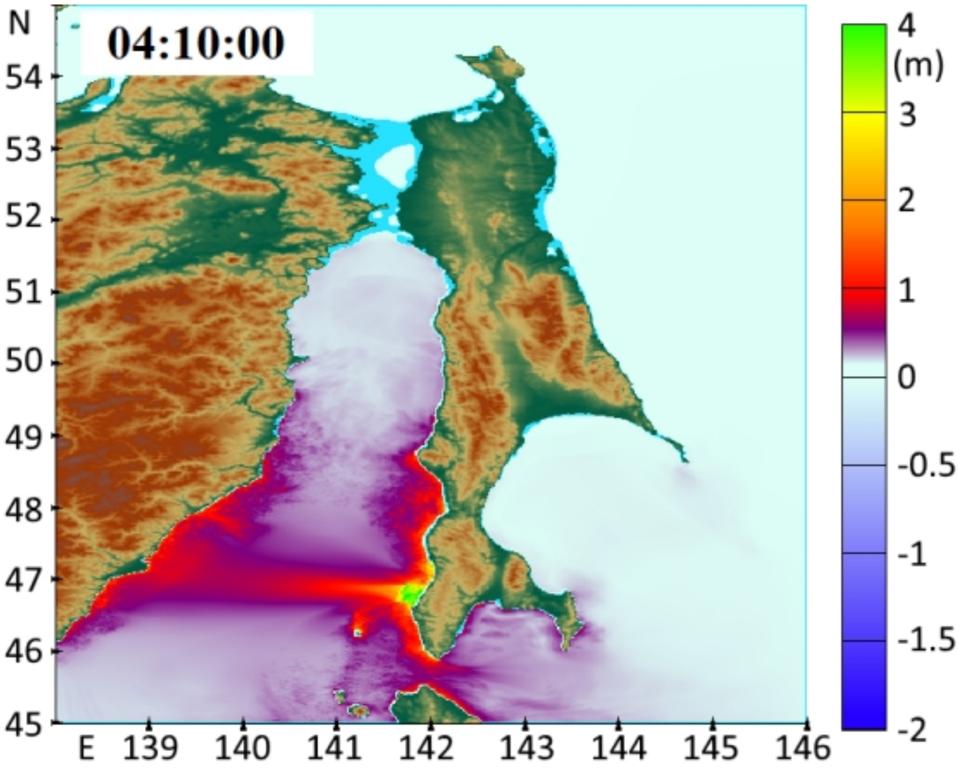


Fig.10. Maximum wave height distribution in the computational basin (Scenario 2).

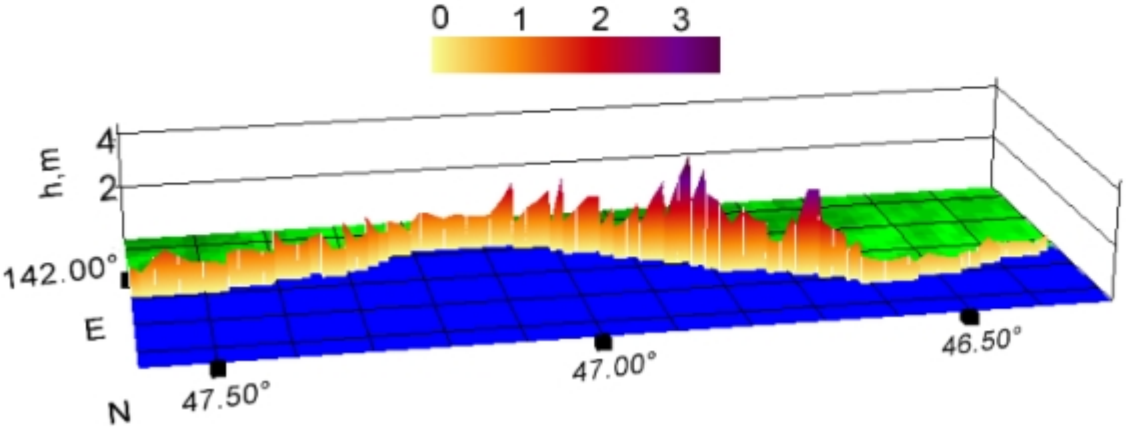
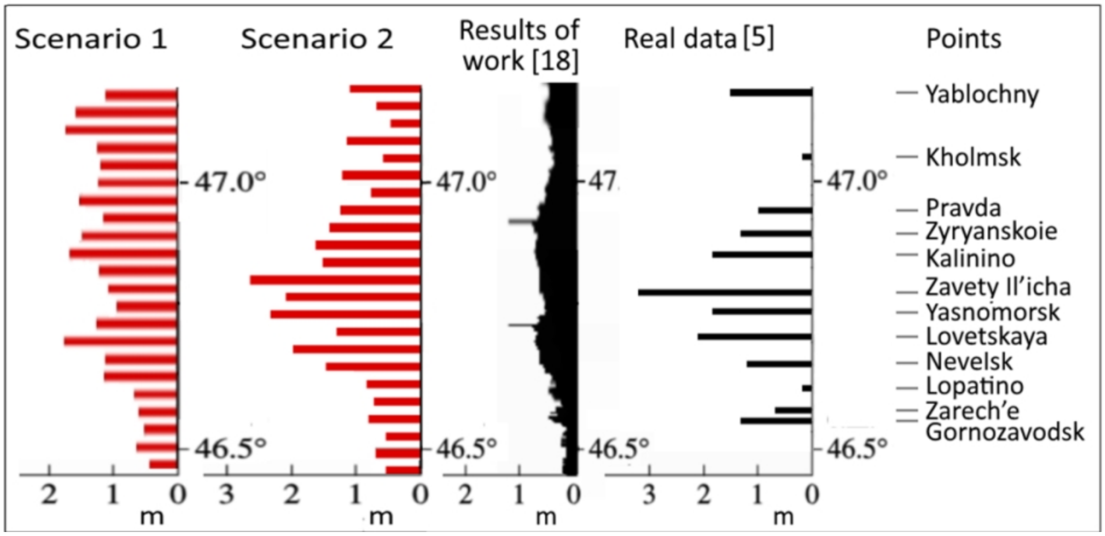


Fig. 11. 3D histogram of maximum tsunami wave height distribution (Scenario 2).

Fig. 10 shows the distribution of maximum wave heights, which is most pronounced along the entire western coast of Sakhalin Island and along the central continental part, which may be due to the peculiarities of the dynamics of this source (Table 2). At the 3d histogram for this scenario, pronounced peaks of heights up to 3.5 m in its central part are observed, alternating with weak rises of water up to 40 cm (Fig.11).

4. *Comparison of computational with empirical data and data of other authors*

The results of comparison of the obtained computations with empirical data and computations of other authors are shown in Fig. 12 and Table 3. It is clearly seen that the computation data for Scenario 1 (Fig.12a) are weakly consistent with the real data (Fig. 12d), being close to the empirical data only in a limited number of points. This can be explained by the fact that the dynamics of the blocks in the source was determined primarily by the character of the bottom bathymetry. However, the factors described in [4,5,10-12] are rather contradictory, which apparently, did not allow to set the correct dynamics of blocks in the source in Scenario 1.



a) b) c) d)

Fig. 12. Comparison of computational and empirical results: a) computation on Scenario 1; b) computation on Scenario 2; c) results from [18-20]; d) real date [4,5].

In Scenario 2, data on the one-dimensional distribution of the co-seismic displacements of the earth's surface [4,16,17] were used (see Fig. 8). It can be seen (Fig. 12b) that the histogram of the distribution of maximum wave heights is closer to the empirical data (see Fig. 12d).

The data from [4,5], which presents the coastal survey results for each item, the results of numerical simulation [21], and the results obtained in calculations for two Scenarios (Scenario 1 and 2) were summarized in Table 3 (column 1, 2, and 3, 4, respectively).

It can be seen that for Znarech'e, Zyryanskoie, Lovetskaya, Pravda the calculated and observed values are close to one other, and a number of calculated data for the maximum run-up heights for points Gornozavodsk, Zavety Il'icha, Kalinino, Yablochny are somewhat underestimated. It is important to note that the calculated data were obtained on a 5-meter isobath, and it is necessary to take into account the gain for the wave height when converting from the shelf zone to the dry shore.

As a result, the calculated wave heights with data obtained on a 5-meter isobath, when recalculated to the coastal zone, may be more consistent with empirical data. At the same time, in such points as Lopatino, Nevel'sk, Yasnomorsk, Kholmsk the estimated heights obtained from Scenario 2 are too high, relative to empirical data. Since in numerical simulations, a multi-block seismic source was preferred, and waveguide effects along the coastal zone, i.e. the captured waves (see above) are possible, these overestimated values of the heights are due to the neglect of these effects.

Table 3

№	**Name points**	**Real data [5] (m)**	**Numerical modeling [21] (m)**	**Numerical modeling Scenario 1 (m)**	**Numerical modeling Scenario 2 (m)**
		1	**2**	**3**	**4**
1	**Gornozavodsk**	**1.3**	**1.4**	**2**	**0.9**
2	**Zarech'e**	**0.7**	**1.28**	**0.8**	**0.7**
3	**Lopatino**	**0.2**	**-**	**0.8**	**0,8**
4	**Nevelsk**	**1.2**	**1.6**	**1.2**	**1,6**
5	**Lovetskaya**	**2.1**	**3.15**	**1.8**	**2.1**
6	**Yasnomorsk**	**1,8**	**-**	**1.6**	**2.3**
7	**Zavety Il'icha**	**3.2**	**3.47**	**1.8**	**2.6**
8	**Kalinino**	**1.8**	**1.69**	**1.0**	**1.5**
9	**Zyryanskoie**	**1.3**	**-**	**1.3**	**1.4**
10	**Pravda**	**1**	**1.67**	**2**	**1,2**
11	**Kholmsk**	**0.2**	**1.13**	**1.1**	**0,5**
12	**Yablochny**	**1.5**	**0.95**	**1.3**	**1.1**

5. CONCLUSIONS

Based on this study, one of the conclusions that can be made is that the assumption that the character of the run-up height distribution of the tsunami that hit the coast of Sakhalin after the submarine earthquake of August 2, 2007, depends to a large extent on the specifics of the dynamics, including the underwater seismic source, which determines not only the magnitude of run-up, but also the run-up phase. However, to clarify the computations, it is necessary to take into account the co-seismic displacements of the earth's surface in the coastal zone along the west coast of Sakhalin, and it is also assumed that the waveguide effects along the coastal zone are necessary.

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