The short-term tsunami forecast

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Abstract. A brief overview of the methods of a tsunami early warning in the Kuril Islands, which turned out to be ineffective during recent events, is presented. A hydrophysical method for short-term tsunami forecasting based on information about a tsunami in the ocean, used in the United States, and an express method, also using information about a tsunami in the ocean, are briefly described. The results of the retrospective forecast of the tsunami that occurred on March 11, 2011, by the express method are presented.

1. Introduction

The main problem of operational tsunami forecasting in Russia is the problem of false alarms. From the moment of creation to the present, tsunami services in Russia have made a large number of false alarms (at least 75 % of the total), and their number is growing (Kuril tsunamis of 2006, 2007 and 2020, M = 8.3, 8.1 and 7.3).

False tsunami alarms, often announced too early, do not cause direct losses, but lead to a significant damage associated with stopping production in dangerous places, evacuating the population, taking ships out to the open sea, and create unjustified stressful situations for the population. Moreover, all kinds of activity in the coastal strip stops for several hours.

An example of a false alarm is the events of March 25, 2020.

An earthquake with a magnitude of 7.3 occurred on March 25, 2020 at 02:49 UTC with an epicenter 220 km east of the Onekotan Island (Kuril Islands, Russia).

8 minutes after the main shock, the Pacific Tsunami Warning Center (PTWC) issued a tsunami warning bulletin for the coast within 1000 km of the epicenter of the earthquake.

After 11 minutes a tsunami alert was announced in the Severo-Kurilsk region.

After 27 minutes Japan Meteorological Agency also warned of possible devastating tsunami waves in the Kuril Islands with an amplitude of 1 to 3 meters.

After 41 minutes after the start of the earthquake (30 minutes after the announcement of the alarm), the evacuation of the population to the safe zone was completed. About 400 people were evacuated.

The arrival of the tsunami to Severo-Kurilsk was expected at 04:04 UTC (75 minutes after the main shock).

According to visual observations, 1.2 km south of the port of Severo-Kurilsk, the first wave arrived approximately 1 hour after the earthquake. Against the background of storm waves, the tsunami height was visually estimated at 50 cm.

The tsunami alarm was canceled at 06:57 UTC (3 hours after the wave arrival).
Due to the small amplitude of the tsunami, the announced alarm turned out to be false. The prolongation of the tsunami alarm after the arrival of the first small amplitude waves was unreasonable.

All three forecasts of the tsunami on March 25, 2020 turned out to be ineffective: with the forecasted 1–3 m, the actual height was about 0.5 m.

2. Methods for early tsunami warning

The Pacific Tsunami Warning Center (PTWC) forecast is based on current regulations, magnitude criterion. The issued bulletin is informative and does not constitute a tsunami alert. The decision to declare an alarm is made by the regional centers.

The Japan Meteorological Agency (JMA), responsible for tsunami forecasting in the Pacific Northwest, is acting in accordance with the new regulations [1]. The forecast uses a database of tsunami heights at a large number of points in the ocean. The database is based on preliminary computations of tsunami waveforms from supposed seismic sources with the most probable earthquake mechanisms. The decision to declare a tsunami alert is also the responsibility of the regional centers. As practice shows, this method is not always effective.

The prediction and announcement of the tsunami alert by the Sakhalin Tsunami Warning Service is carried out on the basis of the magnitude-geographic criterion.

According to modern concepts, a tsunami alarm should be announced with a reasonable advance only at those points where the tsunami poses a real danger, and be accompanied with information about the arrival times of the first wave, the maximum wave, their amplitudes, as well as the expected time of the end of the tsunami (tsunami alarm clearing). These characteristics of a tsunami are listed in the definition of a tsunami forecast formulated by UNESCO Intergovernmental Oceanographic Commission (UNESCO IOC) in 2013 [2].

Hydrophysical methods are an effective tool for operational tsunami forecasting. Information about the formed tsunami obtained in the ocean by deep-sea bottom stations of the DART system (Deep-ocean Assessment and Reporting of Tsunamis) [3] is reliable for assessing the degree of tsunami hazard. The hydrophysical method SIFT (Short-term Inundation Forecasting for Tsunamis) [4] based on information about the tsunami in the ocean (NDBC DART Program) using a pre-computed base of synthetic mareograms provides an early numerical estimate of the amplitude, travel time, and other properties of the tsunami. The forecast is given immediately after receiving information about the passage of the first half-period of the tsunami through the registration point. The method fully meets the definition of the UNESCO IOC tsunami forecast concept.

The SIFT method has been successfully applied both for retrospective forecasting of earlier tsunamis since 1996 and for real-time forecasting of recent tsunamis [5, 6, 7, 8, 9].

The SIFT method is applicable to those points in the ocean or near the coast for which a pre-computed database is available. In particular, the method is applied to the US West Coast, the coast of Alaska and the Aleutian Islands.

For the coast of Kamchatka and the Kuril Islands, the SIFT method is not applicable due to the lack of relevant databases.

3. Express method of short-term tsunami forecast

The express method for short-term tsunami forecasting is based on the fundamental reciprocity principle. Based on this principle, the calculated relation was derived [10].

\[ \zeta(s, A) = \zeta(s, M) \cdot \frac{\eta(s, A)}{\eta(s, M)}, \]

where \( \zeta(s, A) \) is the spectrum (Laplace transform) of the expected tsunami waveform at a given point A near the coast for which the forecast is performed, \( \zeta(s, M) \) is the tsunami spectrum at a point M, where the ocean level is measured, \( \eta(s, A) \) is the spectrum (Laplace transform) of the waveform at a
point A from an auxiliary source, \( \eta(s,M) \) is the spectrum of the waveform at a point M from the auxiliary source.

In the above relation, the ratio on the right side plays the role of a transfer function, which is used to calculate the shape of the expected tsunami at a given point near the coast (point A) from the tsunami data in the open ocean (in a point M).

The main assumption of the express method: an auxiliary source for creating the transfer function is the circular initial elevation of the free surface with the center coinciding with the epicenter of the earthquake. In this case, for the computation (forecast) of a tsunami, the only seismological information on the coordinates of the earthquake epicenter is required.

The inverse Laplace transform gives the time of arrival and the shape of the expected tsunami at a point A, which contains comprehensive information that fully complies with the definition of a tsunami forecast given by the UNESCO IOC.

4. Retrospective forecast of the Tohoku tsunami on March 11, 2011
The event on March 11, 2011, was selected as an example of using the express method.

The strongest earthquake with a magnitude of 9.0 occurred off the northeastern coast of Honshu Island on March 11, 2011.

The tsunami was recorded by almost all stations of the DART system [11], as well as by coastal tide gauges.

4.1. Retrospective forecast of the tsunami on March 11, 2011, near the Kuril Islands
A tsunami alert has been declared on all Kuril Islands. It is recommended for ships in the roads and piers to leave for a safe area. The evacuation of the population was completed 1 hour 24 minutes before the tsunami arrival in Yuzhno-Kurilsk, 2 hours 38 minutes before the wave arrival in Severo-Kurilsk, and 1 hour 18 minutes before the arrival of the wave in Kurilsk.

A retrospective forecast of the expected tsunami was made near settlements and at the location of the DART 21419 station. Their positions are shown in figure 1.

![Figure 1. Scheme of the Northwest Pacific Ocean showing the earthquake epicenter and the points for which the forecast was made. The diagram indicates: S-K – Severo-Kurilsk, Kur – Kurilsk, Y-K – Yuzhno-Kurilsk, H – Hanasaki and K – Kushiro.](image)

For the forecast, a transfer function was created using a difference grid with a step of 900 m at a latitude of 45° for 20 minutes. Taking into account the fact, that the time to obtain data on the coordinates of the earthquake epicenter of 11 min, the transfer function could be ready 31 min after the
main shock of the earthquake. The forecast was made according to the data of the Russian station DART 21401. The waveform recorded by the station is shown in figure 2. The data of the station with a duration of 89 minutes from the beginning of the earthquake were used.

The calculation results are shown in figure 2.

![Figure 2. Results of the tsunami forecast on March 11, 2011, at settlements of the Kuril Islands and Hokkaido Island.](image)

The predicted waveforms of the expected waves are in good agreement with the registered ones. The retrospective forecast was made after the passage of the first tsunami period through DART 21401, i.e. 89 minutes after the main shock. The forecast results are quite suitable for assessing the degree of tsunami danger and making a decision on the need to declare a tsunami alert in each settlement.

The lead time of the forecast according to DART 21401 data for Yuzhno-Kurilsk was 23 minutes, for Kurilsk – 48 minutes and Severo-Kurilsk – 75 minutes.

The lead time according to DART 21418, which is closer to the tsunami source, could be 30 min higher.

4.2. Computation of tsunami waveform in the ocean in the different directions of the source

To confirm the operability of the express method of short-term tsunami forecast, the tsunami waveforms were computed at the points of DART stations in the ocean in different directions from the tsunami source.

The locations of the stations are shown in figure 3. Diamonds with numbers indicate those stations, the computation results for which are shown below in figures 4 and 5.

The data of the Russian station DART 21401 (the first period of the wave, figure 2), located to the northeast of the tsunami source, were used. To construct the transfer function, an auxiliary circular source with a diameter of 100 km and with a center coinciding with the epicenter of the earthquake was used on a difference grid with a step of 3830 m at a latitude of 40°.
Figure 3. Scheme of the Pacific Ocean showing the earthquake epicenter and DART stations for which the computation was performed.

Figure 4. The results of computation the tsunami waveforms on March 11, 2011, in the direction northeast of the tsunami source (left) and similar results obtained by NOAA Center for Tsunami Research [12].
Figure 5. The results of computation the tsunami waveforms on March 11, 2011, in the direction south, southeast of the tsunami source (left) and similar results obtained by NOAA Center for Tsunami Research [12].

The presented results of the computation of the tsunami on March 11, 2011, in the ocean demonstrate good agreement between the computed and recorded waveforms, not only of the head waves, but also of subsequent waves. This indicates that the express method gives a completely adequate forecast.

The same quality of computations is for stations along the coast of the Aleutian Islands and the Alaska Peninsula, as well as along the US West Coast.

Regardless of the relative positions of the source, the level measurement point and the forecast point, the forecast quality is good, despite the fact that an axially symmetric auxiliary source was used to construct the transfer function.

Difficulties with the forecast may arise when computing near the coasts, which is associated with the inaccuracy of the bathymetric data, the coarseness of the difference grids used. The use of fast computation technology, nested grids techniques can eliminate many of the problems of online calculations.

The quality of the computation of tsunami waveforms obtained by the express method is comparable to the quality of similar computations by the NOAA Center for Tsunami Research.

5. Conclusion
The express method of short-term tsunami forecast based on tsunami data in the open ocean makes it possible to compute the waveform of the expected tsunami in real time at specified points in the ocean or near the coast.
To make a forecast, the only seismological information about the coordinates of the earthquake epicenter is needed. The method does not depend on the earthquake mechanism, it can take into account additional effects in the form of subsea landslides.

The method fully complies with the definition of a tsunami forecast formulated by the UNESCO IOC.

The method does not require the creation of giant databases and can be used for tsunami forecasting in areas for which other methods (for example, SIFT) are not applicable.

The use of fast evaluation technology and method of nested grids will make it possible to forecast a tsunami immediately after receiving information about the passage of a tsunami through the DART station closest to the source with a lead time sufficient to make a decision to announce an alarm and evacuate the population.

References

[1] UNESCO/IOC 2019 IOC Tech. Ser. Users’ Guide for the Northwest Pacific Tsunami Advisory Center (NWPTAC): Enhanced Products for the Pacific Tsunami Warning System (Paris, UNESCO) 142 (Electronic materials) https://unesdoc.unesco.org/ark:/48223/pf0000366546?posInSet=1&qureryId=d1288da0-390e-47b1-8a51-a529b04abf93

[2] Intergovernmental Oceanographic Commission. Tsunami Glossary 2016 IOC Technical Series (Paris, UNESCO) 3rd edition 85 (IOC/2008/TS/85 rev. 2)

[3] NOAA Center for Tsunami Research: DART (Electronic materials) http://nctr.pmel.noaa.gov/Dart

[4] NOAA Center for Tsunami Research: Tsunami Forecasting (Electronic materials) https://nctr.pmel.noaa.gov/tsunami-forecast.html

[5] Percival D B, Denbo D W, Eble M C, Gica E, Mofjeld H O, Spillane M C, Tang L and Titov V V 2011 Nat. Hazards 58 pp 567–590

[6] Tang L, Titov V V, Moore C and Wei Y 2017 Real-Time Assessment of the 16 September 2015 Chile Tsunami and Implications for Near-Field Forecast The Chile-2015 (Ilapel) Earthquake and Tsunami (Pageoph Topical Volumes) (Birkhäuser Cham) ed C Braitenberg and A Rabinovich pp 267–285

[7] Titov V V 2009 Tsunami forecasting The Sea (Cambridge, MA; London, England: Harvard Univ. Press) ed E N Bernard and A R Robinson 15 pp 367–396

[8] Wei Y, Bernard E N, Tang L, Weiss R, Titov V V, Moore C, Spillane M, Hopkins M and Kanoglu U 2008 Geophys. Res. Lett. 35 L04609

[9] Wei Y, Cheung K F, Curtis G D and McCreery Ch S 2003 J. Waterway, Ports, Coastal and Ocean Engineering. ASCE 129 2 pp 60–69

[10] Korolev Yu P 2011 Nat. Hazards Earth Syst. Sci. 11 pp 3081–91

[11] National Data Buoy Center (Electronic materials) https://ndbc.noaa.gov/dart.shtml

[12] NOAA Center for Tsunami Research: Events (Electronic materials) https://nctr.pmel.noaa.gov/honshu20110311/