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Satellite Recording of the Indian Ocean Tsunami on December 26, 2004

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The tsunami is the most formidable of all natural hazards. It is usually generated as a result of seismotectonic motions of the ocean bottom in the seismic source zone. Tsunami waves propagate far from the source and can cause damage even in regions where the earthquake was not manifested. The unexpectedness of tsunami is an additional risk factor. The tsunami of December 26, 2004 in the Indian Ocean provides a tragic example, resulting in more than 170 000 deaths in Indonesia, India, Sri Lanka, Thailand, and other countries. The interval between the moment of wave generation in the ocean and the arrival of the tsunami on the coast (from 20 min to a few hours) was sufficient to evacuate people from the possible flooding zone, but the absence of an early warning system in this region meant that timely evacuation was impossible.

Taking into account the specific character of the destructive behavior of the tsunami, this natural hazard can be considered one of the most inevitable of all natural phenomena. In the majority of cases, the enormous volumes of seawater that break onto the shore during a tsunami cannot be stopped by artificial barriers. The tsunami-related onshore flooding height frequently exceeds 10 m. In some coastal (shallow-water shelf, estuary, and so on) zones, this wave takes the form of a bore (water wall). This water swell propagates shoreward with a large velocity, accumulating enormous kinetic energy and destroying ships and buildings on its way. The most effective protections against this hazard are timely evacuation of people to safe regions and withdrawal of ships to the open sea. Obviously, advanced notification concerning the approaching wave is important in this case. A timely *operative forecast of tsunami* is, indeed, the most important aspect of this problem.

The consequences of the tsunami on December 26, 2004 quickly became a tragic lesson for the majority of the countries in the region. The scale of this hazard exceeded all historical cases of catastrophic tsunami. Therefore, at present, the attention of scientists is intensely focused on the problem of how to prevent the consequences of such marine catastrophes.

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TSUNAMI RECORDING IN THE OPEN OCEAN

Traditional methods of tsunami warning are based, first of all, on seismic information obtained immediately after the earthquake and on calculations of the time of wave propagation and its amplitude at each specific point. However, the efficiency of such methods decreases and occurrences of false alarm increase when there is a lack of data about the parameters of tsunami in the source. For example, during the Shikotan tsunami on October 4, 1994, which was a catastrophic event for the Southern Kuril Islands and Hokkaido, the Pacific Tsunami Early Warning System announced tsunami alarm on the Hawaiian Islands and warned of the possible approach of a tsunami with a height of a few meters. Significant finances (approximately 30 mln USD) were spent on the evacuation of thousands of people. Two persons died during this evacuation. The alarm was false: the actual height of tsunami wave did not exceed half a meter.

Direct measurements of tsunami obtained from coastal level recorders contain fluctuations that are strongly distorted with respect to the form of the wave in the open ocean. The arrival of the wave to the shallow-water zone and the reflection from coasts leads to an increase in amplitude, but the spectrum of the signal (wave form) is transformed due to the resonance properties of the shelf, bays, and straits. Quality data for tsunami in the open ocean can be obtained using data of the bottom hydrostatic pressure [1]. However, such systems are expensive and cannot fully embrace all possible zones of tsunami wave generation and propagation.

The advent of remote (satellite) methods for recording parameters at the ocean surface significantly expands the capabilities of oceanography. More specifically, they are also applicable to the study of rare catastrophic events (typhoons and tornados) in the ocean. Remote sensing of sea surface temperature (SST) was the first method that made it possible to detect the influence of strong underwater earthquakes on the ocean surface [2]. It was discovered that powerful oscillations of the ocean bottom lead to destruction of the thermocline and cooling of the sea surface. This effect is reliably recorded by modern satellite systems.

Currently, the application of satellite altimetry and, in particular, the use of high-precision radio measurements of elevation from the GEOSAT, TOPEX/POSEIDON, ERSS-1, ERS-2, JASON, and ENVISAT satellites ensures a cardinal solution to the problem of determining sea level variation, not only near the coast, but also at significant distances from the coast, with precise correlation to the unified geodesic reference system. In the perspective, measurements provided by the Russian *Geoik-2* geodesic satellite can also be used. An exact correlation between the sea level data obtained in these works and the unified altitude system is provided by applying the receivers of any of the GLONASS, GPS, or DORIS navigation systems installed on the satellites in order to determine their orbits.

Satellite altimetry data were used for the first time by American specialists in an attempt to detect tsunami in the open ocean [3]. They analyzed satellite altimetry data obtained in the course of the TOPEX/POSEIDON experiment, which focused on the three strongest earthquakes that generated the corresponding tsunami: the Okushiri tsunami on July 12, 1993, the Java Island tsunami on June 2, 1994, and the Shikotan tsunami on October 4, 1994. Records made after the earthquake were subjected to correlation analysis. The authors of [3] claim that this method makes it possible to identify large-scale displacements of the ocean level with a height of 3–5 cm. However, they failed to detect tsunami manifestations in all records. Interesting data on anomalous level changes near the source were obtained using the TOPEX/POSEIDON data [4].

The next attempt to detect tsunami in the open ocean on the basis of satellite data was made in 1999 [5]. The authors analyzed the records related in time to seven earthquakes that generated tsunami. Using spectral analysis, they managed to positively identify only the Nicaragua earthquake of September 2, 1992.

Since 1985, monitoring of the height of sea surface has been performed almost continuously for the entire World Ocean. At present, the amount of this information accumulated in various international data centers has reached approximately 200 Gb, and it is constantly increasing. The original databases of satellite altimetry available for scientific use were created and regularly updated at the Physical Oceanography Distributed Active Archive Center (PODAAC) in the Laboratory of Jet Propulsion of the California Technological Institute in the United States [6] and at the Center for Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) in Europe [7].

Taking into account the demands of Russian scientists, as well as the types of possible problems and international developments, an Integrated Satellite Altimetry Database (ISAD) [8] (this database is currently being developed and updated [9]) and a System of Automated Processing for the Satellite Altimetry Data were created at the Geophysical Center of the Russian Academy of Sciences (GC RAS) with the support of the Russian Foundation for Basic Research (RFBR).

TSUNAMI ANALYSIS ON THE BASIS OF ALTIMETRY DATA

A tsunamigenic earthquake (M = 9.0) occurred on the northwestern Sumatra Island (Indonesia) at a distance of 42 km from Simeulue Island at 0:59 UTC. The parameters of this seismic source are given below:

Date	December 26, 2004
Epicenter	42 km north of Simeulue Island (Indonesia)
Time at the source	00:58:50 UTC
Latitude	03.298° N (USGS)
Longitude	95.778° E (USGS)
Depth	10.0 km (USGS)
Magnitude	M_w = 9.0 (Harvard CMT)

This tsunami manifestation was of global character. In addition to the catastrophic consequences near the source (Sumatra and Sri Lanka coasts), the waves were recorded everywhere in the World Ocean. According to A.B. Rabinovich (personal communication), preliminary analysis of the data of observation reveals the following values of tsunami height at the coast of the Indian Ocean: 12–15 m in Pasni (Pakistan) and 2 m in Bombay (India). In the Pacific Ocean, the tsunami height reaches 21 cm in British Columbia (Canada), 2.6 m in Manzanillo (Mexico), approximately 0.5 m at the coast of New Zealand, and 28 cm in Severo-Kurilsk (Russia). In the Atlantic Ocean, the tsunami height is 4.5 cm in San Juan (Puerto Rico), 12 cm in the Bermuda Islands, 22.5 cm in Atlantic City, and 41 cm in Halifax.

All available altimetry data of TOPEX/POSEIDON, ENVISAT and JASON-1 in the aftershock period were analyzed. Anomalous level variations were found in individual tracks, which can probably be related to the propagation of tsunami waves. The data record of highest quality was provided by the JASON-1 satellite (cycle 109, track 129) and was taken for further analysis. The ocean level profile corresponding to this track of the altimeter is shown in Figs. 1 and 2a. The time of satellite flight over the Indian Ocean corresponds to the period from 02:51 (12° S) to 03:02 (20° N), which is approximately 2 h after the formation of the tsunami wave. The level profile obtained 10 days before the tsunami (previous cycle 108) is shown on the graph for comparison. The wave front is clearly observable at approximately 6° S. The maximum amplitude of the wave reaches 80 cm. The chart of the Indian Ocean including the epicenters of the main seismic shock (parameters are given above) and aftershocks is shown in Fig. 1. The solid line shows the track of the JASON-1 satellite (cycle 109, track 129). Contour lines of the tsunami traveltime are shown in the figure calculated by K.

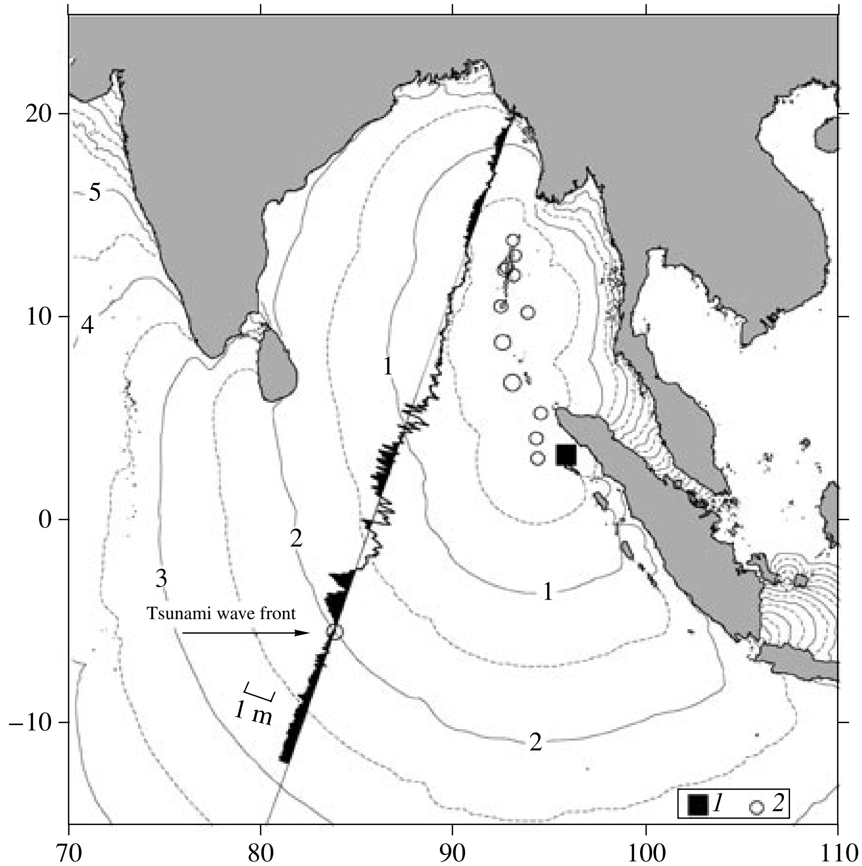

Fig. 1. (*1*) Chart of the Indian Ocean. Location of the earthquake epicenter on December 26, 2004; (*2*) location of the main aftershocks; contour lines of the times of tsunami wave propagation are shown with an interval of 0.5 h (according to Satake calculations). Values of contour lines are given in hours; solid line denotes the JASON-1 satellite track (cycle 109, track 129). The sea level profile based on altimetry data is shown along the satellite track.

Satake (National Institute of Advanced Industrial Science and Technology). The longitudinal scale of the aftershock zone is approximately 1000 km, which is characteristic of the most powerful events only.

It is seen in Fig. 1 that the angle at which the satellite track crosses the wave front is approximately equal to 45°. Therefore, the real horizontal scale of changes in the ocean level should be divided (from geometrical considerations) by approximately 1.4. The main length of the wave in the altimeter records is approximately 700 km, which corresponds to 500 km for the tsunami wave. We can calculate the main tsunami wave period as T = 40 min on the basis of the mean wave velocity in the open ocean (~200 m/s). It is worth noting that the higher-frequency components of sea level oscillations are observed at a significant distance to the north, which is closer to the source. Actually, this reflects the effect of the linear dispersion of tsunami waves, owing to which short-period waves have propagation velocities smaller than those of long-period waves.

The position of the wave front is conventional to a certain degree. The calculation was performed under the assumption of a maximal velocity of surface gravity wave propagation, $c = \sqrt{gH}$, where c is the wave propagation velocity, g is the gravity acceleration, and H is the ocean depth. Actually, the velocity of the wave also depends on its wavelength $c = \sqrt{g\tanh(kH)/k}$, where $k = 2\pi/\lambda$ and λ is the wavelength. The shorter the wave, the slower it propagates. Due to the effect of linear dispersion, the real front is usually behind this theoretical estimate. The longer the route of propagation, the stronger is the effect of dispersion. The wave front can be even more strongly distorted in the shallow water and during its propagation along the straits. However, the estimate of the position of tsunami wave front calculated from relation $c = \sqrt{gH}$ is sufficiently exact, and the error does not usually exceed the size of the tsunami source (~50–100 km).

The evolution of wave train is caused by the dependence of the group velocity on frequency:

$$c_g = \frac{d\omega}{dk} = \frac{\omega}{2k}\left(1 + \frac{2kH}{\sinh 2kH}\right), \tag{1}$$

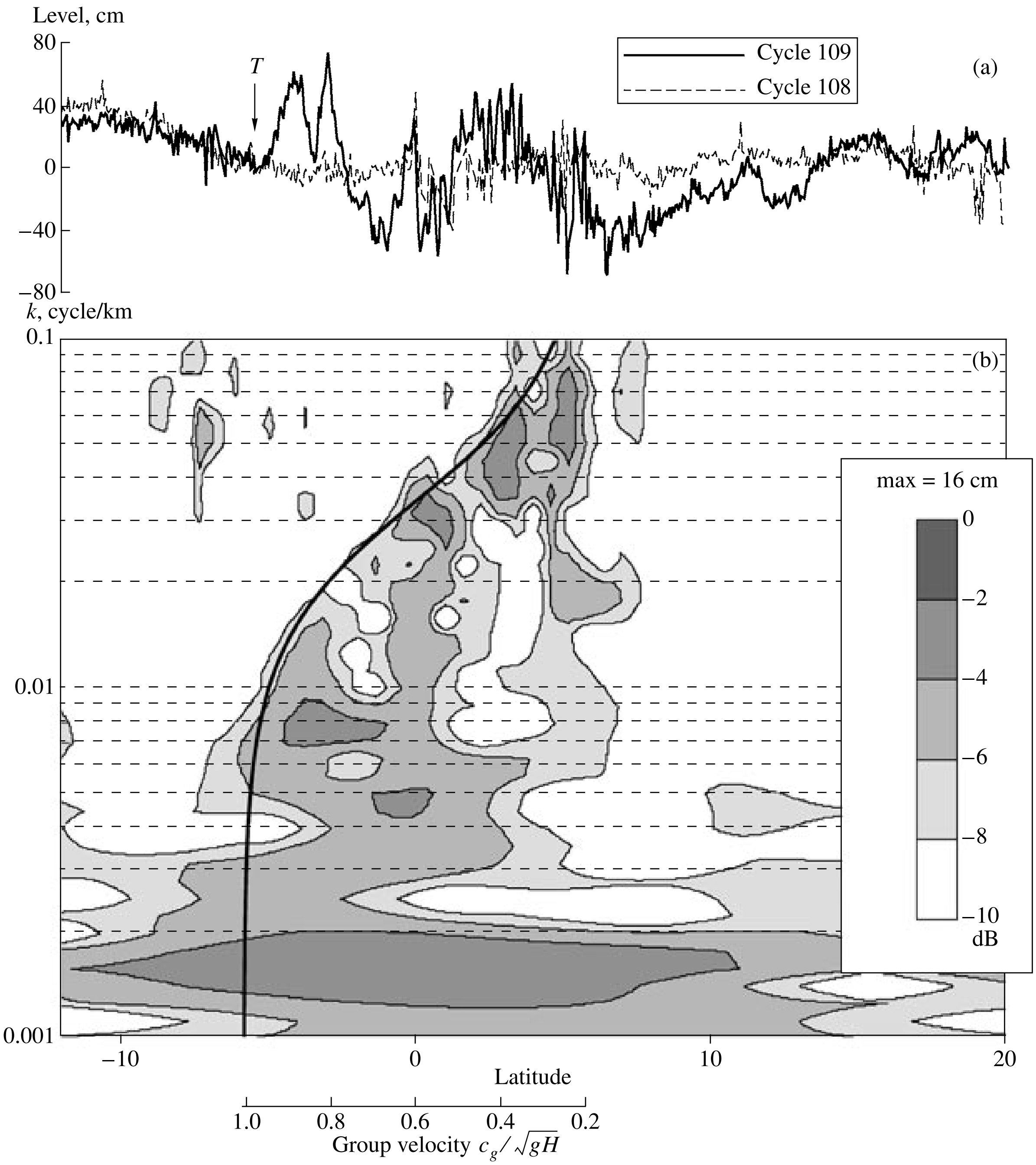

Fig. 2. (a) Ocean level profile as a function of latitude obtained from the JASON-1 altimetry data (cycle 109, track 129). Dashed line shows the same profile corresponding to cycle 108 (December 16) for comparison; letter *T* indicates the location of the wave front. (b) Results of spectral amplitude analysis of the tsunami record (Multiple Filter Analysis). Contour lines are shown with an interval of 2 dB with respect to the maximum (16 cm). Dispersion curve $c_g(k)$ demonstrates the theoretical appearance of the corresponding spectral component calculated for the linear dispersion law for surface gravity waves. The variation scale of dimensionless group velocity is shown in the lower part of the figure.

where ω is angular frequency, k is wavenumber, and H is the depth of the ocean.

In order to analyze the effect of the linear dispersion of tsunami waves, we calculated a diagram of the dependence of the spectral amplitude of the signal on time and wavenumber. This method is widely practiced in seismology [10] as Multiple Filter Analysis. At present, methods of wavelet analysis, which are actually a variety of this method, are widespread. The results of the calculation of spectral amplitudes of the signal are shown in Fig. 2. It is clearly seen that the wave front is confined to the moment at which the lowfrequency components arrive ($k < 0.05$ km^{-1}). High-frequency components appear north of the front. The dispersion curve $c_g(k)$ corresponding to Eq. (1) is shown in the figure. It was calculated taking into account the angle that exists between the satellite track and the wave front at their intersection point. A strong correlation is observed between the arrivals of spectral components of the signal and the theoretical calculations.

The revealed effect of tsunami wave dispersion demonstrates that long-wave approximation, which is widely used in numerical models of tsunami wave propagation, is limited. Owing to the slower velocity of high-frequency components in the wave spectrum, the amplitude of tsunami decreases faster than in the shallow-water model. This error is especially evident in calculations of the wave field at significant distances from the source. It was shown for the first time in [1] that the effect of linear dispersion can actually completely distort the form of tsunami signal in the open sea. In this case, the main energy is concentrated at periods of approximately 30–50 min. Therefore, distortion is not strong at a distance of approximately 100 km from the source.

The results obtained in this work demonstrate the possibility of the early detection of dangerous tsunami waves in the open ocean using modern systems of ocean observation from space. It is clear that existing methods of early tsunami forecasting will develop in a direction that favors the creation of technology for the continuous monitoring of the sea surface, using both ocean level sensors equipped with telemetric connections to processing centers, and satellite altimetry measurements.

Unfortunately, the present-day tsunami service is organized predominantly on a regional basis. Analysis of the response of national services to the events of December 26, 2004 shows that their zones of responsibility are restricted solely to their own coastal control sectors. Taking into account the limited capacities of a number of developing countries to provide a level of early forecast that is presently acceptable, and considering the scale of such catastrophes, it seems reasonable to develop a global system for observations of the sea surface that is controlled by international institutions.

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