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A METHOD FOR THE ESTIMATION OF TSUNAMI RISK ALONG RUSSIA's FAR EAST

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ABSTRACT

A simplified method was developed for estimating the tsunami risk for a coast for possible events having recurrence periods of 50 and 100 years. The method is based on readily available seismic data and the calculation of magnitudes of events with specified return periods. A classical Gumbel statistical method was used to estimate magnitudes of small probability events. The tsunami numerical modeling study used the average earthquake coordinates in the Kuril-Kamchatka high-seismic area. The verification and testing of the method were carried out using events from the North, Middle and South Kuril Islands – the most tsunami-risk areas of Russia's Far East. Also, the study used the regional Kuril-Kamchatka catalogue of earthquakes from 1900 to 2008 - which included earthquakes with magnitudes of at least M=6. The results of the study indicate that the proposed methodology provides reasonable estimates of tsunami risk.

Keywords: *tsunami risk, earthquake, magnitude, numerical modeling*

1. INTRODUCTION

As demonstrated by the tsunami of March 11, 2011, which had disastrous consequences for the northeast coast of Honshu, the risk of tsunami should be properly taken into account when planning of coastal areas development. Even a very good job of a tsunami warning service and a high degree of organization of the population did not help to avoid significant losses of life. This example shows the importance of reliable tsunami risk estimation - the calculation of possible tsunami heights with return periods of 50, 100 or another number of years.

Usually to get the reliable estimates of tsunami risk for the given stretch of the coast we need to conduct the expeditionary survey to assess the run-up heights of historical tsunamis (KAISTRENKO, 2011). The probability regional model of tsunami activity in the given area can be built on the base of these historical data. Numerical simulation of the strongest tsunami in the area required estimating the tsunami risk for the points in which historical data are absent or little. This method gives the reliable results, but it requires a lot of money and time. At the same time, it is often necessary to obtain quick preliminary estimates, although not that reliable.

As the simplified estimation of tsunami heights for the specified return period (H_T for return period of T years) we can take the results of numerical simulations with the corresponding earthquake parameters: estimated magnitude M_T for a given return period, the average focal depth and epicenter coordinates. This approach is based on the assumption of a linear relationship between the tsunami height at the source and magnitude of earthquakes, which is justified for the task.

2. METHODOLOGY

To solve a problem of preliminary tsunami risk estimates, the simplified method of tsunami risk estimation for the coast is developed. The method is based on the easily available seismological data and calculation of magnitudes for the specified return periods. A classical Gumbel (1962) statistical method was used to estimate magnitudes of small probability events. This method is based on a double exponential distribution:

$$1 - P(M) = EXP(-EXP(-y)) \qquad (1)$$

where *P(M)* is a probability of exceeding the magnitude M, and y is the reduced variable, which is associated with the magnitude of the linear

$$M = a\,y + b \qquad (2)$$

or nonlinear dependence

$$y = k(ln(v-\omega)-ln(\omega-M)). \qquad (3)$$

where k, v, and ω-unknown parameters to be determined from the observed values of M_i and their corresponding values of the reduced variable y_i. Here ω is the limiting magnitude that cannot be exceeded.

We analyzed the earthquake with a magnitude of at least 6.5, the weaker events of no interest for the problem of tsunami generation. Empirical probabilities for the ordered ascending series of magnitudes were determined by the modified Weibull formula (GUMBEL, 1962):

$$1 - P_i = iN / T(N + 1)\,, \tag{4}$$

where N - the length of the data set, i - number of the magnitude in the ordered series, T - period of observations (in years).

In the case of linear dependence, the parameters a and b are determined by the least squares method. In the nonlinear case, we used an iterative procedure for determining the parameters of the distribution. First, we set the initial value of the limiting magnitude ω_1; values v_1 and k_1 can be determined by the least squares method from the resulting system of equations. Then for these values a new limiting magnitude ω_2 is calculated, etc. With the reasonable initial value, the iterative procedure converges rapidly.

For the series of the strongest earthquakes in each region, the average values of latitude φ and longitude λ of the epicenter were determined. It is possible to use these values as the source coordinates in the study area for tsunami numerical modeling. The standard deviations of epicenter coordinate σ_φ and σ_λ were also calculated, we used these values for the tsunami source shifting $\{\varphi \pm \sigma_\varphi;\ \lambda \pm \sigma_\lambda\}$ for two additional variants of numerical simulations. As a final assessment, we selected for each coastal point the maximum tsunami height from the three variants of the calculations, considering them equiprobable.

The method was tested on the example of the high-seismic areas adjacent to North, Middle and South Kuril Islands – the most tsunami-risk areas of the Russia's Far East (the location of these areas and epicenters of historical tsunamigenic earthquakes are shown in Fig. 1).

For the North and South Kuril Islands the maps of tsunami risk were constructed as previously (KAISTRENKO ET AL, 2009). This allows us to compare the results of our method with more precise estimations. For non-populated Middle Kuril islands the tsunami risk was not estimated.

The regional Kuril-Kamchatka catalogue of strong earthquakes for the period of 1900-2008 years (which included earthquakes with a magnitude of at least 6) was used.

2.1 Numerical modeling

We used a nonlinear shallow-water finite difference tsunami model by V.N. Kharmushin (POPLAVSKY, KHRAMUSHIN, 2008). The length of the fault and source length and width (axis of ellipse) are expressed through the magnitude M and focal depth of earthquakes h_0 as

$$L\text{ (km)} = 0.5\text{ M} - 1.8;\ \ a\text{(km)}=L/2+h_0,\ \ b\text{ (km)} = h_0. \tag{5}$$

Initial tsunami height in the center of the source we can find from the equation

$$lg\,\xi = 0.97\,(1.5M - 4.5\lg h_0 - 4.45), \quad (6)$$

which is the empirical formula based on the statistical analysis of Kuril earthquakes. The typical focal depth of tsunamigenic earthquakes in the high-seismic Kuril-Kamchatka area equals h_0=36 km (POPLAVSKY, KHRAMUSHIN, 2008).

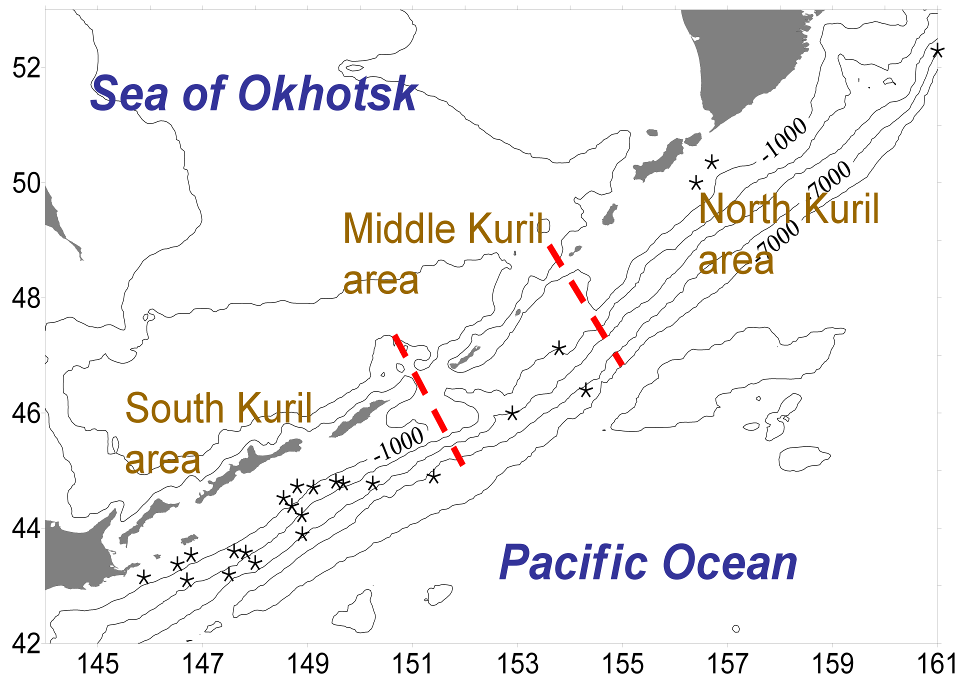

Figure 1. The location of the North, Middle and South Kurile areas. The epicenters of the strong tsunamigenic earthquakes in each area are marked by stars.

3. RESULTS AND DISCUSSION

For the area adjacent to the North Kurile Islands the linear function was well consistent with the empirical distribution of extreme magnitude (Fig. 2). The magnitude for return period 100 years equals 8.2. The magnitude of Great Kamchatka earthquake of November 5, 1952 (M=8.5) corresponds to return period about 200 years. According to magnitude M_{100}=8.2 and focal depth h_0=36, the length of the source equals 272 km (width=72 km), initial height ξ=6.6 m (Fig. 3). The calculated maximal tsunami heights 9 -11 m were obtained on the coast of the Second Kuril Strait (the results for the central position of the source are shown in Fig. 3). This is the most tsunami dangerous (and most populated) stretch of the coast in the North Kuril Islands; there is no settlement in the present time on the safe Okhotsk Sea Coast of Paramushir Island. Another area of relatively high tsunami risk (obtained for the southwestern position of the source) is located on the southeastern coast of the Island. These results are well consistent with more precise estimations (KAISTRENKO ET AL, 2009).

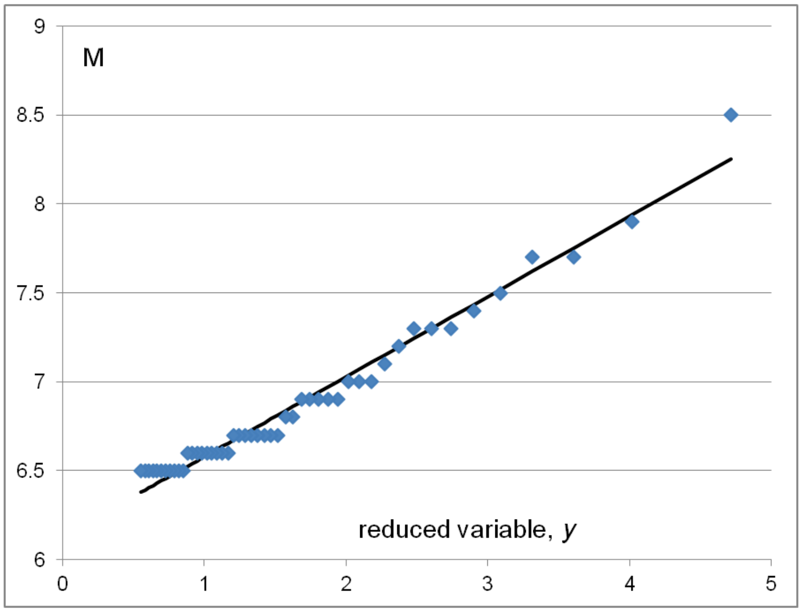

Figure 2. The empirical distribution of earthquake magnitudes and its approximation by linear dependence (2) for the area adjacent to the North Kuril Islands.

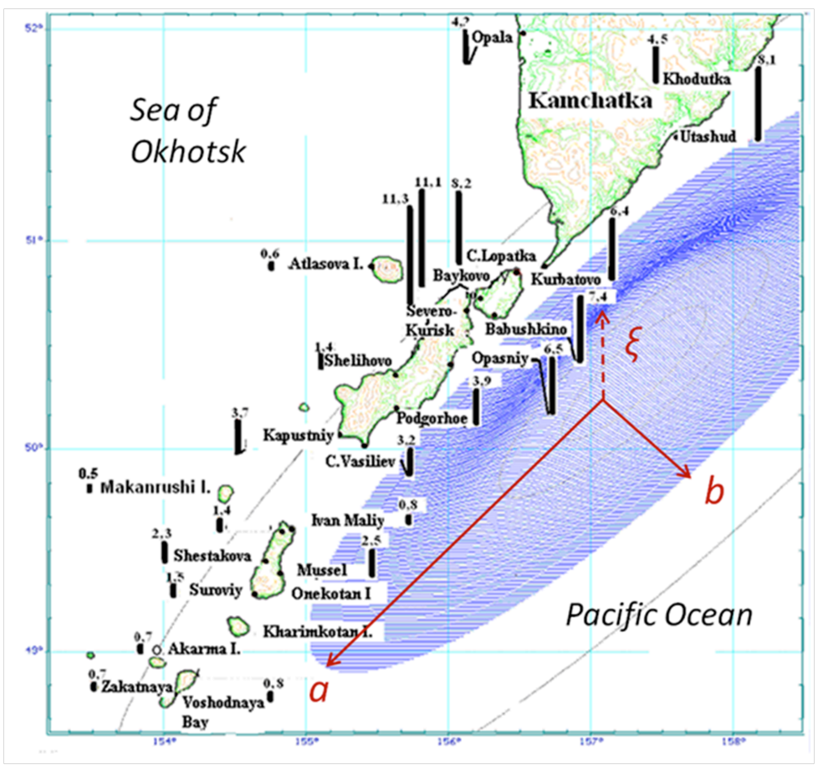

Figure 3. The central location of tsunami source and calculated tsunami heights on the coasts of North Kuril Islands and the southern part of Kamchatka Peninsula.

For the area adjacent to the Middle Kurile Islands the linear function was well consistent with the empirical distribution of extreme magnitude too (Fig. 4). The magnitude for return period of 100 years equals 8.1. This value corresponds to magnitude of strongest Simushir January 13, 2007 earthquake. According to M_{100}=8.1 and typical focal depth h=36 km, the length of the source equals 248 km and the initial height ξ=5.4 m. The calculated maximal tsunami heights 7 - 9 m were obtained on the coast of Simushir, Matua, and Ketoy Islands (Fig. 5a). The maximal historical tsunamis run-up of 12-15 m was found in the same areas after the Great Simushir tsunami of November 15, 2006 (LEVIN ET AL, 2008). However we think that we obtained reasonable results because this tsunami was unusually strong for the magnitude M=8 earthquake (some researchers have attributed the unusual intensity of the tsunami with an underwater landslide).

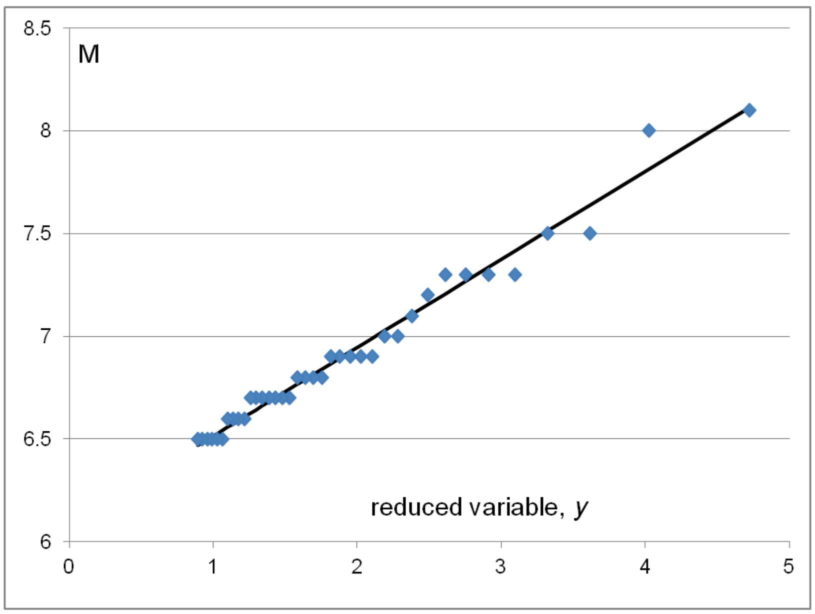

Figure 4. The empirical distribution of earthquake magnitudes and its approximation by linear dependence (2) for the area adjacent to the Middle Kuril Islands.

For the area adjacent to the South Kurile Islands the nonlinear function corresponds to empirical distribution of extreme magnitude, the magnitude for return period 100 years equals 8.3 (M_{100}=8.5 for liner model). According to M=8.3 and typical focal depth h=36 km, the length of the source equals 296, the initial height ξ=9.2 m.

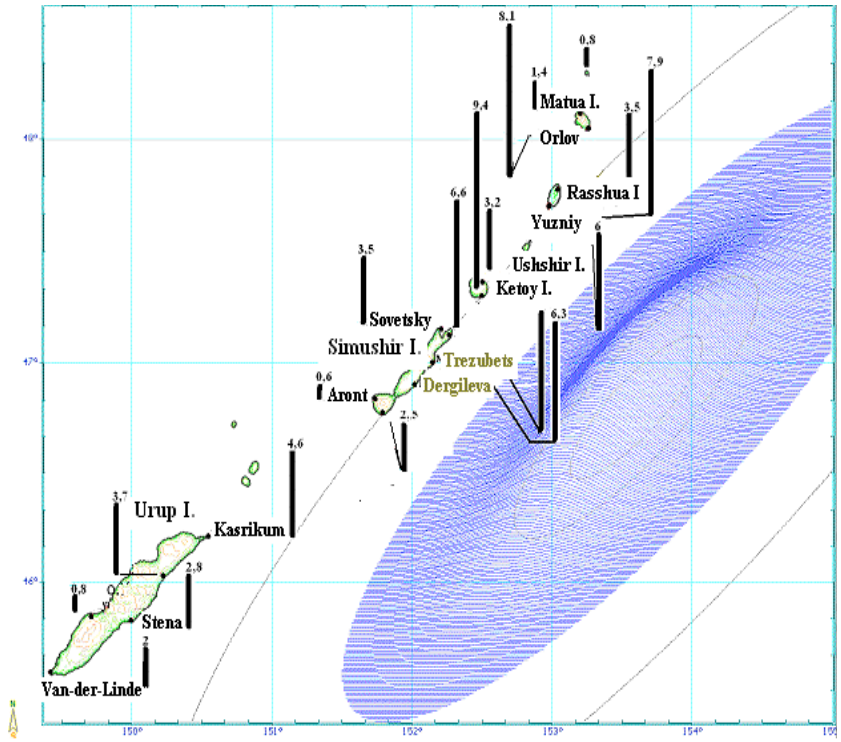

Figure 5a. The central position of tsunami source and spatial distribution of calculated tsunami heights on the coasts of the Middle Kuril Islands.

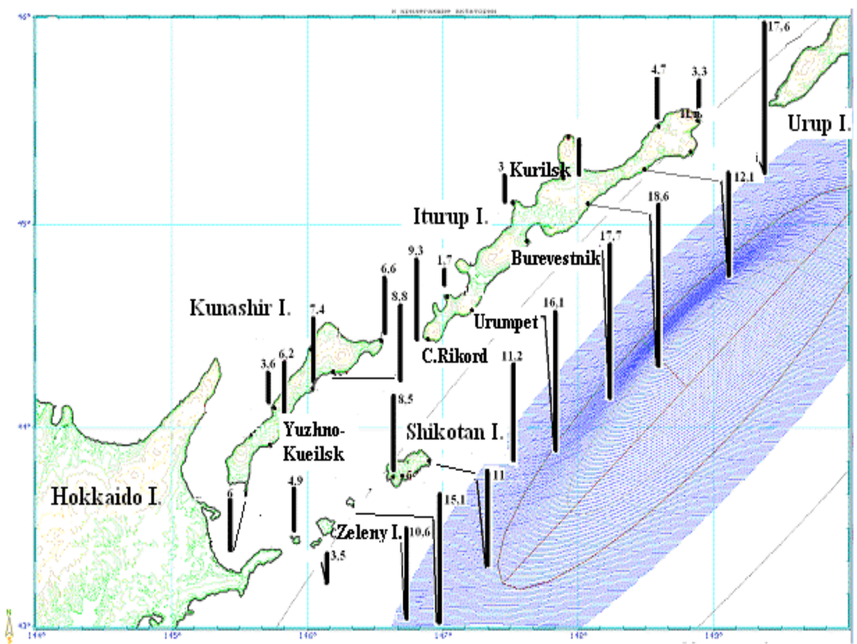

Figure 5b. The central position of tsunami source and spatial distribution of calculated tsunami heights on the coasts of the South Kuril Islands.

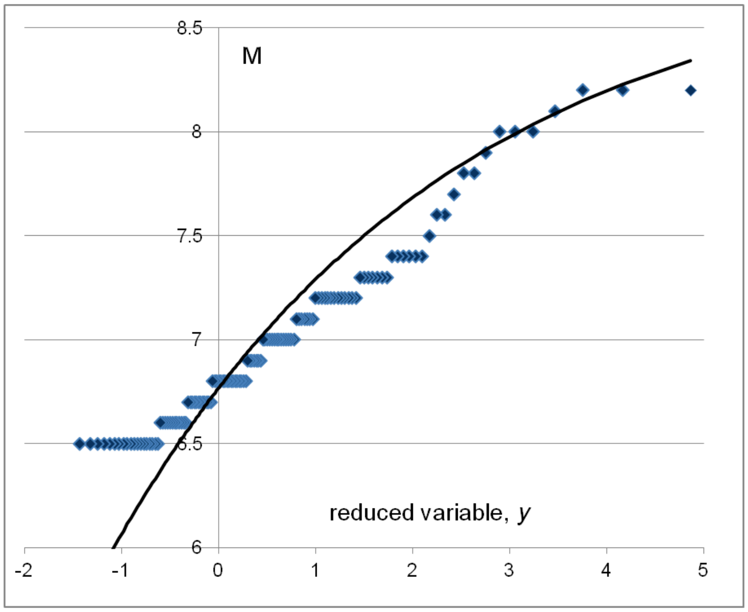

Figure 6. The empirical distribution of earthquake magnitudes and its approximation by nonlinear dependence (3) for the area adjacent to the South Kuril Islands.

To the Pacific coast of Iturup Island the estimated tsunami height were 16-18 m (Fig. 5b), which is significantly higher than for a more accurate method (KAISTRENKO, 2009) (8-10 m). The reason for this overestimation is the fact that earthquakes with M = 8.3 in the South Kuril Islands were not observed during the analyzed period. In addition, the sources of the strongest tsunami were not located in front of Iturup Island as in our model. The calculated maximal tsunami heights 15 -18 m for oceanic coast of Shikotan Island seems quite reasonable and realistic.

4. CONCLUSIONS

For the area adjacent to the North Kuril Islands, the linear function was determined to be in good agreement with the empirical distribution of extreme magnitude. The magnitude for return period 100 years equals 8.2. The calculated maximal tsunami heights 9 - 11 m were obtained for coastal areas bordering the Second Kuril Strait. This stretch of the coast is most vulnerable to tsunamis because of its higher population density. For area adjacent to the South Kuril Islands, the nonlinear function corresponds to empirical distribution of extreme magnitude. The magnitude for return period 100 years equals 8.3. For the Pacific Ocean coasts of Iturup and Shikotan Islands, the maximal tsunami heights were calculated to range from 15-to18 m. In summary, the calculations showed that reasonable estimates of tsunami risk can be obtained under the proposed approach.

5. ACKNOWLEDGEMENTS

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