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MONITORING OF THE TSUNAMIGENIC EARTHQUAKES BY MEANS OF SATELLITE GEODESY

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Abstract. One of the practical measures to mitigate the consequences of the tsunami after recording the undersea earthquake is an early warning of the approaching wave and estimation of the tsunami risk, which requires the development of a hydrodynamic model of wave propagation. This model should include initial conditions in terms of the seafloor uplift amplitude due to the earthquake. The methods of satellite geodesy used to estimate coseismic displacements of the surface in the vicinity of the earthquake epicenter can be applied to estimate this uplift in near real time.

Based on the satellite geodetic data (GPS data) for the Kuril Islands and Japan, fault plane solutions are modeled for three strong seismic events in the Pacific region: two Simushir earthquakes 15.11.2006 (M_W=8.3) and 13.01.2007 (M_W=8.1) and the catastrophic Tohoku earthquake 11.03.2011 (M_W=9.0). Patterns of vertical coseismic displacements of the seafloor are constructed for these events.

Keywords: tsunami, undersea earthquake, earthquake source, satellite geodesy, GPS data.

Introduction

Tsunami is one of the most dangerous and unpredictable natural phenomena that threaten coastal areas of the World ocean. The overwhelming majority (about 80%) of tsunamis are the results of the undersea earthquakes [*Nosov*, 2014]. Practical measures of mitigating the consequences of tsunami along with a priori investigations that imply mainly tsunamizoning includes also early warning of the approaching wave after the seismic event is recorded. For reliable determination of the kinematic and dynamic characteristics of the probable effect of the wave it is necessary to create the hydrodynamic model of its propagation which requires data on the submarine topography and initial conditions. The focusing of the waves is determined by the underwater topography, mainly by the trenches and submarine ridges. Information about the topography is usually known in details according to the bathymetry. The key question for each seismic event is the initial conditions, namely, the initial form of the seafloor uplift in the epicenter. One of the ways to determine this uplift is the satellite geodetic measurements. In the study of the earthquake sources, the displacements of the Earth crust, calculated by *GPS* data, are used for the estimation of slip distribution in the earthquake source [*Vladimirova*, 2013; *Steblov et al*., 2008; *Steblov et al*., 2013]. Concerning the question of the tsunami investigation these data can be used for rapid determination of the coseismic uplift of the seafloor. In practice the ability to receive and to interpret the *GPS* data in the near real time mode is especially important.

GPS observations in the region of Japan-Kuril-Kamchatka island arc

The Pacific coast of North-Eastern part of Eurasia and adjacent waters belong to the one of the most seismic dangerous regions of the Earth and as a result they are in the area of high tsunami risk. It was already mentioned above that for timely warning of an approaching tsunami and its risk level the efficient estimation of the sea (ocean) floor displacement in the epicenter of the recorded undersea earthquake is needed. Currently to solve this problem the data of the satellite geodetic observations are used (the GPS observations data).

There are three regional networks of *GPS* stations (Fig. 1) on the regarded area, providing the continuous monitoring of the Earth surface displacements, that allows to estimate the coseismic displacements in the online mode: the Kamchatka regional network of the Geophysical survey of RAS, the Kuril network of the Institute of marine Geology and Geophysics FEB RAS and the network of Japan, the most dense with more than 1000 stations working in the real-time mode.

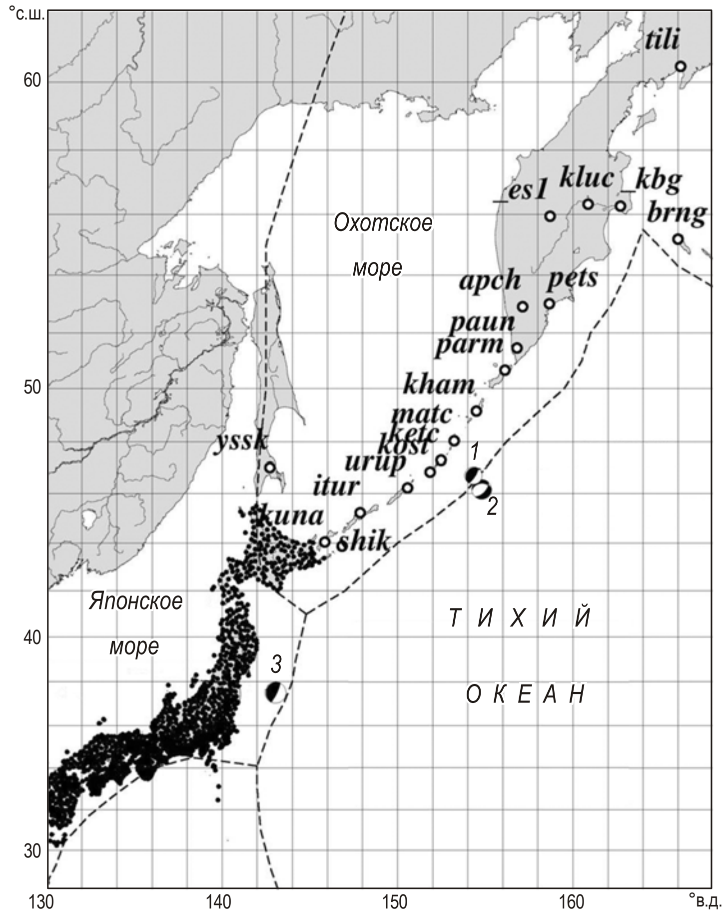

Fig.1. The layout of the stations of three regional satellite geodetic networks in the Japan-Kuril-Kamchatka island arc: *filled circles* are stations of the Japan network; *circles without filling* are Kamchatka (GS RAS) and Kuril (IMGG FEB RAS) stations; abbreviations are names of the stations approved in GS RAS and IMGG FEB RAS. The dashed lines are the boundaries of the plates. *1–3* are the focal mechanisms of the two Simushir earthquakes (*1* – 15.11.2006, M_W=8.3; *2* – 13.01.2007, M_W =8.1) and the Tohoku earthquake (*3* – 11.03.2011, M_W =9.0) according to the *Global CMT* catalogue data.

The data from the stations of Kamchatka and Kuril networks can be received in the real time mode if there is a satellite communication link. The dual-frequency phase measurements from these stations are processed with the *GAMIT*/*GLOBK* software [*Herring, King, McClusky*, 2010] with the tie to the stations of the Continental reference frame of the Northern Eurasia. The precision of the obtained coordinate estimates is 1-2 mm. Besides the observed coseismic displacements at the GPS stations within several hundred kilometers of the strong earthquake sources can reach several centimeters and near the sources – several meters.

In the present work the data about the coseismic displacements during the Simushir earthquakes, 2006 and 2007, from [*Steblov et al*., 2008] and during the Tohoku earthquake, 2011, from [*Pollitz*, *Bürgmann, Banerjee,* 2011] are analyzed.

Modeling of the coseismic uplift of the ocean floor in the epicenter

The modeling of vertical displacements pattern of the ocean floor consists of two main stages. At the first stage the fault slip distribution is calculated from the displacements over the land; at the second stage according to the found fault slip distribution the field of vertical displacements of the bottom is calculated.

The desired distribution is estimated by minimization of the difference between displacements, resulting from the seismic event, that are registered at the stations $\bar{U}_{(obs)i}$, and displacements, modeled at the same points from the distributed source in the elastic spherically layered media:

$$\bar{k} = \arg\min_{\bar{k}} \left\{ \sum_i \left| \sum_j M_{ij} k_j - \bar{U}_{(obs)i} \right|^2 + \lambda \sum_j \left| k_j \right|^2 \right\}. \qquad (1)$$

Here $\bar{k}$ is a set of desired parameters of the model, representing the slip components over the non-intersecting rectangular elements S_j, that cover the area of seismic rupture S considering the vertical profile of the seismic focal zone, so that

$$S = \bigcup_j S_j\,,\ S_p \bigcap S_q = \varnothing \text{ with } p \neq q;$$

M_{ij} is a response function, that determines the displacement at a surface point $\bar{r}_i$ from the unit uniform slip $\bar{e}_j$ over the rectangular rupture S_j comprising the points $\bar{r}_s$; M_{ij} has the form

$$M_{ij} = \iint_{S_j} G(\bar{r}_i, \bar{r}_s)\bar{e}_j dS\,. \qquad (2)$$

For constructing the Green function $G(\bar{r}, \bar{r}_s)$ the method and the corresponding software codes from [*Pollitz*, 1996] were used, where the spherical functions expansion of $G(\bar{r}, \bar{r}_s)$ is proposed and the relations are given for the dislocation of the form of the uniform slip over rectangular patch in the spherically symmetric layered Earth.

The damping coefficient λ in (1) is selected in such way, so that the statistics χ^2_{red} of the found solution $\bar{k}$ satisfied the condition

$$\chi^2_{\text{red}} = \frac{1}{n} \sum_i \frac{\left| \sum_j M_{ij} k_j - \bar{U}_{(obs)i} \right|^2}{\sigma_i^2} \to 1\,. \qquad (3)$$

Found from (1) parameters of the model $\bar{k}$ enable to determine the displacement of the ocean floor at the arbitrary point $\bar{r}_{oc}$ by a formula

$$U_{up}(\bar{r}_{oc}) = \sum_j \left[k_j \iint_{S_j} G(\bar{r}_i, \bar{r}_s)\bar{e}_j dS \right]. \qquad (4)$$

The vertical component $U_{up}(\overline{r}_{oc})$ from (4) determines the field of the vertical displacements in the epicenter of the earthquake.

Results

In accordance with the described method the authors constructed the fault slip distributions (Fig. 2) and the field of vertical displacements (Fig. 3) in the epicenter of two Simushir earthquakes and the Tohoku earthquake. The found slip distributions are in a good agreement with the results obtained from another data, in particular from the teleseismic observations data [*Lay et al.*, 2009].

For the first of the Simushir earthquakes (15.11.2006, M_W=8.3, Fig. 3, *a*) the maximum uplift was 1.8 m. This earthquake caused a transoceanic tsunami, with the waves of more than 1 m in height that were reported in different parts of the Pacific Ocean – in Mexico, Peru, Chile, New Zealand. The maximum wave height was recorded on the island of Shikotan in the village Malokurilsk (155 cm) and on the coast of California (177 cm) [*Laverov and others*, 2009].

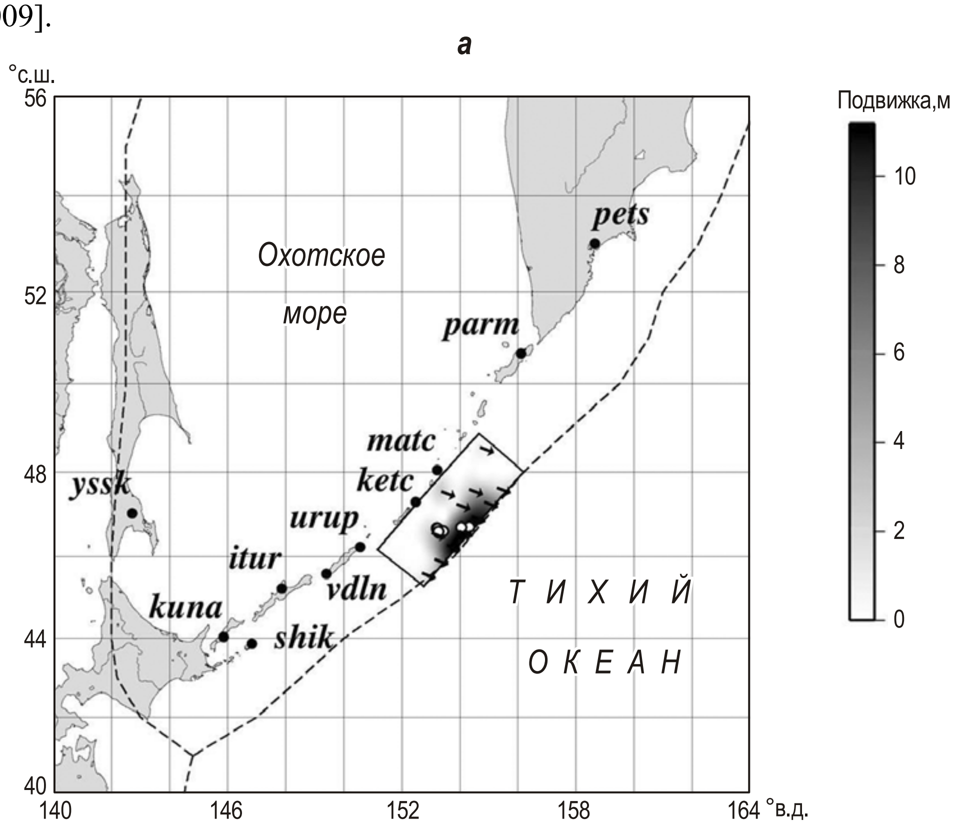

Fig. 2

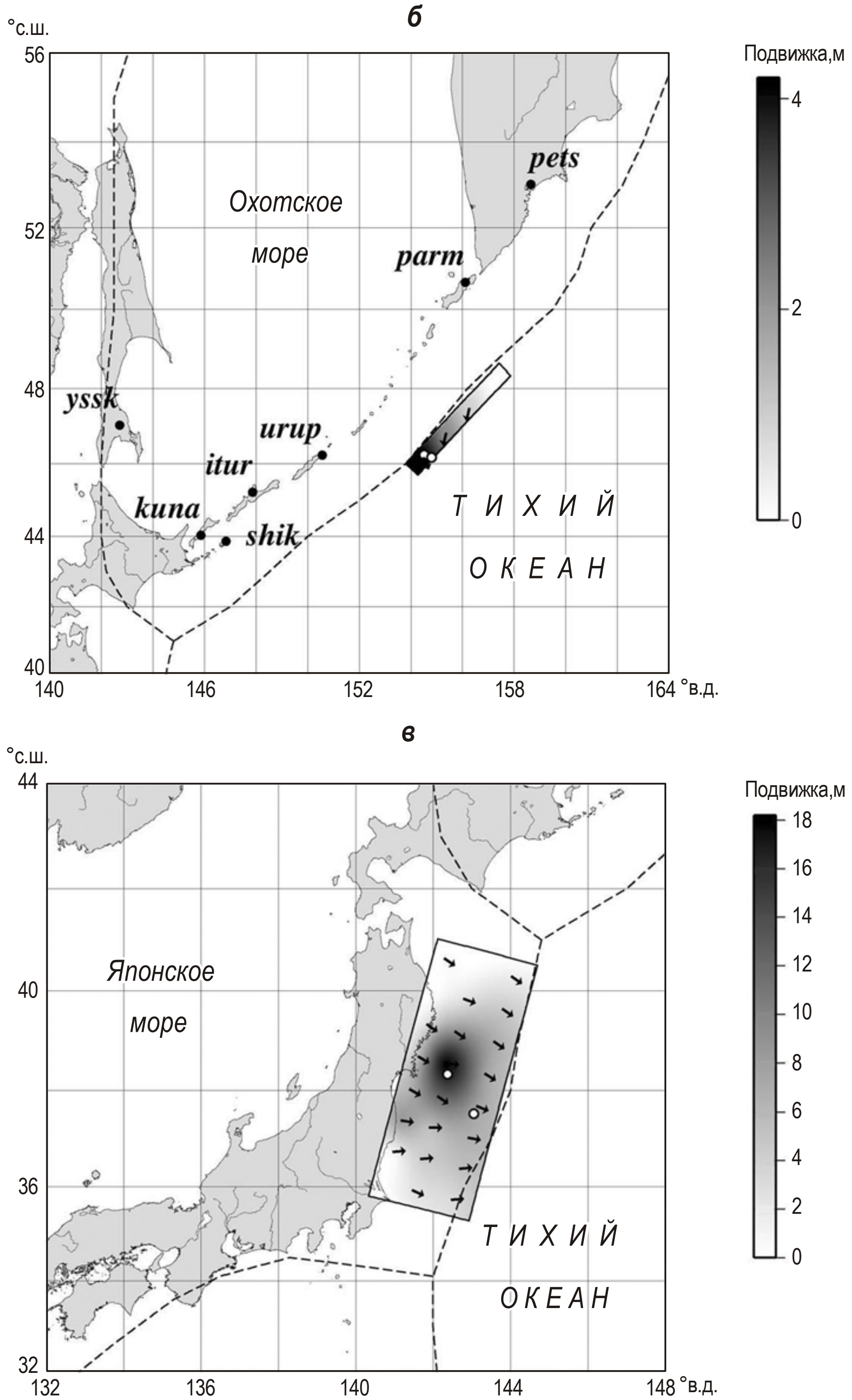

Fig.2. The calculated fault slip distribution of three earthquakes: *a* is the first Simushir earthquake (15.11.2006, M_W=8.3); *б* is the second Simushir earthquake (13.01.2007, M_W=8.1); *3* is the Tohoku earthquake (11.03.2011, M_W=9.0). Black arrows are the directions of the fault slip model; white circles are the hypocenters of the earthquakes according to the data from various catalogues. The scale of the fault slip, m, is given to the right

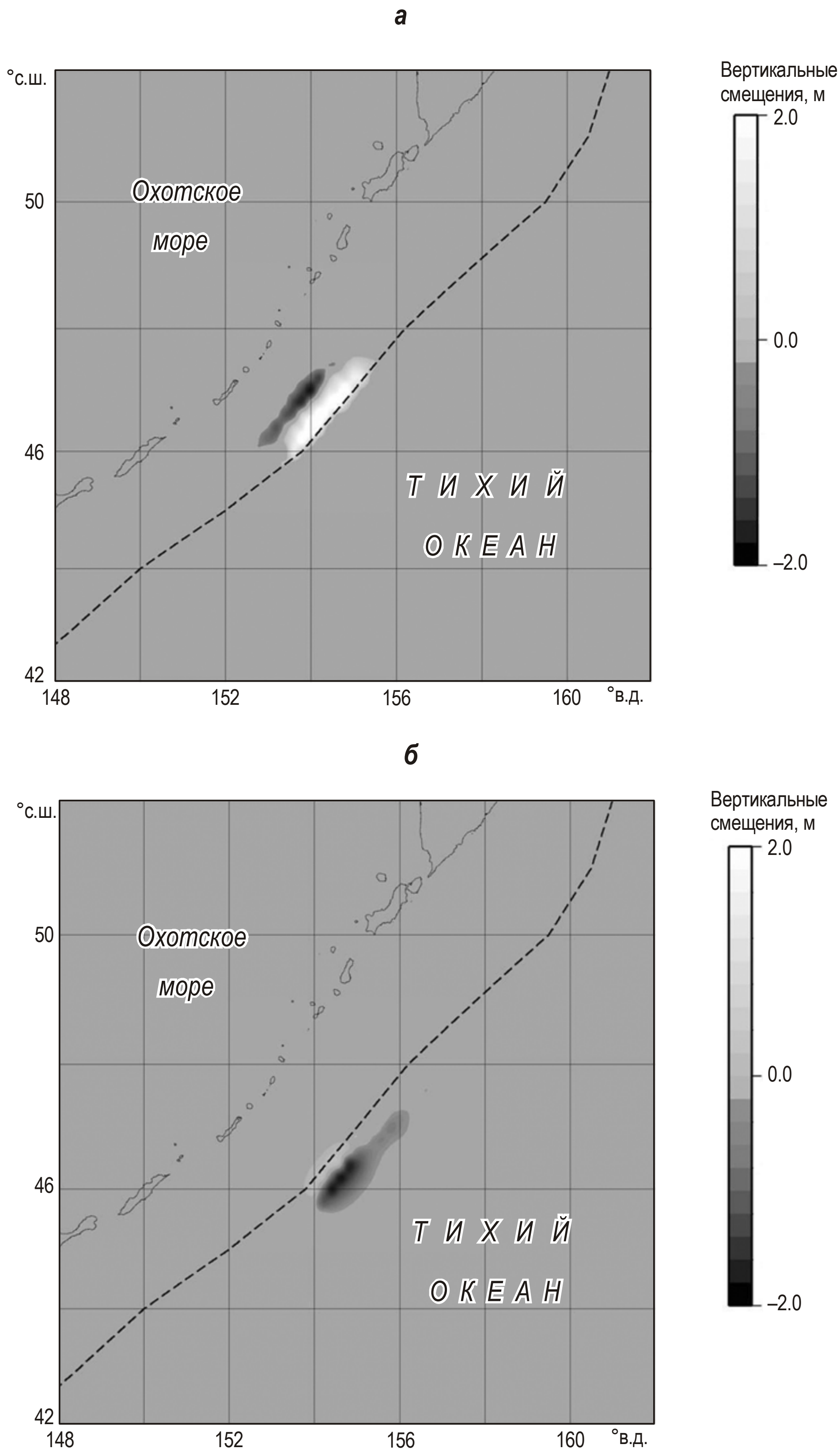
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Fig. 3

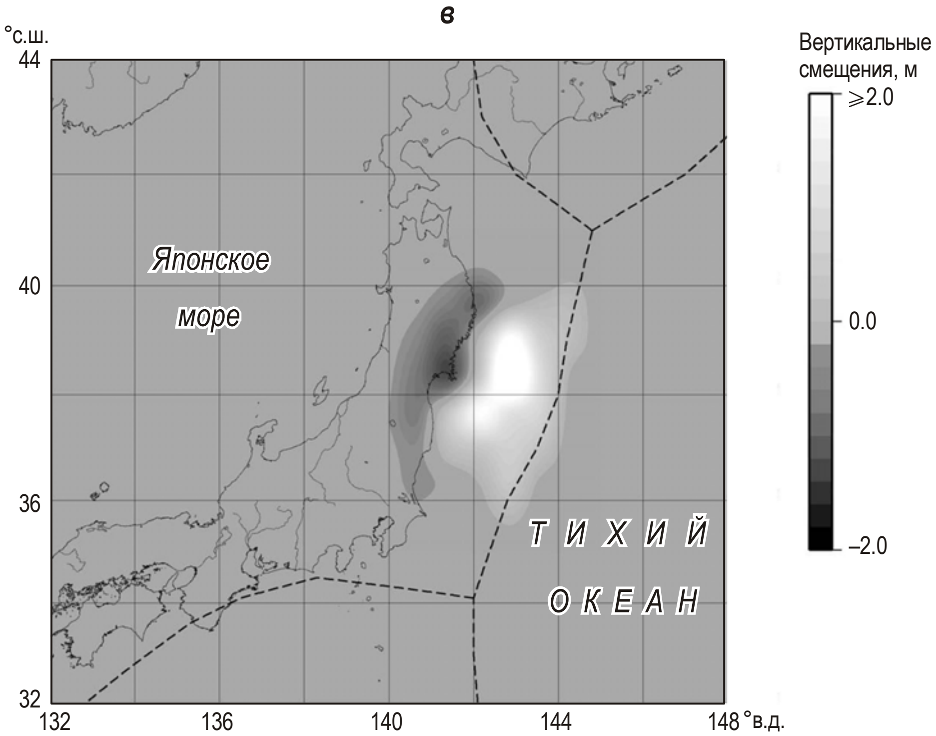

Fig.3. The calculated field of the vertical displacements of the ocean floor in the epicenter of (*а*) the first, (*б*) the second Simushir earthquakes and (*в*) the Tohoku earthquake. The dashed lines are the boundaries of the plates. The scale of vertical displacements, m, is given to the right.

During the second Simushir earthquake (13.01.2007, M_W =8.1, Fig. 3, *б*) the insignificant uplift of the ocean floor amounted to 0.4 m, and the subsidence –1.6 m due to the normal fault type of the earthquake. This earthquake also generated the transoceanic tsunami, but it was weaker compared to the tsunami of 2006.

After the Simushir events of 2006 and 2007 in the Kuril Islands were organized several complex expeditions to study their consequences. On the coasts of the Islands of Matua, Ketoy and South-Eastern part of the Simushir the maximum runups amounting to 17–20 m were recorded [*Levin and others*, 2008]. Some authors (see, for example [*Laverov and others*, 2009]) relate these runups to the tsunami of 2006. The other, based on the results of numerical calculations [*Rabinovich et al.*, 2008], consider them to be the consequences of the tsunami of 2007.

For the Tohoku earthquake (Fig. 3, *в*) the average uplift of the ocean floor was 2 m except for the narrow area where the peak uplift up to 5 m was recorded.

Comparing the analyzed seismic events it should be noted that the average uplift of the floor during the Tohoku earthquake is comparable in value with the uplift during the first Simushir earthquake. At the same time, the area of the uplift during the Tohoku earthquake was considerably bigger and that was reflected in its tangible consequences – in many points of the Honshu coast the height of tsunami waves exceeded 20 m with its maximum value of 40 m [*Mori et al.*, 2011].

Discussion

The constructed distributions of the vertical displacements in the epicenters of the earthquakes used as initial conditions for modeling the tsunami distribution can be obtained (and it is really important) in the real-time mode. This provides the possibility to use the GPS technology for solving the problem of the tsunami early warning. The practical applicability of the given approach is mainly determined by the ratio of the arrival time of the tsunami wave and time necessary for uplift modeling.

The speed of the tsunami propagation in the open ocean is usually estimated as $c = \sqrt{gH}$, where g is the gravity acceleration; H is the ocean floor depth. If the average depth in the Pacific Ocean is about 4 km, and the average velocity of tsunami propagation is equal to ~0.2 km/s, then the distance of 200 km from the earthquake source the wave will travel approximately in 20 min. It is known, that the first wave after the Simushir, 2006, earthquake reached the nearest settlement (the village Malokurilsk) in 68 min, and a maximum wave after 4 h 56 min. During the Simushir, 2007, earthquake the first wave reached the village Malokurilsk in 69 min after the earthquake, and the maximum after 2 h 30 min [*Laverov and others,* 2009]. According to the data of the Meteorological Agency of Japan, during the Tohoku, 2011, earthquake the earliest maximum impacts of the tsunami were recorded in 26–35 min after the earthquake.

The time required for the modeling consists of three parts.

1. *The arrival time of the seismic signal to the recording station,* depending on how far from the earthquake source are the stations where it is possible to register a noticeable seismic displacements by GPS in the real-time mode. The maximum distance between the source and the station where the noticeable jump is recorded is about 500km. The most tangible coseismic signal for the *GPS* method comes with the Rayleigh wave within few minutes after the earthquake.

2. *The arrival time of the measurements to the processing center*. Thanks to the modern communication channels, including the satellite ones, the data from almost any station can be transmitted in the real-time mode.

3. *The processing time*, that can be reduced to several minutes, if the most resource consuming calculations will be done in advance.

Conclusions

The use of the data about the displacement of the Earth crust at the moment of the earthquake obtained by the methods of satellite geodesy enables for epicentral distances up to the first several hundreds of kilometers to solve the inverse problem of finding the coseismic slip distribution correctly (with smoothing) almost in the real-time mode. This, in turn, makes possible the modeling of the vertical displacements pattern of the seafloor in the focal area by solving the direct problem.

The surface displacements measured using the satellite geodesy allow to determine more accurately in comparison with the seismological data the slip distribution directly in the source. Unlike seismic observations, the satellite geodetic measurements are not limited by the bandwidth, especially at low frequencies. It also helps to describe the more accurate pattern of the vertical displacements of the seafloor. In addition, the travel time of the tangible signal, recorded by the geodetic measurements at small epicentral distances, is considerably less than the transit time of *P*-waves, recorded at teleseismic distances, due to this the process of estimating the desired parameters is significantly accelerating.

Thus, the satellite geodetic monitoring of surface displacements can be effectively used to determine the uplift of the ocean floor during the undersea earthquakes that is necessary for the early warning of the approaching wave and is relevant at distances up to several hundred kilometers from the source of the event.

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