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Original article

Express Method for Operational Tsunami Forecasting: Possibility of its Application on the Pacific Coast of Russia

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Abstract
Purpose. The work is aimed at studying the possibility of short-term tsunami forecasting in the Kuril Islands based on the data on tsunamis in the open ocean.
Methods and Results. The methods underlying the actions of tsunami warning services in the northwestern Pacific Ocean are considered. The warning services relying on primary seismological information on an earthquake (magnitude criterion), produce a large number of false tsunami alarms. An adequate forecast is provided by the services that use information on a tsunami formed in the open ocean (hydrophysical methods). The problem of short-term (operational) tsunami forecasting for the Kuril Islands is described. Information on the actions of tsunami warning services during the events is provided. The process of forecasting using the express method of tsunami operational forecast is numerically simulated under the assumption of obtaining real-time information on tsunamis in the ocean. The events of 2006–2020 in the northwest Pacific Ocean are simulated. The results of numerical experiments involving actual data confirms the fact that the express method can be used for a short-term tsunami forecast in specific locations of the Kuril Islands with an advance time sufficient for taking a timely decision to declare an alarm and evacuate the population from hazardous places.
Conclusions. Development of the express method for short-term tsunami forecasting, provided that information on tsunamis in the ocean is available quickly, will make it possible to improve in future the quality of forecasting and thereby reduce the number of false tsunami alarms on the Kuril Islands. The necessity of creating own, Russian, deep-sea ocean level measurement stations is shown.

Keywords: tsunami, tsunami forecast, short-term tsunami forecast, operational tsunami forecast, tsunami alarm, false tsunami alarms, Tohoku tsunami, ocean level, ocean level measurements, tsunami warning services, Pacific Ocean, Kuril Islands

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Introduction

Short-term (operational) tsunami forecasting still remains an unsolved problem in a number of countries in the Pacific, Indian and Atlantic Ocean basins. Tsunami warning services in these countries issue timely tsunami alarms in the event of underwater earthquakes, often false alerts [1, 2]. It is generally accepted that a false

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tsunami alarm is an event in which an alarm is issued, the population is evacuated, but the waves do not cause flooding or damage [1]. False tsunami alarms, often issued too early, do not cause direct losses, but they do cause damage associated with the shutdown of production in hazardous areas, the evacuation of the population to safe zones, and the removal of ships to the open sea. In this case, all types of activity in the coastal zone stop for several hours [3].

The objective of operational (short-term) tsunami forecast is to obtain information about the expected tsunami in advance. It should include the time of arrival of the first wave, the number of waves, their amplitudes, time intervals between them, and the duration of the tsunami [4]. These characteristics of the tsunami are also listed in the definition of the concept of "tsunami forecast" formulated by the UNESCO Intergovernmental Oceanographic Commission (IOC) in 2013.[1] Based on such information, a decision should be made to declare a tsunami alarm with reasonable lead time only at those points where the tsunami poses a real threat. The lead time of the forecast is understood to be the time that passes from the moment the forecast is developed until the expected tsunami arrives at a given point.

The purpose of the operational tsunami forecast is to ensure the safety of population, movable property, sustainability of the coastal infrastructure and coastal territories functioning in conditions of a probable tsunami risk.

A review of the state of the art in the field of tsunami forecasting is given in [1, 2]. The works describe the principles underlying the actions of various tsunami warning services (TWS). The principles of operation of tsunami warning services in the northwestern Pacific Ocean are described in [3].

In the practice of tsunami warning services, two main approaches are used, based on information about an earthquake or tsunami in the open ocean. The first of them, the magnitude-geographical method, proposed about 60 years ago at the very beginning of the development of tsunami warning services, is based on empirical relationships between the magnitude of an earthquake and the intensity of a tsunami. This approach is the cause of a large number (at least 75%) of false tsunami alarms declared by all services [1, 5, 6]. Approaches based on the relationship between the magnitude of an earthquake and its probable mechanism are proposed and implemented by tsunami warning services in Japan [2], Australia [7], and Russia [8]. Tsunami forecasting is performed using a database of precomputed mareograms near the coast from many seismic sources with the most probable mechanism.

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[1] UNESCO, 2019. *Tsunami Glossary. Intergovernmental Oceanographic Commission. Fourth Edition*. Paris: UNESCO, pp. 35-36. (IOC Technical Series; 85). [online] Available at: https://unesdoc.unesco.org/ark:/48223/pf0000188226 [Accessed: 15 June 2024].

[2] UNESCO, 2019. Users' Guide for the Northwest Pacific Tsunami Advisory Center (NWPTAC): Enhanced Products for the Pacific Tsunami Warning System. Paris: UNESCO, 35 p. (IOC Technical Series; no. 142). [online] Available at: https://unesdoc.unesco.org/ark:/48223/pf0000366546?posInSet=1&queryId=d1288da0-390e-47b1-8a51-a529b04abf93 [Accessed:15 June 2024].

Another approach is associated with the development of a network of DART stations (Deep-ocean Assessment and Reporting of Tsunamis) for observing ocean levels [3]. The expected tsunami is forecast using the NOAA (National Oceanic and Atmospheric Administration) hydrophysical forecasting method [3], also known as the SIFT (Short-term Inundation Forecasting for Tsunamis) method [4] [9, 10]. Based on ocean tsunami data, wave forms are computed at specified points in the ocean or near the coast using a pre-created giant database of synthetic mareograms. The degree of coincidence between the computed wave forms and real mareograms is not assessed during the computations [3]. Tsunami forecasts using the NOAA method correspond to the UNESCO IOC definition. This real-time forecasting methodology is currently officially used by the US tsunami warning services [2]. The NOAA (SIFT) method is not applicable to areas for which there is no pre-computed database of synthetic mareograms [3].

A similar but more rigorous approach proposed in [11] identifies the most informative points for tsunami forecasting. Using a set of such points specific to each event can be useful in developing an optimal tsunami observation system. This approach assumes the possibility of operational tsunami forecasting.

The Far East coast of the Russian Federation, especially the Pacific coast of the Kuril Islands, is considered a tsunami-hazardous area [5].

In 2024, it was 72 years since the devastating tsunami of November 4–5, 1952, on the northern Kuril Islands. The tsunami was caused by an earthquake with a magnitude of 9 southeast of the Kamchatka Peninsula and caused flooding on the coasts of Paramushir Island and Shumshu Island (northern Kuril Islands) up to 23 m high [6]. The city of Severo-Kurilsk and all settlements on these islands were destroyed. There are many publications dedicated to this event, for example [7].

After the 1952 tsunami, a tsunami warning system was created in Russia, based on information about earthquakes (magnitude and epicenter coordinates).

The strongest earthquake with a magnitude of 9.1 on March 11, 2011east of the Honshu Island caused flooding of the Kuril Islands coast with a maximum splash height of up to 2.5 m on Paramushir Island, over 2 m on Kunashir Island and up to

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[3] NOAA, 2024. *NOAA Center for Tsunami Research*. [online] Available at: http://nctr.pmel.noaa.gov/ [Accessed:15 June 2024].

[4] Gica, E., Spillane, M.C., Titov, V.V., Chamberlin, C.D. and Newman, J.C., 2008. *Development of the Forecast Propagation Database for NOAA's Short-Term Inundation Forecast for Tsunamis (SIFT)*. Seattle, WA: Department of Commerce, 95 p. (NOAA Technical Memorandum OAR PMEL-139).

[5] FSBI "Sakhalin Administration for Hydrometeorology and Environmental Monitoring", 2024. *Tsunami Center*. [online] Available at: http://sakhugms.ru/index.php/o-nas/strutura/tsentr-tsunami [Accessed: 15 June 2024] (in Russian).

[6] NCEI, 2024. *Hazard Tsunami Search.* [online] Available at: https://www.ngdc.noaa.gov/hazel/view/hazards/tsunami/event-search [Accessed: 15 June 2024].

[7] *1952 Tsunami, Severo-Kurilsk*. [online] Available at: http://www.sakhalin.ru/Region/Tsunami_1952/tsunami_1952.htm [Accessed: 15 June 2024] (in Russian).

2 m on Iturup Island [6]. Based on the magnitude of the earthquake and information DART 21401 station, a tsunami alert was promptly issued for the Kuril Islands, and the population was evacuated [12].

In 2006 and 2007, two earthquakes occurred to the east of Simushir Island (central Kuril Islands). The first of them (15.11.2006) had a magnitude of 8.3, the second one (13.01.2007) – 8.1. In both cases, in all populated areas of the Kuril Islands, in accordance with the regulations based on the magnitude criterion, tsunami alerts were simultaneously issued, and the population was evacuated. The tsunami splashes were up to 21.9 m on the nearest uninhabited central Kuril Islands [13, 14]. At the same time, in populated areas the tsunamis were insignificant and did not pose a danger: for example, in Yuzhno-Kurilsk the maximum amplitudes were 0.28 m in the first event and 0.06 m in the second one [6].

On March 25, 2020, an earthquake with a magnitude of 7.5 occurred east of Onekotan Island (Northern Kuril Islands) at 13:49 Sakhalin time. Since information on the actions of warning services during an event is usually not published, the actions of tsunami warning services during this event are described below. This will allow you to understand the current order of actions of the TWS and assess possible changes in the future.

At 13:57 Sakhalin time, the Pacific Tsunami Warning Center (PTWC) issued a bulletin warning of dangerous tsunami waves for the coast within 1000 km from the epicenter of the earthquake. A tsunami alert for the Severo-Kurilsk district was declared by the Yuzhno-Sakhalinsk seismic station at 14:00 based on the magnitude criterion. The Tsunami Advisory Center for the Northwest Pacific Ocean, namely the Japan Meteorological Agency (JMA), also warned at 14:16 about possible destructive tsunami waves on the Kuril Islands with an amplitude of 1–3 m. The tsunami was expected to arrive in Severo-Kurilsk at 15:04. The evacuation of 400 people was completed at 14:30, half an hour before the expected arrival of the wave. The wave height at the expected time outside the settlement, according to visual assessment against the background of storm waves, was 50 cm [5]. There is no data on the manifestation of a tsunami in the port of Severo-Kurilsk. The duration of the alarm mode was about 4 hours [15].

In the last three events, due to the small amplitude of the waves in the settlements, the alarms declared in them were clearly false.

At present, when deciding to issue a tsunami alert, Russian tsunami warning centers rely on the magnitude-geographic criterion developed about 60 years ago and warnings issued by the PTWC and JMA, which results in false tsunami alerts. The Russian tsunami warning service does not have its own deep-sea ocean level measurement stations that allow for ocean level monitoring and operational tsunami forecasting, and does not use open ocean tsunami data in its activities [8]. For this

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[8] *Kamchatka Branch of Geophysical Survey RAS.* [online] Available at: https://emsd.ru/conf2019/pdf/solution.pdf [Accessed: 07 October 2024]; https://emsd.ru/files/conf2021/resolution_tsunami.pdf [Accessed: 07 October 2024]; https://emsd.ru/files/conf2023/result.pdf [Accessed: 07 October 2024].

reason, as well as due to the lack of modern operating forecasting methods, tsunami centers do not provide an adequate tsunami forecast for the coast of the Far East. The NOAA (SIFT) method for forecasting tsunamis on the Russian Far East coast is not applicable due to the lack of an appropriate synthetic mareograms database.

A legitimate question arises: is it possible to fundamentally improve the work of tsunami warning services, to significantly increase the quality of the forecast?

The aim of the work and the statement of the problem

For the Russian warning service, transoceanic tsunamis occurring off the coast of South America do not cause concern. The decision to declare an alarm is based on information about the manifestation of a tsunami in the Hawaiian Islands. However, the criterion for the danger of a tsunami in the Kuril Islands depending on the heights of the tsunami in the Hawaiian Islands has not been developed. Waves with amplitudes of 2 m, recorded in the Hawaiian Islands, are not considered as a factor in the occurrence of a noticeable tsunami hazard in the Kuril Islands [16, 17].

When a tsunami occurs near the Kuril Islands, the decision to declare an alarm is made based on the magnitude-geographic method. If the magnitude is above the threshold, a tsunami alarm is declared in all populated areas of the islands.

Based on the question posed above, the purpose of the work was to study the possibility of an operational, reliable tsunami forecast in the Kuril Islands based on data on tsunamis in the open ocean.

To achieve the goal, a numerical simulation of the process of operational tsunami forecasting using the express method was performed under the assumption of obtaining information about tsunamis in the ocean in real time. It was assumed that the time of forecast generation and the time of tsunami alarm announcement coincide. Information from deep-sea ocean level measuring stations of the DART system located near the Kuril Islands, which were in operation during the event, or reconstructed data from stations that were in operation earlier or installed later, were used.

The quality of the tsunami forecast is assessed by its ability to determine the degree of threat and the need to announce an alarm only in those places where a tsunami poses a real threat [3].

The method for operational (short-term) tsunami forecast

As noted, tsunami centers currently do not provide adequate tsunami forecasts for the Far East coast. Detailed information on the expected tsunami based on ocean level data could be obtained using the express method of operational forecasting [4].

The express method consists of computing the waveform of the expected tsunami at a given point A based on data on the tsunami in the ocean at point M using the transfer function (the ratio on the right-hand side) in accordance with the relation:

$$\zeta(A,s) = \zeta(M,s) \cdot \frac{\eta(A,s)}{\eta(M,s)}. \tag{1}$$

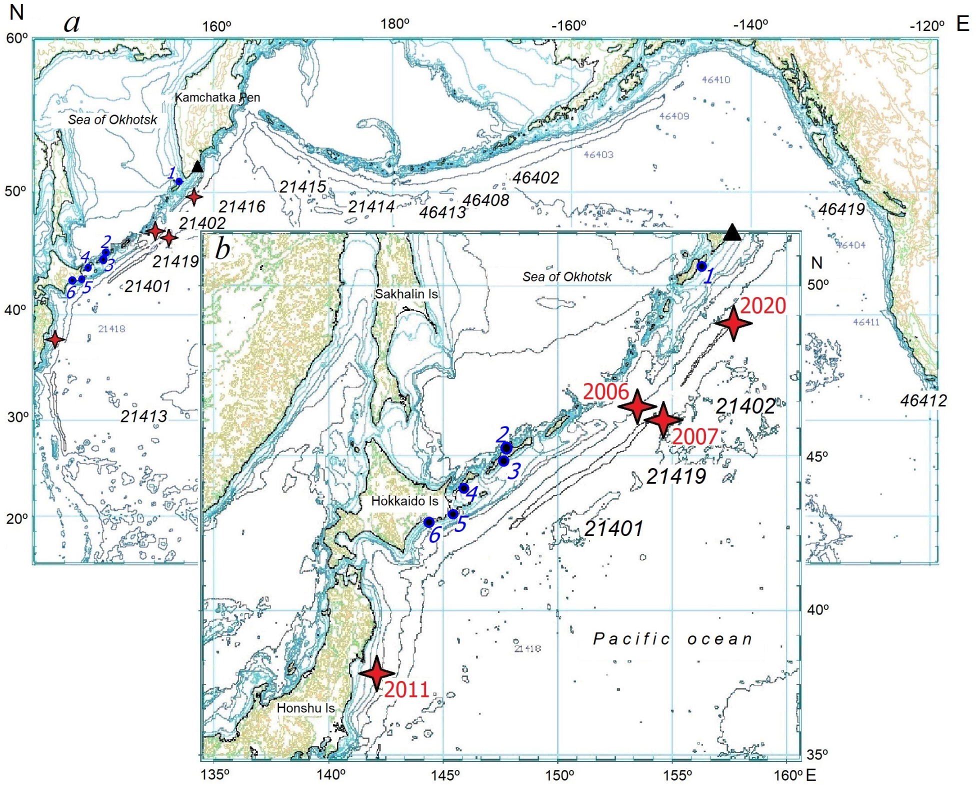
All functions included in (1) are images (spectra) of the discrete integral Laplace transform of the corresponding data series. Expression (1) is a consequence of the similarity relation of the spectra of wave forms at points A and M of two different tsunamis (functions $\zeta(A, s)$, $\zeta(M, s)$ and functions $\eta(A, s)$, $\eta(M, s)$) with the same epicenter $\frac{\zeta(A,s)}{\zeta(M,s)} = \frac{\eta(A,s)}{\eta(M,s)}$, which is derived from the fundamental reciprocity principle [4].

If the functions $\eta(A, s)$, $\eta(M, s)$ are known for each point A, then the inverse Laplace transform of relation (1) yields the waveforms of the expected tsunami at each of these points. In practice, due to the fact that in the operational mode only the coordinates of the epicenter are known about the earthquake (the magnitude does not matter), a numerical model of waves propagating from a model (auxiliary) source in the form of an initial circular elevation of the free surface of arbitrary amplitude, for example, 10 m, with the center coinciding with the epicenter of the earthquake is adopted as the second tsunami. The diameter of the source is a characteristic transverse horizontal size of the tsunami source, 100 km. This is the main assumption of the method. It is assumed that the similarity, although approximate, is observed. The computation of waveforms from the auxiliary source at points M and A is performed during the event immediately after receiving information about the coordinates of the earthquake epicenter. In this case, there is no need to create a giant database of precomputed mareograms. Due to the approximate nature of the method, a complete match between the computed and actual waveforms is not expected. A fairly accurate forecast of the main characteristics of the expected tsunami is expected: arrival time, amplitude and duration of the head wave, arrival time and amplitude of the maximum wave.

The initial version of the method is described in [4]. Later, for operational use, it was proposed to use data on tsunamis with a duration equal to the first half-period/period of the tsunami in the ocean [18]. In [4], the success of the short-term tsunami forecast method is shown in computing waveforms at DART stations that recorded the 2006, 2007 and 2009 tsunamis in the northern Pacific Ocean. The effectiveness of the express method for forecasting transoceanic tsunamis occurring near the coast of South America, in the ocean, and near the Kuril Islands is shown in [3, 19]. The quality of tsunami forecasts for points in the ocean using the express method and the NOAA method is comparable [3].

Results

The processes of operational forecasting of the 2006, 2007 Simushir and 2020 Onekotan tsunamis, as well as the 2011 Tohoku tsunami on the Kuril Islands, were simulated.



F i g. 1. Scheme of the computation areas: *a* – location of *DART* stations in the northern Pacific Ocean, the data from which are used for comparison with the calculated ones; *b* – the area near the Kuril Islands used in modeling the process of operational tsunami forecasting (black numbers indicate the location of *DART* stations; red stars – the earthquake epicenters with the year indicated; black triangle – the location of automated tide gauge "Vodopadnaya" (southeastern tip of Kamchatka); blue numbers – the settlements: *1* – Severo-Kurilsk (Paramushir Island), *2* – Kurilsk (Iturup Island), *3* – Burevestnik (Iturup Island), *4* – Yuzhno-Kurilsk (Kunashir Island), *5* – Hanasaki (Hokkaido Island) and *6* – Kushiro (Hokkaido Island))

In numerical experiments, actions similar to those that would be performed in real conditions were performed, observing the time frames: obtaining information on the coordinates of the earthquake epicenter (7–11 minutes after the main shock), constructing a transfer function immediately after receiving this information, receiving information on the sea level from the station closest to the source. The construction of the transfer function must be completed before receiving information on the level. Modern fast computation methods make it possible to do this in a short time [20]. The final computations (inverse Laplace transform) are performed immediately after receiving information on the passage of the first quarter of the first period, half-period or full period of the tsunami through the registration point. The forecast lead time was determined. The moment of tsunami arrival at a given point was estimated as the moment of the first wave arrival (sometimes this moment is understood as the time of arrival of the first wave maximum). Subsequently, as level information is received, the forecast can be refined.

The scheme of the computation areas indicating the epicenters of earthquakes (tsunami sources), locations of DART stations and points on the coasts of the Kuril Islands and Hokkaido Island, for which the forecast was made, is shown in Fig. 1. Figure 1, a shows the locations of DART stations in the northern Pacific Ocean. The data from these stations were compared with the calculated ones to confirm the adequacy of the results. The computations were performed in spherical coordinates. The step of the difference grid covering the northern part of the Pacific Ocean is 3800 m at a latitude of 40º. Bathymetric data [21, 22] were used in computing wave propagation in the ocean. The computational domain of the Kuril Islands region (Fig. 1, *b*) was used to model the process of operational tsunami forecasting using the express method. The step of the difference grid of this region had a step of 900 m at a latitude of 45º.

Data from DART stations [9] and tide gauges [10, 11] were used. Tidal components and oscillations caused by the passage of seismic waves along the bottom (seismic noise) were removed from the records during the computations.

Several DART stations, installed at different times, are or were located near the Kuril Islands: DART 21401 (operating years 2009–2014), 21402 (2012–2017), 21419 (since 2009). The location of the stations is optimal for each specific case depending on the proximity to the tsunami source. For the events of 2006 and 2007, the optimal position is DART 21419, for the event of 2020 – the position of DART 21402. Due to the fact that the stations were not operating during the period of the corresponding tsunami, a preliminary reconstruction of tsunami waveforms was performed at these stations based on data from more distant stations using the express method. The original and reconstructed waveforms for each described event are given below. Based on the reconstructed data, tsunami waveforms were computed at more distant stations and near populated areas.

The lead time of tsunami forecasting is directly related to the efficiency of obtaining data on tsunamis in the ocean: using shorter time intervals for analysis

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[9] National Data Buoy Center, 2024. *Station List*. [online] Available at: https://ndbc.noaa.gov/to_station.shtml [Accessed: 15 June 2024].

[10] Russian Tsunami Warning Service, 2024. *Sea Level*. [online] Available at: http://rtws.ru/sea-level/ [Accessed: 15 April 2024] (in Russian).

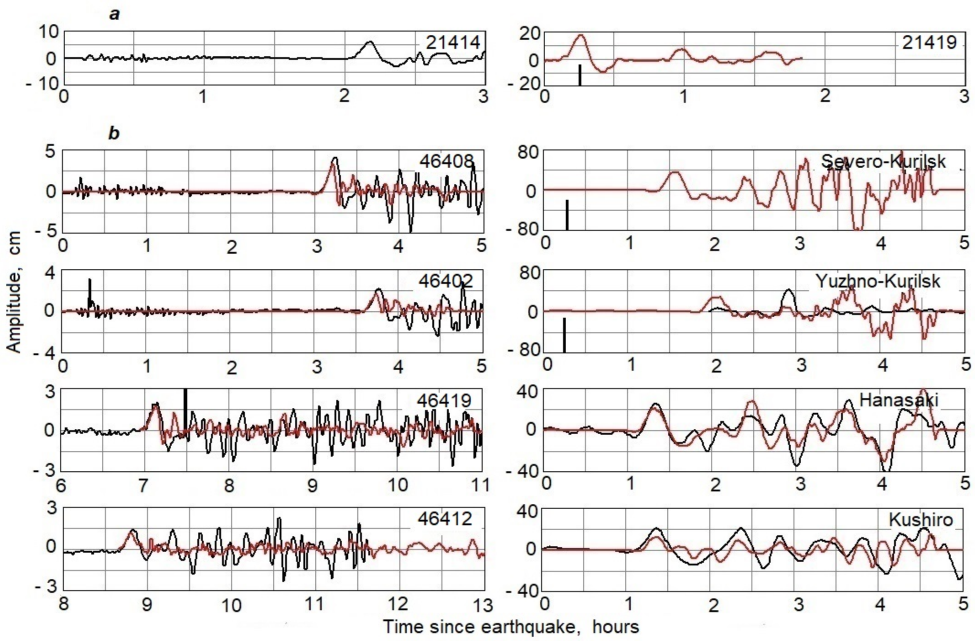
[11] IOS, 2024. *Sea Level Station Monitoring Facility*. [online] Available at: http://www.ioc-sealevelmonitoring.org/list.php?showall=a&output=general&order=location&dir=asc [Accessed: 15 June 2024].

allows forecasts to be made earlier. This is especially important in cases of earthquakes occurring near the coastline. Tsunami waveforms were computed based on reconstructed data from DART 21419 for 16 minutes after the earthquake onset (including a quarter of the first wave period), 20 minutes (including half the period), 32 minutes (including one full period) and 108 minutes. The computation results were found to be virtually identical, as confirmed by comparison with actual data on the 2006 Simushir tsunami.

In subsequent numerical experiments, data from the corresponding DART station, starting from the moment of the earthquake onset and covering the first quarter of the period, were used to compute tsunami waveforms for each event.

2006 Simushir tsunami

The earthquake occurred on November 15, 2006 on the western slope of the Kuril-Kamchatka Trench [6]. The epicenter was located 90 km east of Simushir Island.



F i g. 2. Waveforms of the 2006 Simushir tsunami: a – recorded by *DART 21414* station (*left*) and reconstructed at *DART 21419* station (*right*); *b* – recorded (black line) and computed (red line) based on the reconstructed data from *DART 21419* station. Here and further on, each graph is indicated by the *DART* station number or the settlement name, vertical black line is the boundary of the data used in forecasting, as well as the moment of forecast generation for the points on the Kuril Islands

The resulting tsunami (the epicenter is shown in Fig. 1) was recorded by DART stations located along the Aleutian Islands, the US West Coast to the California Peninsula [9]. The closest station to the Kuril Islands was DART 21414 (Fig. 1), the tsunami travel time to which was more than 2 hours (Fig. 2, *a*). The tsunami travel time to the point where DART 21419 was installed in 2009 was 10 minutes. In this event, the station's position would have been optimal (Fig. 1). The reconstructed tsunami waveform at point 21419 based on DART 21414 station data was used for forecasting. The initial data and the reconstruction result are shown in Fig. 2, *a*.

To confirm the adequacy of the reconstructed tsunami waveform at point 21419, computations were performed at points in the ocean where more distant DART stations were located based on these data. A series of reconstructed data from DART 21419 station with a duration of 16 min from the onset of the earthquake was used (Fig. 2, *a*, on the right). The results for some stations are shown in Fig. 2, *b*, left column. Good agreement is observed between the head waves of the real and computed waveforms.

The tsunami was recorded by tide gauges in Yuzhno-Kurilsk, Hanasaki and Kushiro. The construction of transfer functions for points on the Kuril Islands and Hokkaido Island began 7–11 min after the earthquake (the moment the data on the epicenter coordinates were obtained) and was completed before the first quarter of the tsunami period passed through point 21419 (16 min after the onset of the earthquake). The forecast for selected points based on the reconstructed DART 21419 data for 16 min is shown in Fig. 2, *b*, right column.

No tsunami was recorded in Severo-Kurilsk. According to the computation, the expected tsunami did not pose a serious threat. There is no evidence of a tsunami in Severo-Kurilsk. In Yuzhno-Kurilsk, although the structures of the computed and actual waves do not match, the values of the maximum amplitudes are in good agreement, up to 0.5 m, which indicates an insignificant tsunami that does not pose a threat. Quite good agreement between the actual and computed waveforms is observed for Hanasaki and Kushiro.

The earlier arrival of the tsunami in Hanasaki and Kushiro than in Yuzhno-Kurilsk is explained by the fact that the wave in these points spreads over a deep-water basin, while in Yuzhno-Kurilsk – over a shallower shelf and strait.

When developing a forecast based on the data of the DART 21419 station at a time of 16 minutes from the onset of the earthquake, the forecast lead time for Severo-Kurilsk and Yuzhno-Kurilsk is 66 and 94 minutes, respectively.

This time is sufficient to decide on the need to declare a tsunami alarm. The moment of declaring an alarm is not regulated, but practice shows that for populated areas of the Kuril Islands, an alarm can be declared 30 minutes before the expected tsunami arrival.

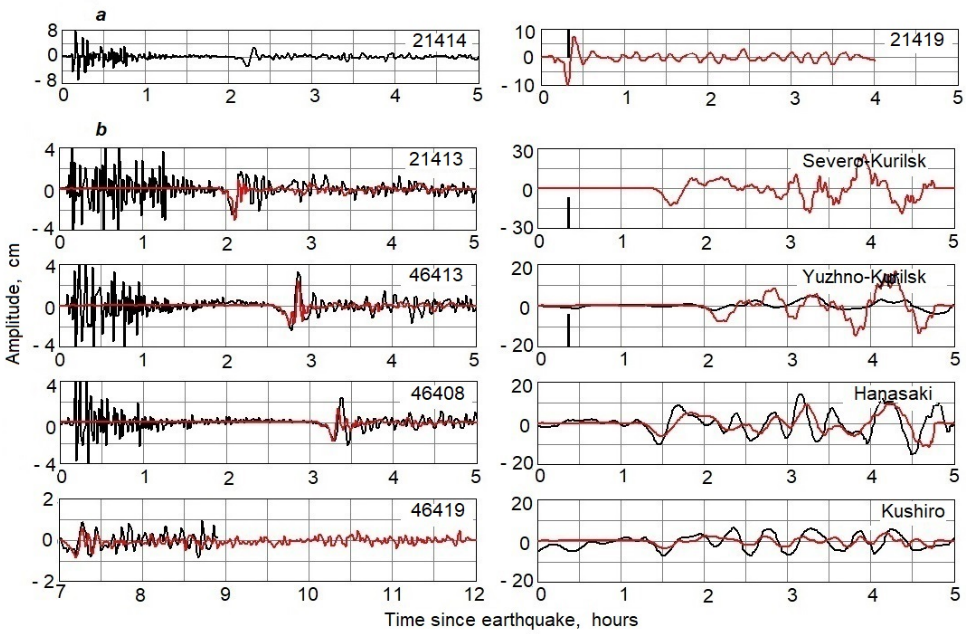
2007 Simushir tsunami

Two months later, an earthquake occurred on the eastern slope of the Kuril-Kamchatka Trench approximately 170 km southeast of Simushir Island on 13.01.2007 [6].

In this event, the tsunami was recorded by stations along the Aleutian Islands, the US West Coast to the California Peninsula [9]. In addition, the tsunami was recorded by the DART 21413 station, located to the south of the source. Based on the data from the DART 21414 station (Fig. 3, *a*, left), the tsunami waveform was reconstructed at point 21419, where the DART 21419 station was subsequently installed, the wave travel to which is 15 minutes. The reconstruction results are shown in Fig. 3, *a*, right.

Based on the reconstructed tsunami waveform at point 21419, computations were performed at points in the ocean where more distant DART stations were located. A time series of 19 min from the onset of the earthquake was used. The results for some stations are shown in Fig. 3, *b*, left column. Good agreement was obtained between the head waves of the real and computed waveforms, both in the easterly and southerly directions from the tsunami source. In all cases, the tsunami arrival begins with a decrease in the ocean level.

The tsunami was recorded by tide gauges in Yuzhno-Kurilsk, Hanasaki and Kushiro. As for the previous event, the construction of transfer functions for points on the Kuril Islands and Hokkaido Island began 7–11 min after the earthquake occurred and was completed before the first quarter of the tsunami wave passed point 21419 (19 min after the onset of the earthquake).



F i g. 3. Waveforms of the 2007 Simushir tsunami: a – recorded by the *DART 21414* station (*left*) and reconstructed at *DART 21419* station (*right*); *b* – recorded (black line) and computed (red line) based on the reconstructed data from *DART 21419* station

In Severo-Kurilsk, as during the previous event, no tsunami was registered. According to the computation, the expected tsunami did not pose a serious danger. There is no evidence of a tsunami in the Severo-Kurilsk area. In Yuzhno-Kurilsk, although the structures of the computed and actual waves do not match, the values of the maximum amplitudes are in good agreement, up to 0.1 m, which indicates an insignificant tsunami that does not pose a danger. Quite a good match between the actual and calculated waveforms is observed for Hanasaki and Kushiro.

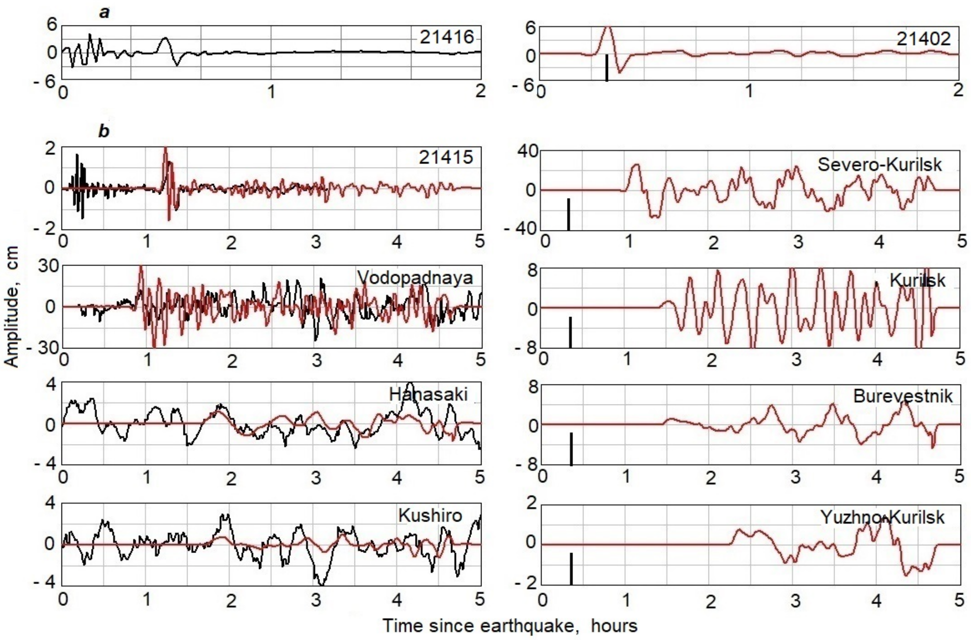
When generating a forecast at a time of 19 minutes from the onset of the earthquake, the forecast lead time for Severo-Kurilsk and Yuzhno-Kurilsk is 69 and 101 minutes, respectively.

2020 Onekotan tsunami

An earthquake occurred east of Onekotan Island, 220 km from Paramushir Island (Northern Kuril Islands) on March 25, 2020 [6]. The resulting weak tsunami was recorded by DART stations 21415, 21416 and 21419 [9], as well as by the Vodopadnaya automated sea level measurement station [10]. The closest station to the source was DART 21416 (Fig. 1), the tsunami traveled to it 25 minutes. The closest to the tsunami source of those indicated in Fig. 1 is the position of the previously operating Russian station DART 21402. The tsunami traveled to this point is about 15 minutes. The tsunami forecast based on the data from this station could have been obtained earlier than based on the data from the DART 21416 station [15].

The tsunami waveform reconstruction at point 21402 was performed using the express method based on the data from the DART 21416 station (Fig. 4, *a*). The reconstructed tsunami waveform at the DART 21402 station is shown in Figure 4, *a*, on the right. The computation of the tsunami waveforms (based on the ready transfer function) at the specified points could have been performed immediately after receiving the data from the DART 21402 station on the passage of the first quarter of the tsunami period (at the 20th minute after the onset of the earthquake). The tsunami computation based on the reconstructed data series of the DART 21402 station (Fig. 4, *a*) with a duration of 20 min was performed for the DART 21415 station and the Vodopadnaya (southeast Kamchatka) (Fig. 1) and populated areas (Fig. 1). The computation results are shown in Fig. 4, *b*. A good match was obtained between the computed and recorded waves at the DART 21415 station. The oscillations preceding the tsunami in the records of this station are the effect of Rayleigh waves on the ocean floor. A good match in amplitudes was obtained between the computed waveform near the Vodopadnaya and the record obtained by this station [15].

According to the computation results, the expected time of arrival of the first wave in Severo-Kurilsk is 69 minutes after the onset of the earthquake, the computed amplitude is 15 cm. The amplitude of 15 cm was obtained at the node of the difference grid closest to the shore, where the sea depth is 17 m. In accordance with the well-known Green's law, according to which the wave amplitude a_1 at a depth of D_1 is related to the amplitude a_0 at a depth of D_0 by the ratio $a_1/a_0 = (D_0/D_1)^{1/4}$, recalculating the amplitude of 15 cm to a point where the depth is 1 m gives an amplitude of about 30 cm. A visual estimate of the wave height (from crest to trough) of 50 cm was made 1.2 km south of the port of Severo-Kurilsk near the water's edge at a depth of about 1 m [15]. The lack of instrumental measurements of the sea level in Severo-Kurilsk, as well as on all the Kuril Islands, does not allow us to confirm either the visually estimated tsunami height of 50 cm, or the computed amplitude of 30 cm.



F i g. 4. Waveforms of the 2020 Onekotan tsunami: a – recorded by *DART 21416* station (*left*) and reconstructed at *DART 21402* station (*right*); *b* – recorded (black line) and computed (red line) based on the reconstructed data from *DART 21402* station

According to computations, in other populated areas of the Kuril Islands, the amplitude of the expected tsunami should be insignificant.

The forecast lead time according to the DART 21402 station, which is 43 minutes for Severo-Kurilsk, 65 minutes for Kurilsk, 65 minutes for Burevestnik, and 116 minutes for Yuzhno-Kurilsk, is quite sufficient to make a decision to declare an alarm in these areas [15].

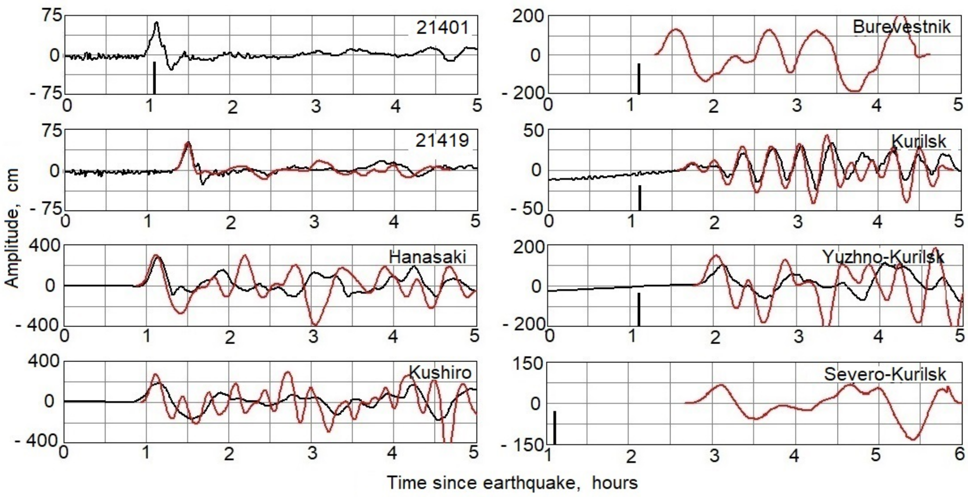
The warning issued by JMA about possible destructive waves on the Kuril Islands with amplitudes of 1–3 m was not confirmed. The event of 25.03.2020 shows that the method of tsunami forecasting based on the magnitude criterion, preliminary computations, on which the JMA relies, cannot always give a correct forecast.

2011 Tohoku tsunami

A powerful earthquake occurred on March 11, 2011, off the northeastern coast of Honshu Island [6]. The resulting tsunami was unusual: its amplitude exceeded the value predicted by computations for an earthquake with a magnitude of 9.0. The initial amplitude of the wave that arose after the main shock was 2 m. After 11 minutes, it unexpectedly increased to 5 m [16]. A qualitative explanation of this effect is given in [23]. Presumably, it is similar to the effect of an underwater landslide.

In the area of the Kuril Islands, the tsunami was recorded by DART 21419 and Russian DART 21401 [9], stations, coastal tide gauges in Kurilsk and Yuzhno-Kurilsk, as well as in Hanasaki and Kushiro on the island of Hokkaido [11].

Computations were performed using data from the DART 21401 station for 68 minutes, including the first quarter of the wave period (Fig. 5).



F i g. 5. Waveforms of the 2011 Tohoku tsunami: recorded (black line) and computed (red line) based on the data from *DART 21401* station

A good match was obtained between the computed and actual waveforms at the DART 21419 station closest to the islands (Fig. 5). The quality of the express forecast at this station and the quality of the tsunami waveform computations in the ocean, performed by the NOAA method, are comparable [12].

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[12] NOAA Center for Tsunami Research. *Tohoku (East Coast of Honshu) Tsunami, March 11, 2011*. [online] Available at: http://nctr.pmel.noaa.gov/honshu20110311/ [Accessed: 19 June 2024].

The results of computing the tsunami waveform near populated areas of the Kuril Islands and Hokkaido Island are presented in Fig. 5.

The computed and recorded tsunami waveforms in Hanasaki and Kushiro are in good agreement with each other. In Yuzhno-Kurilsk, there is also agreement between the model and real waveforms. The time of tsunami arrival at the forecast point and the wave structure coincide. According to the forecast, the amplitude of the maximum wave should not exceed 1.5 m. In Kurilsk (the Okhotsk side of Iturup Island), the structure, amplitudes and characteristic periods of the waves coincide well. In Severo-Kurilsk, the computed range of water level fluctuations should not exceed 1.5 meters, which agrees with the information from ships located near Severo-Kurilsk, where the water level under the keel fluctuated from 4.2 m to 2.6 m with a difference of 1.6 m [16]. The computed wave amplitudes (up to 2 m) correspond to visual observations in the Burevestnik port point (Iturup Island) [12].

The forecast lead time is 92 minutes for Severo-Kurilsk, 37 minutes for Yuzhno-Kurilsk, and 30 minutes for Kurilsk. It is quite sufficient to make a decision on declaring a tsunami alarm. Tsunami alarms could be declared sequentially in Kurilsk, Yuzhno-Kurilsk, and Severo-Kurilsk. Due to the small amplitude of the expected wave in Kurilsk, the alarm could not be declared or cancelled in a timely manner if it was declared based on the magnitude criterion. For the Burevestnik port point, the time of wave front arrival practically coincides with the moment of forecast development. For this point, as well as points on Shikotan Island and the islands of the Small Kuril Ridge, the tsunami alarm should be declared in accordance with the current regulations, based on the magnitude criterion. In the computations performed in [18], the data from the DART 21401 station with a duration of 20 min (the first period of the wave) were used, the arrival of the tsunami was estimated as the arrival of the first wave crest. This explains the difference in the lead time estimate.

The results of the experiment confirm that, despite the anomalous mechanism of excitation of the Tohoku tsunami on March 11, 2011, the computation performed using the data from the DART 21401 level measurement station, using information only on the coordinates of the earthquake epicenter without involving additional seismological information, gives an adequate result.

Discussion

The paper shows that the tsunami forecast for the Kuril Islands based on the magnitude-geographical method used by Russian tsunami warning services is ineffective. Tsunami alarms announced simultaneously on all the Kuril Islands often turn out to be false in populated areas due to the small amplitude of the wave. However, this is not due to the actions of the Tsunami Center, but to the approved regulations based on the magnitude criterion. The Northwest Pacific Tsunami Advisory Center (JMA), relying on pre-computed mareograms from a number of sources in tsunamigenic zones with the most probable earthquake mechanisms, also cannot always provide a correct forecast.

Currently, hydrophysical methods using information about the tsunami formed in the open ocean are effective. The NOAA (SIFT) method using DART station data is successfully used to forecast tsunamis in the USA. However, the forecast is more difficult when tsunamis occur near the coast. Often, tsunami information from DART stations comes later than the tsunami reaches the nearest coasts.

As noted above, the NOAA method cannot be used to forecast tsunamis in the Kuril Islands. For such situations, the express method of short-term tsunami forecasting can be used. To perform a forecast using the express method, seismological information is required only on the coordinates of the earthquake epicenter and tsunami information from DART stations, received in real time.

The moment of forecast generation is determined by the time (from the onset of the earthquake) of the tsunami passing through the registration point. The forecast for a specific point will be successful if its lead time is not less than the time required to evacuate the population, which is specific to each point. For points on the Kuril Islands, the forecast lead time can be estimated at no less than 30 minutes. Accordingly, a tsunami alarm can be declared 30 minutes before the expected tsunami arrival at the corresponding point. The tsunami travel time to a specific settlement is estimated in real time. If the forecast lead time is less than 30 minutes, a tsunami alarm should be declared based on the magnitude criterion. The alarm can be promptly cancelled upon receipt of information about the non-hazard of a tsunami.

The aim of the work was to study the possibility of an operational tsunami forecast for the Kuril Islands based on data on tsunamis in the open ocean. The tsunamis of 2006–2020 that occurred near the Kuril Islands are considered. It is shown that with prompt receipt of information about the coordinates of the earthquake epicenter and about tsunamis in the ocean, an operational tsunami forecast in settlements is possible with the required lead time. Despite its approximate nature, the express method allows adequately assessing the degree of danger of an expected tsunami for any part of the coast. In this case, it is sufficient to have information about the passage of a quarter of the first period of the tsunami through a registration station located in the optimal location for each event. In case of earthquakes in the area of the central Kuril Islands, the optimal position is the location of DART 21419 station. The forecast lead time for settlements of the northern and southern islands is 66–101 minutes. In case of earthquakes in the area of the northern Kuril Islands, the optimal position is the location of the previously operating Russian station DART 21402. The forecast lead time in such cases is 43–116 minutes. In the case of earthquakes off the east coast of Japan, the previously operating Russian station DART 21401 would allow forecasting to be carried out in real time. The tsunami forecast lead time for these events is 30–92 minutes for nearby and more remote settlements.

Conclusion

Many areas in the Sakhalin Region are tsunami-hazardous, especially the Kuril Islands. The problem of operational tsunami forecasting has not yet been fully resolved. The declaration of tsunami alarm on the Pacific coast of Russia is based on the magnitude method created in the middle of the last century. There are a large number (over 75%) of false alarms. These alarms, often declared too early, are accompanied by damage caused by the suspension of production and other activities in the coastal zone for a long time.

Currently, in the Russian Far East, there is no hydrophysical subsystem of the tsunami warning service that would monitor the wave regime in the ocean and assess the tsunami hazard. The tsunami warning service needs to create such a subsystem in order to increase the efficiency, reliability and accuracy of tsunami warnings.

An express method for operational tsunami forecasting can be used for the coast of the Russian Far East. Implementation of the express method for operational tsunami forecasting as a single complex, provided that information on tsunamis in the ocean is received, will improve the quality of forecasting in the future and thereby reduce the number of false tsunami alarms on the Kuril Islands. The previously operating Russian stations DART 21401 (in 2010–2014) and DART 21402 (in 2012–2017) could provide a reliable tsunami forecast for the Kuril Islands with sufficient advance notice in the event of earthquakes in the areas of the northern and central Kuril Islands and the east coast of Japan.

Russia is almost the only country in the Pacific Ocean basin that does not have deep-sea stations for measuring ocean levels, which would allow for operational tsunami forecasting. There is a need to create our own, Russian, deep-sea stations for measuring ocean levels.

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