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УДК 550.344.42+551.466.62
https://doi.org/10.30730/gtrz.2025.9.1.056-065
https://www.elibrary.ru/kktwzl

Assessment of the tsunami in the Pacific Ocean caused by the explosion of the Hunga Tonga–Hunga Ha'apai volcano on January 15, 2022, using the express method of operational forecasting*

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Abstract. The aim of the study was to confirm the possibility of forecasting tsunamis of non-seismic (volcanic) origin using the express method of operational forecasting. The surface wave formed as a result of the explosive volcanic eruption on January 15, 2022 was a superposition of forced (baric) waves caused by an atmospheric pressure wave and free (gravity) waves generated by the disintergration of the disturbance in the source. The express method of operational tsunami forecasting was used to compute the gravitational component of the surface wave. The method allows one to compute the tsunami waveform at any point in the ocean and near the coast in real time based on the data from the sea level measurement stations. The computation of the tsunami on 15.01.2022, its gravitational component, at the DART stations remote from the source was performed based on the data from the DART stations 51425 and 52406 closest to the volcano. For an adequate forecast, the information on the tsunami of the DART stations closest to the source with the duration of a quarter of the first period is sufficient, which is especially important in the operational mode. The result satisfies the definition of the concept of "tsunami forecast" formulated by the Intergovernmental Oceanographic Commission of UNESCO. It has been confirmed that the express method can provide a tsunami forecast regardless of the mechanism of its excitation. It remains unclear how adequate the assessment of the amplitude of surface waves is based on the bottom pressure data is.

Keywords: tsunami, operational tsunami forecast, tsunami warning services, Pacific Ocean, sea level measurements, Lamb waves, forced waves, free waves

Оценка цунами в Тихом океане, вызванного взрывом вулкана Хунга Тонга–Хунга Хаапай 15 января 2022 г., экспресс-методом оперативного прогноза

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Резюме. Целью работы являлось подтверждение возможности прогнозирования цунами несейсмического (вулканического) происхождения экспресс-методом оперативного прогноза. Образовавшаяся в результате взрывного извержения вулкана 15.01.2022 поверхностная волна представляла собой суперпозицию вынужденных (барических) волн, вызванных волной атмосферного давления, и свободных (гравитационных) волн, генерированных распадом возмущения в очаге. Для расчета гравитационной составляющей поверхностной

*The translation from Russian: Королев Ю.П., Королев П.Ю. Оценка цунами в Тихом океане, вызванного взрывом вулкана Хунга Тонга–Хунга Хаапай 15 января 2022 г., экспресс-методом оперативного прогноза. [Electronic resource]. *Геосистемы переходных зон*, 2025, т. 9, № 1. http://journal.imgg.ru/web/full/f2025-1-4.pdf; https://doi.org/10.30730/gtrz.2025.9.1.056-065. *Translated by Yury P. Korolev*.
Полный текст статьи на русском языке см. на сайте журнала «*Геосистемы переходных зон*»: http://journal.imgg.ru/web/full/f2025-1-4.pdf

волны применен экспресс-метод оперативного прогноза цунами. Способ позволяет по данным станций измерения уровня океана в режиме реального времени рассчитывать форму цунами в любой точке океана и вблизи побережья. Расчет цунами 15.01.2022, его гравитационной составляющей, на удаленных от очага станциях системы DART выполнен по данным ближайших к вулкану станций DART 51425 и 52406. Для адекватного прогноза достаточно информации о цунами ближайших к очагу станций DART длительностью четверть первого периода, что особенно важно в условиях оперативного режима. Результат удовлетворяет определению понятия «прогноз цунами», сформулированному Межправительственной океанографической комиссией ЮНЕСКО. Подтверждено, что экспресс-метод может давать прогноз цунами независимо от механизма его возбуждения. Остается невыясненным вопрос, насколько адекватной является оценка амплитуды поверхностных волн по данным о давлении на дне.

Ключевые слова: цунами, оперативный прогноз цунами, службы предупреждения о цунами, Тихий океан, измерения уровня океана, волны Лэмба, вынужденные волны, свободные волны

For citation: Korolev Yu.P., Korolev P.Yu. Assessment of the tsunami in the Pacific Ocean caused by the explosion of the Hunga Tonga–Hunga Ha'apai volcano on January 15, 2022, using the express method of operational forecasting. *Geosistemy perehodnykh zon = Geosystems of Transition Zones*, 2025, vol. 9, No. 1, pp. 56–65. (In Russ. & in Engl.). https://doi.org/10.30730/gtrz.2025.9.1.056-065; https://www.elibrary.ru/kktwzl. [The translation from Russian: Королев Ю.П., Королев П.Ю. Оценка цунами в Тихом океане, вызванного взрывом вулкана Хунга Тонга–Хунга Хаапай 15 января 2022 г., экспресс-методом оперативного прогноза [Electronic resource]. *Геосистемы переходных зон*, 2025, т. 9, № 1. http://journal.imgg.ru/web/full/f2025-1-4.pdf]

Introduction

A powerful explosive eruption of the Hunga Tonga–Hunga Ha'apai volcano (hereinafter Tonga) occurred in the South Pacific Ocean on January 15, 2022*. It is estimated to be the largest underwater volcanic eruption in almost a century and a half since the catastrophic destruction of Krakatoa in Indonesia in 1883. The volcanic island formed shortly before the eruption was completely destroyed. The products of the explosion rose to a height of 58 km [1]. The effect of the explosion was observed in all environments: the ionosphere, the atmosphere, in the ocean and on its surface [2].

The eruption of the volcano caused a catastrophic tsunami on the nearby islands of the Tonga archipelago: up to 22 m at a distance of about 90 km from the volcano. The tsunami caused damage not only to nearby island nations, including the Kingdom of Tonga and Fiji, but also to coastal areas along the Pacific coast, including New Zealand, Japan and Peru [1]. Run-ups of up to 1.3 m were observed in Japan, over 3.5 m in California, about 1 m in Chile and up to 1 m in Peru*.

The high-pressure wave in the atmosphere was recorded by many barographs not only on the islands of the Pacific Ocean, but also on the continents. The pressure wave above the ocean surface (also called the Lamb wave), propagating at a speed close to the speed of sound in the atmosphere, caused disturbances of the free surface of the ocean in the form of a forced wave moving at the same speed. Hereinafter, such a wave is called a baric wave. Along with this, changes in the water surface level in the explosion area generated gravity (free) waves in the ocean, propagating at the speed of long waves. Baric and/or gravity waves were recorded by many deep-sea bottom stations of the DART system (NOAA Center for Tsunami Research**) in the Pacific Ocean (according to National Data Buoy Center NOAA; https://ndbc.noaa.gov/to_station.shtml). A small number of stations recorded both waves from the moment of arrival of the baric wave. Due to the difference in propagation speeds, the gravity wave noticeably lags behind the baric wave. The amplitudes of the baric and gravity waves, according to the data of deep-sea stations, are comparable even at large distances from the disturbance. The attenuation

* NOAA National Centers for Environmental Information. URL: https://www.ngdc.noaa.gov/hazel/view/hazards/tsunami/event-search (accessed 08.02.2025).

** http://nctr.pmel.noaa.gov/Dart (accessed 08.02.2025).

of the amplitude of baric and gravity waves is the same and inversely proportional to the square root of the distance from the source [3]. Waves of this type, described in the space of two variables, have a leading edge and no trailing edge. The oscillations behind the front, decreasing, continue for a long time.

The mechanism of waves excitation, both in the atmosphere and on the ocean surface by the processes that occurred in the eruption center of the Tonga volcano, is quite complex. It is possible that pressure waves in the atmosphere were not caused by a single explosion. In [4], it is assumed that five explosions of varying intensity occurred in the area of the volcano within half an hour or an hour. A rapid (explosive) change in atmospheric pressure is itself a source of gravity waves. The shift (repulsion) of water masses and/or products of the destruction of a volcanic island can also be an additional source of gravity waves. In any case, surface waves are a superposition of baric and gravity waves after the arrival of the latter at the observation point.

Various aspects of phenomena in the atmosphere, on the surface and on the ocean floor are described in numerous works. Pressure waves in the atmosphere based on natural data were analyzed in works [5, 6]. Numerical modeling of pressure waves based on a specially constructed source was performed in the article [3]. The influence of atmospheric pressure waves on the generation of waves on the ocean surface based on numerical modeling was studied in [3, 7–12] and on the website of the NOAA Center for Tsunami Research*. The process of generating gravity waves as a result of disturbances of the water surface in the source was considered using a numerical model in [3, 13]. The parameters of the disturbance source were selected based on the degree of coincidence of the waveforms of the computed and recorded waves in the ocean.

In work [14], a one-dimensional model of excitation of forced waves in a liquid layer under the action of a high-pressure wave in the atmosphere was considered. It is shown that the amplitude of the bottom pressure variations is higher than the amplitude of the pressure variations above the free surface by a factor of $U^2/(U^2–gH)$, where U is the pressure wave velocity in the atmosphere, H is the depth of the liquid layer, and g is the gravity acceleration. The validity of this statement is verified by comparing the data on the ocean floor pressure measured by the deep-sea stations DART 21418, 21420, and 51407, and the data from the land-based barographs closest to these stations [2, 14]. The amplitude of the bottom pressure variations, expressed in centimeters of water column, is higher than the amplitude of forced waves on the free surface by a factor of U^2/gH. The effects studied in [2, 14] were not considered in the above-mentioned works.

The all above-mentioned works did not discuss issues related to the operational tsunami forecast. It was only noted that the existing tsunami warning services were not prepared for forecast this type of event [3, 5, 8]. It is proposed to supplement existing methods of short-term tsunami forecasting with algorithms that allow taking into account the excitation of tsunamis by atmospheric pressure waves [1, 3–5, 8].

The US Tsunami Warning Service, relying on the current NOAA method, also known as the SIFT method**, did not form a forecast for the 15.01.2022 tsunami, its gravity component, due to the fact that there are no corresponding synthetic mareograms in the database for the eruption area. In accordance with the methodology underlying the method, a tsunami was computed in the Pacific Ocean after the event. To obtain the gravity wave form, synthetic mareograms were computed from 9 Gaussian sources in the focal area of the volcano. Tsunami wave forms at remote locations were calculated using the computed synthetic mareograms and data from three DART stations. The data from these stations did not include the initial parts of the records corresponding only to baric waves. The superposition of baric and gravity waves in the DART records complicated the tsunami analysis and the source inversion process for event modeling (https://nctr.pmel.noaa.gov/

* NOAA Center for Tsunami Research: Volcano-generated Tsunami Event – January 15, 2022 Hunga Tonga–Hunga Ha'apa Tsunami. URL: https://nctr.pmel.noaa.gov/tonga20220115/ (accessed 08.02.2025).

** NOAA Center for Tsunami Research: Tsunami Forecasting. URL: https://nctr.pmel.noaa.gov/tsunami-forecast.html (accessed 08.02.2025).

tonga20220115/). The amplitudes of the computed waves are generally reproduced, even for remote locations. The difficulty of inverting the mixed DART records may be the main reason for some of the model's shortcomings.

For other events, the sea level data used for forecasting may also be distorted by the presence of signals (noise) as a result of seismic waves passing along the ocean floor. This is possible when the sea level monitoring stations are close to the source, for example, the DART 46409 station during the event on 23.01.2018 near Kodiak Island. In such cases, difficulties with identifying the tsunami itself may arise. The tsunami computation based on sea level data containing seismic noise is carried out in [15], where it is shown that the calculated waveforms may be distorted, but, nevertheless, allow us to assess the degree of danger of the expected tsunami.

The tsunami forecast for 15.01.2022 could have been made using the express method of operational tsunami forecast [16]. Previously [17, 18], when modeling the 2011 Tohoku tsunami, it was shown that the method gives an adequate result, despite the fact that the tectonic excitation mechanism was accompanied, presumably, by an underwater landslide [19]. The method is approximate, but allows for an adequate assessment of the expected tsunami at a given point in real time.

The aim of the work and problem statement

The aim of this study was to confirm the applicability of the express method of operational forecasting in cases of tsunami generation by nonseismic sources. The eruption of the Tonga volcano is a good example to demonstrate the capabilities of the express method.

In accordance with the algorithm of the express method [16], auxiliary computations of waves from an elementary circular source with a center coinciding with the epicenter of the volcanic eruption were carried out to construct the transfer function. No assumptions were made about the mechanism of excitation of these waves. In operational mode, the computation is performed immediately after receiving information about the coordinates of the tsunami source. Based on data on tsunamis in the ocean, the expected tsunami waveforms at specified points are calculated using the transfer function. In real time – after receiving information about the passage of a tsunami through an ocean level measuring station. In the event on 15.01.2022, the data from the bottom stations DART 51425 or 52406 closest to the explosion site were used for the forecast. Only the part of the record containing the gravitational component was used. The computation was performed for the DART stations whose records contain both baric and gravitational components.

Unlike the NOAA method, only one elementary source was used for auxiliary computation; the tsunami calculation was performed based on data from one DART station.

In operational conditions, it is advisable to use, if possible, short segments of the DART station data series (for example, a quarter of the first period) to form a forecast. The quality of the computation (forecast) is assessed by the possibility of adequately determining the degree of danger of the expected tsunami when compared with the available actual data.

Results and discussion

Preliminary experiments

The computation area diagram of numerical experiments with the indication of the epicenter and location of the DART system stations is shown in Fig. 1. The coordinates of the stations were taken from the National Data Buoy Center website (https://ndbc.noaa.gov/to_station.shtml).

To check the adequacy of further computations, tsunami waveforms at remote DART stations were preliminarily calculated based on data from the station closest to the source for different durations: from a quarter of the period to a full period and more. These data contain information on both the gravitational and baric components, which cannot be separated. The presence of the baric component may affect the adequacy of the gravity wave assessment at remote points. As an example, Fig. 2 shows the results of calculating waveforms at the DART 52401 based on data from the DART 51425 for different durations (17, 22, 30, and 42 min), corresponding to a gravity wave.

Wave forms, natural and computed based on initial data of different duration, from a quarter to the full first period, generally coincide well. There are minor discrepancies in the calculated forms, which are due to the approximate nature of the express method, as well as the presence of a baric component in the initial data. A further increase of the data segment does not lead to an improvement of the forecast, since the data from the DART 51425 and the DART 52401 stations contain information about the baric wave. The result shows that under operational conditions, the use of short segments of a data series gives a completely adequate forecast of the expected tsunami.

Computation of gravitational components of waves caused by the Tonga volcano eruption

The express method of operational tsunami forecasting was used to compute gravity waves generated as a result of the explosive eruption of the Tonga volcano at points in the ocean where DART stations are located (data taken from the National Data Buoy Center website; https://ndbc.noaa.gov/to_station.shtml). For auxiliary computations, an elementary source in the form of a circular initial elevation of the free ocean surface in the epicentral region of the eruption was used. Data from the DART 51425 or the DART 52406 stations, which are closest to the epicenter of the explosion, were used. The published data from the

Fig. 1. Map of the area used for computation. The asterisk shows the epicenter of the explosion. Five-digit numbers are the positions of the DART system stations. The stations that registered both baric and gravity waves are marked in blue (in larger font).

DART bottom stations on pressure are expressed in meters. Parts of the records containing gravitational components were used, the arrival of which was determined by the travel time of the wave from the auxiliary source. For the DART 51425, this time is 120 minutes from the beginning of the eruption, for the DART 52406 – 252 minutes. As noted above, the records contain both baric and gravitational components.

The computation was performed for the DART stations in the ocean that recorded both baric and gravity waves. The numbers of these stations are shown in larger font in Fig. 1.

The initial data from DART 51425 are shown in Fig. 2 in the left column at the top. The segment of the series (a quarter of the first period) used for the calculations is highlighted in red (from 120 to 137 minutes after the volcanic explosion).

The DART station data shown in Fig. 3 include both baric and gravitational components.

The results of the express method calculation based on the data from DART 51425 with duration of a quarter of the first period are shown in Fig. 3.

The computation shows the arrival of a gravity wave, starting with a decrease in the level. At some stations, the most distant from the source, the amplitudes of the computed waves are lower than the recorded ones. This is explained, firstly, by the fact that the initial data for the computation contain a baric component, and secondly, by the fact that the records of remote stations also contain both components.

Qualitatively, the waveforms of the calculated waves coincide with the low-frequency components of the recorded waves, including the baric and gravitational components. A detailed spectral analysis of the signals was not included in the objectives of the work.

The results of similar computation based on data from another station, DART 52406, are shown in Fig. 4. The record of this station is shown by a thin black line in Fig. 4 (left column, above), where the segment of the series used for the calculations is highlighted in red (a quarter of the period, from 252 to 273 minutes after the volcanic explosion).

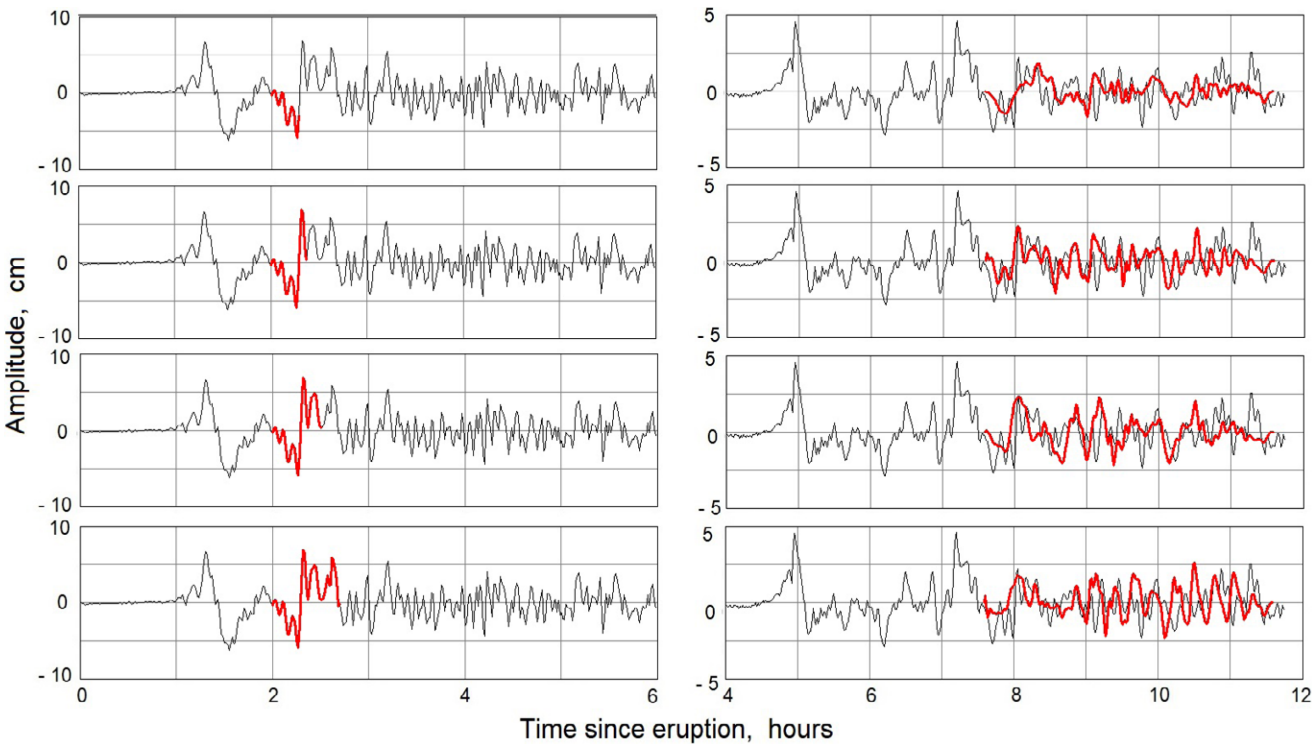

Fig. 2. The left column shows the data from the DART 51425 station of varying duration (17, 22, 30 and 42 min). The red line highlights the section of the data series used for calculations. The right column shows waveforms at the DART 52401 station: natural (thin black line) and computed based on the data from the DART 51425 station of varying durations (red line), starting from 120 minutes after the start of the eruption.

As shown in [2, 14], the amplitudes of forced surface (baric) waves estimated from bottom station data are apparently overestimated. The correction factor gH/U^2 was applied to the part of the baric component preceding the arrival of the gravity wave in accordance with [2, 14]. The values of the correction factors are given in the table. When calculating the factors, the propagation velocity of the atmospheric pressure wave was taken to be 312 m/s [14]. The corrected forms of baric waves are shown in Fig. 4 with a thick black line. The same figure shows the uncorrected data from the DART stations (thin black line), including both the baric and gravitational components. It is evident that the corrected amplitudes of forced waves on the ocean surface are almost 2 times less than those measured by the bottom sensors. The use of a correction factor for data containing both baric and gravitational components is not appropriate.

The same figure shows the results of computing the gravitational component (red line) based on the DART 52406 station data. As in the previous example of computing based on the DART 51425 station data, the arrival of the gravity wave begins with a decrease in the level. At some stations, the amplitudes of the calculated waves are lower than the recorded ones, which are explained by the presence of a baric component in the initial DART 52406 station data for the computation and in the records of remote stations. The structures of low-frequency oscillations of the calculated and actual ones generally correspond to each other.

The waveforms of the gravitational components of the waves computed based on the DART 51425 and DART 52406 stations coincide with the accuracy necessary to assess the degree of tsunami hazard.

The structure of the wave on the free surface is quite complex and includes both the wave caused by the main wave of atmospheric pressure and secondary waves excited when the atmospheric pressure wave passes over irregularities in

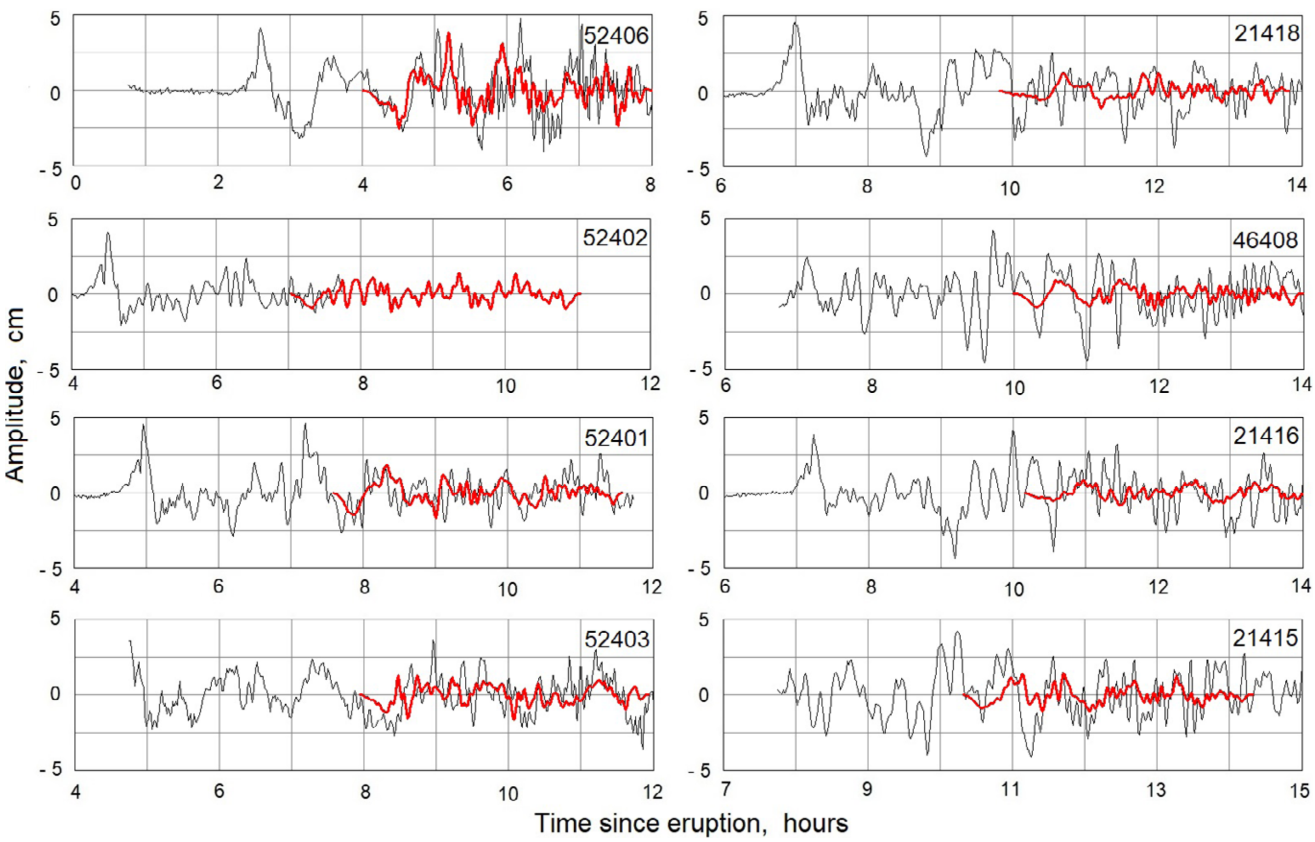

Fig. 3. Tsunami waveforms obtained by the express method of operational tsunami forecasting (red line) based on the 17-minute data from the DART station 51425. The DART station data in centimeters of water column are shown by a thin black line. Each fragment of this and the following figure shows the DART station number.

Table. Correction factor values

Indicator	DART station							
	52406	52402	52403	52401	21418	46408	21416	21415
Ocean depth H, м	1800	5963	4542	5590	5664	5374	5812	4775
Correction factor gH/U^2	0.181	0.601	0.458	0.563	0.571	0.542	0.586	0.481

Note. U is the velocity of the pressure wave in the atmosphere, H is the depth of the liquid layer, and g is the acceleration due to gravity. The ocean depths at the locations of the DART stations given in the table were taken from the National Data Buoy Center website (https://ndbc.noaa.gov/to_station.shtml).

the earth's surface. In addition, when passing over areas of the ocean with an irregular bottom, the atmospheric pressure wave generates free gravity waves. These waves are superimposed by a free gravity wave excited by a volcanic explosion and other accompanying effects in the source. It is impossible to separate these components. The amplitudes of the waves on the ocean surface excited by atmospheric pressure waves, estimated from the data of bottom stations, as shown in [2, 14], are apparently overestimated. It is impossible to apply a correction factor to the total wave without separating the components. In this regard, the question arises as to how adequate the assessment of the amplitudes of surface waves based on the data on the pressure at the bottom is.

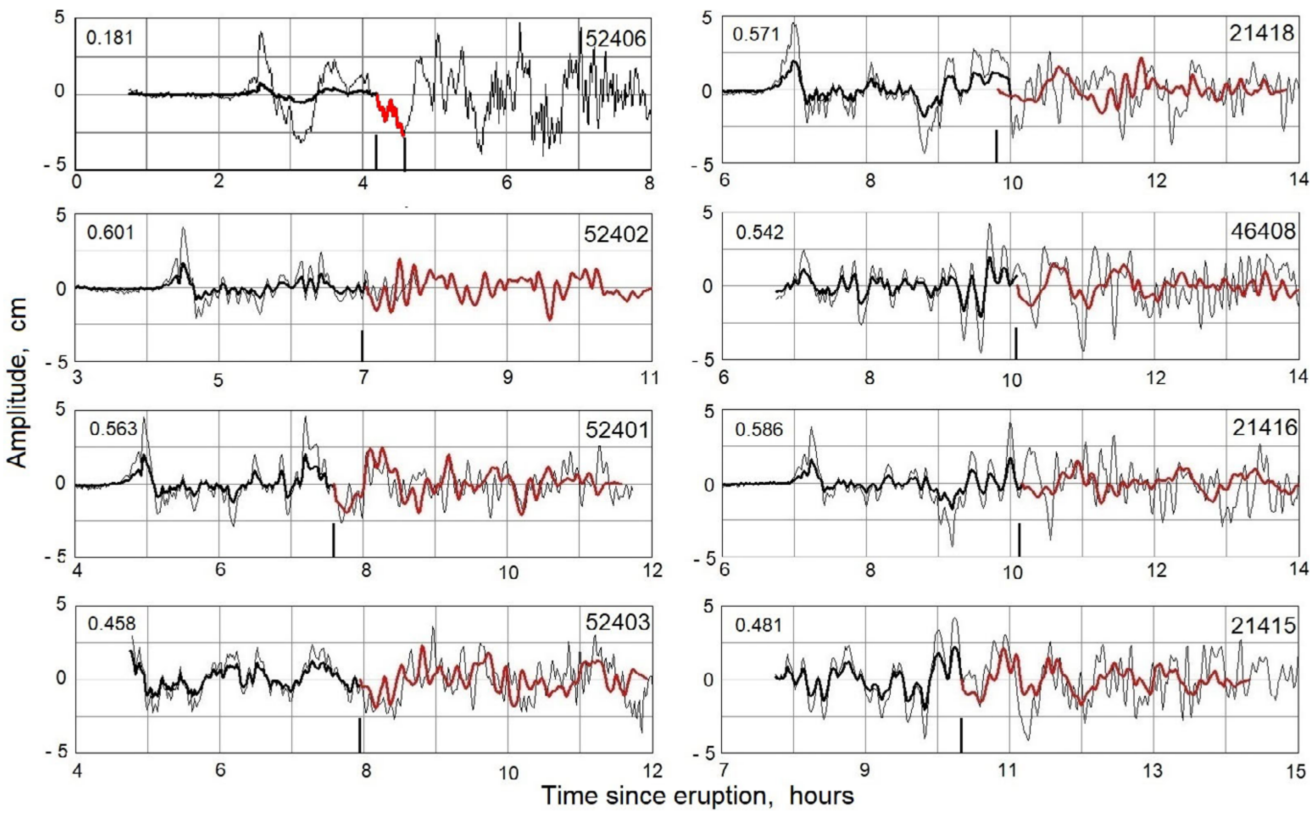

Fig. 4. Tsunami waveforms (red line) computed based on the 21-min data from the DART 52406 station data (left column, top; the section of the data series used for the computation is highlighted in red and marked with vertical lines). The moment of entry of the gravitational component is marked by a vertical line. The bottom station data are shown by a thin black line. The amplitude of the part of the record preceding the gravity wave is multiplied by the correction factor gH/U^2 (thick black line). The value of the factor is indicated for each DART station (top left in each fragment).

In general, the computed tsunami waveforms (gravitational component) give quite adequate results, despite the interference caused by the baric component. This confirms the assumption that the express method is applicable for forecasting tsunamis of non-seismic origin. The quality of the computation is comparable to the quality of tsunami calculations by the current NOAA method.

The assessment of tsunami waveforms near the coast was not included in the objectives of the work. Nevertheless, the result satisfies the definition of the concept of "tsunami forecast" formulated by the Intergovernmental Oceanographic Commission of UNESCO*: the time of arrival of the expected tsunami at a given point is given, the amplitudes of individual waves and the time of their arrival are determined. Earlier [18] it was shown using actual data that the express method can be used to forecast tsunamis in advance near the coasts based on ocean tsunami data. The moment of forecast generation is determined by the time of receiving information about the passage of the first quarter of the tsunami period through the registration point.

Conclusions

The express method of operational tsunami forecasting was used to compute the gravitational component of the wave from the explosive eruption of the Tonga volcano on January 15, 2022.

It was shown that for an adequate forecast, information on tsunamis from the DART stations closest to the source with duration a quarter of the first period is sufficient, which is especially important in the operational mode.

A good match was obtained between the waveforms computed by the express method of operational tsunami forecasting and the waveforms recorded by the DART bottom stations measuring the ocean level. The differences in these waveforms are explained by the presence of baric components in the bottom pressure data.

It was confirmed that the express method can provide a tsunami forecast regardless of the excitation mechanism. The express method, like other methods of operational tsunami forecasting, can be supplemented with an algorithm for calculating baric waves. However, the question of how adequate the assessment of the amplitude of surface waves based on the data on the bottom pressure in events similar to the one considered remains unclear.

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Received 20 February 2025
Accepted 13 March 2025

Поступила 20.02.2025
Принята к публикации 13.03.2025