The hindcast of recent tsunamis in Northern Pacific

P Korolev\textsuperscript{1,\ast}, Yu Korolev\textsuperscript{1} and A Loskutov\textsuperscript{1,2}

\textsuperscript{1}Institute of Marine Geology and Geophysics Far Eastern Branch of Russian Academy of Science, Yuzhno-Sakhalinsk, 693022, Russia
\textsuperscript{2}Laboratory of tsunamis, P P Shirshov Institute of Oceanology RAS, Moscow, 117997, Russia

E-mail: \ast pasha200482@mail.ru

\textbf{Abstract.} Three earthquakes occurred in the North Pacific in 2020, causing observable tsunamis. The tsunamis were not devastating. Numerical modelling of tsunami propagation was performed to reproduce operational forecasting (retrospective analysis) of waveforms at deep-water stations. Direct calculation of tsunami using USGS finite-fault source data on GPU was carried out. The leap-frog (Arakawa staggered grid) scheme calculation over the Pacific Ocean on a regular grid with a spatial step of 0.5 arc minutes of 1440 min (1 day) tsunami propagation was performed in approximately 90 min of computer time. With use of a hybrid cluster with several GPU accelerators and proper optimization of the simulation algorithm, this time can be reduced by tens of times. Consequently, the time for estimating the transfer function will be comparable to the travel time of a tsunami to the stations, where the forecasts data is. It will make possible to forecast the shape of a tsunami at any point with a lead time enough to decide for tsunami alert at sites where a tsunami poses a real danger. The calculation results are in good agreement with the real data of deep-ocean measurements. The quality of the forecast is comparable to the quality of calculations by other methods.

1. Introduction

The problem of the fast tsunami forecasting remains an unresolved problem for many coasts of the Pacific and Indian oceans. For several coasts (the Russian Far East, the Pacific coast of South America), the main method of operational tsunami forecasting is the magnitude-geographical criterion, which spawns unacceptable level of false alarms.

Methods based on computational fluid dynamics and using information about the generated tsunami wavefield in the open ocean (DART stations [5]) allow a better forecast [7].

Based on the forecasts, a tsunami alarm could be declared in a reasonable time only at the points where the tsunami poses a real danger and supplemented with information about the arrival times of the first wave, the maximum wave, wave amplitudes, as well as the expected time of the end of tsunami (cancelling the alarm). These characteristics of tsunamis are listed in the definition of a tsunami forecast formulated by the Intergovernmental Oceanographic Commission (IOC) of UNESCO in 2013 [1].

In 2020 several earthquakes have occurred in the North Pacific Ocean, causing the observed tsunamis. Earthquakes on March 25 with $M_w = 7.5$ near the central Kuril Islands (east of Onekotan Island), July 22 with $M_w = 7.8$ and on October 19 with $M_w = 7.6$ near the Alaska Peninsula (the area of the Shumagin Islands) [3].
Tsunamis did not cause damage, but they were the events, which might be used to test different tsunami excitation models and the effectiveness of different forecasting methods.

Purpose of the work is a development of technology for fast tsunami calculation for operational forecasting using examples of recent tsunamis.

Figure 1 shows the map of the North Pacific Ocean plotting the positions of the DART deep-water stations and earthquake epicenters.

![Figure 1. Positions of DART stations and earthquake epicenters in North Pacific Ocean.](image)

2. Results

Simulation of tsunami by the fast method of operational forecasting of tsunamis on March 25, 2020, in the Northwest Pacific was performed.

For the events of July 22 and October 19, 2020, the tsunami waveforms from the sources constructed according to the USGS data [8] were calculated using GPU accelerators.

2.1. Tsunami on March 25, 2020, east of Onekotan Island

The fast method of operational forecasting of tsunamis is based on a transfer function for each point, which allows using the data from the DART station (in the present experiment, station 21416, which is closest to the epicenter of the earthquake), to calculate the shape of the expected tsunami near this point. The transfer function is built immediately after receiving information about the coordinates of the epicenter of the earthquake caused the tsunami. The transfer function is based on calculation of waveforms from a point-like source with a center coinciding with the epicenter of the earthquake at the points of registration and forecast with no earthquake magnitude data required [2]. The comparison of the results of a numerical simulation and calculations by the NOAA Center for Tsunami Research are shown in figures 2, 3.

The calculation results (red line) are in good agreement with the real tsunami measurements data (blue line). The quality of the forecast is comparable to the quality of the calculations provided by the NOAA Center for Tsunami Research [6].

For the successful implementation of the method, it is necessary to use algorithms that allow us to calculate the shape of the expected tsunami at specified points on the coast of the Kuril Islands in time not greater than 10 minutes.
Figure 2. Results of the tsunami forecast on March 25, 2020, at DART stations near the Kuril Islands.

Figure 3. Results of the NOAA Center for Tsunami Research [6].

2.2. Tsunami on July 22, 2020, near Shumagin Islands
For the event on July 22, the tsunami waveforms from the USGS finite-fault sources calculated according to the [8] using GPU accelerators. The leap-frog depth-average numerical calculation of
tsunami propagation over the Pacific Ocean on a regular grid with a spatial step of 0.5 arc minutes with a process duration of 1440 min (1 day) was performed in approximately 90 min of computer time on one GPU only [4].

The calculation results are represented in figure 4, 5. To verify the results, the calculations of the Center for Tsunami Research (NOAA Center for Tsunami Research) [6] are presented in figure 3 too.

Obviously, the calculation results and the results presented by the Center for Tsunami Research (NOAA Center for Tsunami Research) [6] match up pretty good. Though the discrepancy with the recorded tsunami forms indicates that calculations using seismic sources do not always give adequate results.

Evidently, the calculation results and the results presented by the Center for Tsunami Research (NOAA Center for Tsunami Research) [6] match up pretty good. Though the discrepancy with the recorded tsunami forms indicates that calculations using seismic sources do not always give adequate results.

2.3. Tsunami October 19, 2020, near Shumagin Islands

For the event of October 19, we also calculated tsunami waveforms from finite-fault seismic sources provided by USGS [8] using GPU. The same simulation parameters as for previous case were engaged. We presume that with use of a hybrid cluster with several GPU accelerators and proper optimization of the simulation algorithm, this time can be reduced by tens of times. Consequently, the time for estimating the transfer function will be comparable to the travel time of a tsunami to the stations, on which the forecasts data are based on. It will make possible to forecast the shape of a tsunami at any point with a time enough to decide for tsunami alert at sites where a tsunami poses a real danger. The calculation results are shown in figures 6, 7 where the results of the Center for Tsunami Research (NOAA Center for Tsunami Research) [6] are also shown.

![Figure 4. Results of calculations of tsunami on July 22, 2020, generated numerically using USGS finite-fault sources, compared to measurements at DART stations.](image-url)
Figure 5. Results of calculations of tsunami on July 22, 2020, of the NOAA Center for Tsunami Research [6].

Figure 6. Results of tsunami calculations on October 19, 2020, from finite-fault seismic sources provided by USGS at DART stations.
3. Conclusion
On the example of the tsunami on March 25, 2020, which occurred in the Kuril Islands region, it is shown that the fast method of operational tsunami forecast based on tsunami data in the open ocean makes it possible to calculate in real time the shape of the expected tsunami at specified points in the ocean or near the coast. To make a forecast, the seismological subsystem needs information about the coordinates of the earthquake epicenter only. The calculation results are in good agreement with the actual data on the tsunami in the ocean. The quality of the forecast is comparable to the quality of calculations by other methods.

To simulate the tsunami on July 22 and October 19, 2020, near the Alaska Peninsula, we used the calculation of waveforms using GPU accelerators. The leap-frog depth-average numerical calculation of tsunami propagation over the Pacific Ocean on a regular grid with a spatial step of 0.5 arc minutes with a process duration of 1440 min (1 day) was performed in approximately 90 min of computer time.
on one GPU only. The calculation results are in good agreement with the calculation results obtained by other methods.

We propose to use of a hybrid cluster with several GPU accelerators and proper optimization of the simulation algorithm, this time can be reduced by tens of times. Consequently, the time for estimating the transfer function will be comparable to the travel time of a tsunami to the stations which data the forecasts are based on. It will make possible to forecast the shape of a tsunami at any point with a lead time enough to decide for tsunami alert at sites where a tsunami poses a real danger.

References
[1] Intergovernmental Oceanographic Commission. Tsunami Glossary 2016 IOC Technical Series (Paris, UNESCO) 3rd edition
[2] Korolev Yu 2011 Nat. Hazards Earth Syst. Sci. 11 pp 3081–91
[3] National Centers for Environmental Information: Search Tsunami Events (Electronic materials) https://www.ngdc.noaa.gov/hazel/view/hazards/tsunami/event-search (accessed 06/28/2021)
[4] Nickolls J, Buck I, Garland M and Skadron K 2008 Queue 6 pp 40–53
[5] NOAA Center for Tsunami Research: DART (Electronic materials) http://nctr.pmel.noaa.gov/Dart
[6] NOAA Center for Tsunami Research: Events (Electronic materials) https://nctr.pmel.noaa.gov/database_devel.html
[7] Titov V 2009 Tsunami forecasting The Sea (Cambridge, MA; London, England: Harvard Univ. Press) ed E Bernard and A Robinson 15 pp 367–396
[8] US Geological Survey 2021 Significant Earthquakes archive (Electronic materials) https://earthquake.usgs.gov/earthquakes/browse/significant.php