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Short-term Forecast of Tsunami Occurred on April 1, 2014 on the Kuril Islands Coast

Yu. P. Korolev[a, b] **and V. N. Khramushin**[a]

[a]*Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences, ul. Nauki 1B, Yuzno-Sakhalinsk, 693022 Russia, e-mail: y.korolev@imgg.ru, khram@mail.ru*
[b]*Sakhalin State University, ul. Lenina 290, Yuzno-Sakhalinsk, 693008 Russia*

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Abstract—The results of forecasting the Chilean tsunami in the Pacific Ocean on April 1, 2014 are presented. For the first time in Russia the forecast was prepared in the near real-time mode 9.5–10.5 hours before the tsunami attacked the Russian coast. A good agreement was obtained with the tsunami forms registered by DART stations along the US West Coast and the Aleutian and Kuril Islands. The information about the expected tsunami meets the requirements to the short-term tsunami forecast formulated by UNESCO Intergovernmental Oceanographic Commission.

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INTRODUCTION

The earthquake with the magnitude $M_w = 8.2$ occurred at 23:46:46 UTC on April 1, 2014 off the northern coast of Chile with the epicenter at the point with the coordinates of 19.642 S, 70.817 W [16]. The tsunami warning was issued for the coasts of Chile, Ecuador, and Costa Rica, and population was evacuated from hazardous areas. The tsunami caused the flooding of the closest area of the Chilean coast to the epicenter with the height up to 4 m [16].

Despite the relatively low earthquake magnitude, the national tsunami warning services in the Pacific Ocean (including the Russian service) were in trim for a long period of time. In particular, the Russian tsunami warning service put off making the decision on tsunami warning for the Kuril Islands till the information was received that the tsunami reached the Hawaii Islands. It was key information for such kind of tsunami.

It is known that tsunamis generated off the Chilean coast are potentially dangerous for the Russian Far East coast. The 1960 Chilean tsunami induced by the earthquake with the magnitude of 9.5 caused the registered wave run-ups with the height up to 7 m on the coast of the Kamchatka Peninsula and the Kuril Islands [16]. During the Chilean tsunami on February 27, 2010 caused by the earthquake with the magnitude of 8.8 the tsunami on the Kuril Islands was also expected. The tsunami warning was issued and population was evacuated. Fortunately, the waves with the amplitude of about 1 m did not cause destructions and fatalities [2].

Tsunami is a natural disaster whose danger can be predicted in order to provide timely alert and evacuate population. At the moment the tsunami forecast is possible using the information about the formed tsunami obtained from the open ocean. This idea was proposed almost synchronously in the USSR and USA in the late 1960s [6, 8]. It was not realized in practice for a long time due to technical difficulties, mainly because there were no methods of its implementation. After high-accuracy deep bottom stations for measuring the hydrostatic pressure (DART system [12]) which could measure the sea surface level had appeared, it became possible to realize the idea. Two stations of this system (DART 21401 and 21402) were installed in 2010 and 2012 in the interests of the Russian tsunami warning service in the area of the Kuril Islands on the oceanic side of the Kuril–Kamchatka Trench [13, 15].

The problem of short-term tsunami forecasting consists in the fact that warning services should issue not only the grounded general warning but also the warning that differentiates the degree of danger for the concrete areas of the coast. In the ideal case, the tsunami warning should be issued only for the areas where tsunami may cause real danger. It should be accompanied by information about the arrival time of the first wave, wave height, number of waves and time periods between them, about the arrival time and height of the maximum wave as well as about the expected time of the tsunami end (all-clear signal) [4, 10]. The same requirements are contained in the definition of the short-term tsunami forecast recently formulated by UNESCO Intergovernmental Oceanographic Commission (IOC) [9].

The regulations in force based on the magnitude criterion do not give quantitative information on the expected tsunami and do not differentiate the alert for separate areas that leads to the significant number of false alarms [4]. It was recognized in [7] that the quality criteria of the operation of tsunami warning services cannot be considerably improved if only the magnitude-geography forecasting method is used without the hydrophysical information on tsunami.

In the USA the forms of expected tsunami are successfully computed from the data of DART deep stations [12]. However, currently the results are not used in the normal mode. Some results are presented, for example, at the website [14].

METHOD OF SHORT-TERM TSUNAMI FORECASTING

The method of short-term tsunami forecasting used in the present paper develops the idea proposed in [6, 8]. The method enables computing the form of tsunami at the specified points off the coast using the tsunami data received from DART bottom stations.

The data of offshore tide gages and coastal automatic sea-level observation stations cannot be used for short-term forecasting because they do not provide the required lead time.

The method is based on the well-known principle of reciprocity [1], in particular, on its consequence, that is, on the tsunami spectrum similarity ratio [10]:

$$\frac{(s,\ A)}{(s,\ A)} \qquad \frac{(s, M)}{(s, M)}$$

where (s, A) and (s, M) are the spectra of the same tsunami at points A and M; (s, A) and (s, M) are the spectra of another tsunami at the same points A and M. Epicenters of both tsunamis coincide. The spectrum is an integral transform (for example, Laplace or Fourier). This ration does not prove but corroborates the well-known empirical fact that the spectra of the same tsunami at different registration points are different, but the spectra of different tsunamis at the same point are similar [11].

The computation formula follows from the similarity ratio:

$$(s,\ A) \qquad (s, M)\frac{(s,\ A)}{(s,\ A)}$$

where (s, A) is the spectrum of tsunami at the specified point A off the coast (of tsunami expected at the point to warn); (s, A) is the spectrum of numerical tsunami at the same point; (s, M) and (s, M) are the spectra of real and simulated tsunami, respectively, at point M where the sea level is measured.

The ratio in the right part of the equation is a transfer function which enables converting the form of tsunami at the distant point M into the form of tsunami at the specified point A off the shore. To construct the transfer function, the auxiliary (model) source is specified in the form of circular initial elevation of free surface with the center coinciding with the earthquake epicenter, and the wave form at points M and A is computed. The result of computation is the wave form of expected tsunami with the needed duration located close to the points for which the forecast is made [3, 10]. The rather long duration of the forecast allows taking into account possible secondary waves which often have the amplitudes much above those of leading waves; it also allows estimating the duration of the possible tsunami alert. To produce the forecast, information only on earthquake epicenter coordinates is needed from the seismic subsystem. There is no need in the broad detailed network of seismic stations [4].

The forecast lead time is defined by the tsunami travel time to the registration point in the open sea plus the time of tsunami detection (the first half-period with the duration of about 15 minutes). The method enables determining the degree of tsunami danger at the specified coastal points with the accuracy sufficient for the practical use.

The method of operational tsunami warning was used for the hindcasting of past events [4, 10]. The results demonstrate good coincidence of simulated and registered tsunamis both in the open sea and near the Kuril Islands settlements.

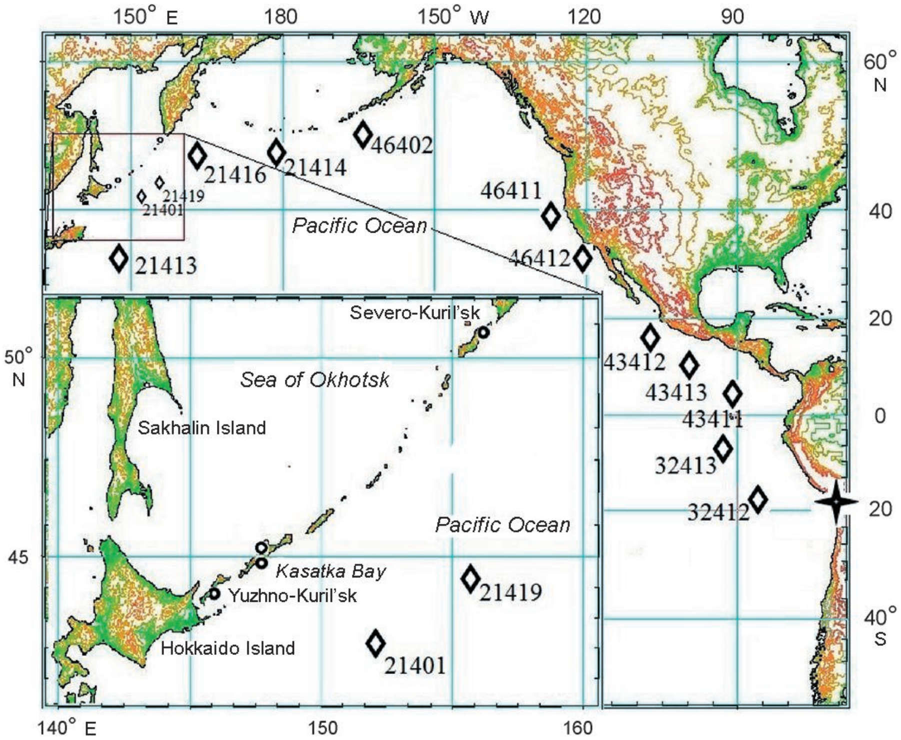

Fig. 1. The scheme of location of DART stations (rhombs). The asterisk is the earthquake epicenter on April 1, 2014.

THE FORECAST OF THE CHILEAN TSUNAMI ON APRIL 1, 2014

The proposed method was applied to the forecast of the Chilean tsunami on April 1–2, 2014. Below the process and result of forecasting are described. The forecast was made almost in the real-time mode; therefore, the characteristic time moments of the computation process are presented below. Unless otherwise stipulated, the time is given in UTC (local (Sakhalin) time differs by 11 hours).

The beginning of computation of transfer functions is 09:00. For this purpose the source was specified in the form of circular initial elevation of free surface with the maximum amplitude of 10 m and with the diameter of 75 km with the center coinciding with the earthquake epicenter. Figure 1 presents the scheme of location of DART stations in the Pacific Ocean as well as of the settlements under protection on the Kuril Islands. The computation was carried out for the offshore points where DART stations are located as well as near Severo-Kuril'sk (Paramushir Island), Yuzhno-Kuril'sk (Kunashir Island), and Burevestnik port station in the Kasatka Bay (Iturup Island). The computation of sea waves was carried out using the software described in [5] at the difference grid in the geographic coordinates with the grid spacing of 5 km at the equator.

At 09:40 transfer functions for DART 43413 and 43412 stations were constructed (the sea level data from DART 32412, 32413, 43413 (with the duration of 115 minutes), and 43412 (with the duration of 45 minutes) were available [15]). The data from DART 32413 station were taken as reference data (on their basis the forecast was made). The comparison of computations with DART 43413 data (Fig. 2) demonstrated their adequacy and enabled counting on the rather accurate forecast for the area of the Kuril Islands.

The results of computations (by 10:00) for some points and comparison with the actual data are presented in Fig. 2. The comparison of the results of computation with actual data [14] for other points was carried out after the tsunami had passed these points (in the morning on April 3 (local time)).

In the process of propagating from California along the US western coast, along the Aleutian Islands to the Kuril Islands and Japan, the tsunami remained almost invariable, the wave form and amplitude equal to 0.5 cm were kept. The same form and amplitude were predicted for the point where DART 21416 station is located which did not register the tsunami.

The duration of computation (the forecast production for the points in the ocean off the Aleutian and Kuril islands) is about an hour. The rather good agreement between the results of computation and the

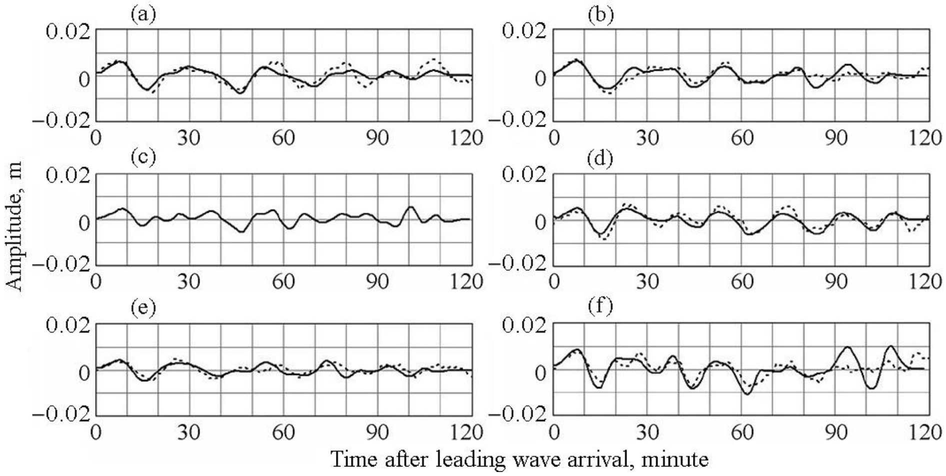

Fig. 2. Simulated and observed forms of tsunami in the ocean. The solid line is the forecast, the dotted line is observations. DART stations: (a) 21414, (b) 46402, (c) 21416, (d) 46411, (e) 21419, and (f) 43413.

forms of tsunami registered in the open ocean by DART stations corroborates the possibility of using the method for short-term tsunami forecasting.

TSUNAMI FORECAST FOR THE KURIL ISLANDS

The preliminary forecast for the Kuril Islands localities was made proceeding from the analogy with the Chilean tsunami in 2010. This tsunami was registered by the nearest station (DART 21416) to the Kuril Islands as well as in Severo-Kuril'sk. The measurement data are presented in Fig. 3. The maximum amplitudes of the 2010 tsunami were about 5 cm at DART 21416 station and 1 m in Severo-Kuril'sk. The amplification factor was equal to about 20.

The simulated 2014 tsunami at the nearest stations to the Kuril Islands DART 21419 (subsequently corroborated by instrumental measurements, see Fig. 2) and DART 21416 should have the amplitude of 0.5 cm. Thus, in the morning of April 3, 2014 (local time), proceeding from the simulated tsunami at DART 21416 station and from the amplification factor equal to 20, the tsunami should be expected to have the maximum amplitude of about 10 cm in Severo-Kuril'sk and not more than 5 cm at other points of the Kuril Islands. This preliminary forecast was produced at 10:30, that is, 10 hours before the expected tsunami arrival to Severo-Kuril'sk.

It should be noted that the expected time of receiving information about the tsunami occurrence on the Hawaii Islands is about 15:00. The preliminary forecast of expected tsunami on the Kuril Islands was issued 4.5 hours before that time moment. When the information was received that the amplitude of tsunami on the Hawaii Islands was equal to 1 cm and reached 0.5 m only in some places [16], at 15:00 (02:00 local time) the tsunami center decided not to issue the tsunami warning for the Kuril Islands.

At 10:00 the transition was carried out to the grid with the higher resolution of 900 m at the latitude of 45 N in order to compute transfer functions for the Kuril Islands localities. As a result, the forms of expected tsunami were obtained (Fig. 3).

In Severo-Kuril'sk (Paramushir Island; Fig. 1; at the distance of 1.1 km to the east of the port, the depth is 16 m) leading waves with the amplitude up to 4 cm and the arrival time at 20:40 on April 2, 2014 (07:40 on April 3 (local time)) were predicted. In Burevestnik (the Kasatka Bay, Iturup Island; Fig. 1; at the distance of 2.1 km to the north of the port, the depth is 30 m), the waves with the amplitude up to 4 cm and the tsunami arrival time at 21:15 on April 2, 2014 (08:15 on April 3 (local time)) were expected. In Yuzhno-Kuril'sk (Kunashir Island; Fig. 1; at the distance of 5.4 km to the east of the port, the depth is 29 m) leading waves with the amplitude up to 3 cm and the arrival time at 21:40 on April 2, 2014 (08:40 on April 3 (local time)) were predicted.

The structure of predicted tsunami way in Severo-Kuril'sk is similar to that of the 2010 tsunami: the arrival of waves with maximum amplitudes up to 8 cm, the lag relative to the leading wave arrival equals 3.5 hours. The duration of the second stage of computation is about an hour. The updated forecast was

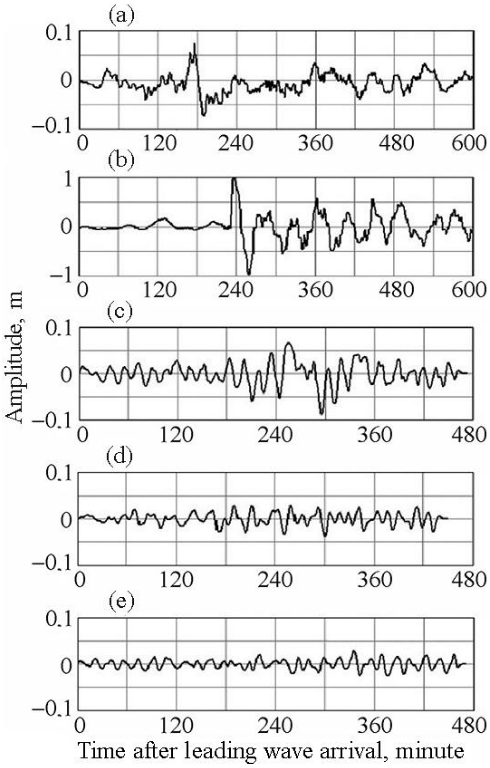

Fig. 3. The forms of the 2010 tsunami registered by (a) DART 21416 station and (b) tide gage in Severo-Kuril'sk and the forecast of the 2014 tsunami near the Kuril Islands localities: (c) Severo-Kuril'sk, (d) the Kasatka Bay, and (e) Yuzhno-Kuril'sk.

produced by 11:00, that is, 9.5–10.5 hours before the expected tsunami arrival to the Kuril Islands localities. Unfortunately, it is impossible to compare the forecast with the real tsunami registered with instrumental observations, because the recorders of tsunami warming service at the mentioned points were demounted in the summer 2013.

The estimation of wave amplitudes from the computation point (Severo-Kuril'sk) towards the shore almost to the shoreline gives a 10–25 cm increase in amplitudes. According to visual sea level observations by L. Kotenko, the tsunami had the maximum amplitude of about 20 cm near the shoreline at the distance of about 1 km to the south of the Severo-Kuril'sk port. Visual evidences of tsunami in Burevestnik and Yuzhno-Kuril'sk are absent.

DISCUSSION AND CONCLUSIONS

The forecast of the Chilean tsunami on April 1, 2014 was produced almost in the real-time mode for the first time in Russia. The comparison of the results of computation of tsunami in the ocean with the data from DART stations demonstrates the sufficient accuracy of wave form simulation.

The forecast of the amplitudes of expected tsunami gave their insignificant value, mainly up to 4 cm, and the arrival of maximum waves with the amplitude up to 8 cm in Severo-Kuril'sk with the lag of about 3.5 hours. The amplitudes of expected waves in Burevestnik and Yuzhno-Kuril'sk were also insignificant, up to 3–4 cm.

The preliminary forecast for the Kuril Islands was produced 4.5–4.0 hours before receiving information on tsunami occurrence on the Hawaii Islands. The detailed forecast for the Kuril Islands was made 9.5–10.5 hours before the wave arrival to the Kuril Islands coast. Based on these computations, the tsunami warning could not have been issued. The full time of computation (forecast preparation) is about 2 hours, and the time of tsunami propagation from the source to the Kuril Islands is 21–22 hours.

For the close tsunamis (for example, tsunami Tohoku, 2011) the time of transfer function construction did not exceed 25 minutes whereas the tsunami travel time to the nearest station DART 21401 is 58 minutes. Taking into account the time of tsunami detection at the registration point (the first half-period with the duration of 20 minutes), the preliminary forecast could have been made in 78–80 minutes after the main shock of the earthquake [4].

The quality of the forecast produced in accordance with the proposed method for the short-term tsunami forecast is comparable with that of the method proposed in [12]. To provide computations by the described method, information only on earthquake epicenter coordinates was required. The time of computations by this method is much larger than that of the method from [12]. However, unlike in [12], the proposed method does not require the creation of the giant base of synthetic mareograms, and the computation can be carried out using any computer providing the possibility of receiving the sea level data from DART stations.

The presented results (as well as those published before [4, 10]) of using the method of the short-term tsunami forecast demonstrate that the quality of the early tsunami forecast is sufficient to make the decision of tsunami alerting. It is also possible to identify the localities, where the tsunami is of real danger, in advance. The computed form of expected tsunami enables determining the basic tsunami parameters such as the time of leading wave arrival, wave amplitudes, the arrival time and amplitude of the maximum waves, and the time of tsunami end. Thus, the tsunami forecast based on the proposed method meets all requirements to the short-term tsunami forecast stated by UNESCO IOC [9].

The method of short-term tsunami forecast implemented within the single software package, may be an instrument which could improve the quality of operational tsunami warning and significantly reduce the number of tsunami false alarms.

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