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GEOPHYSICS

Geomechanical Models and Ionospheric Variations Related to Strongest Earthquakes and Weak Influence of Atmospheric Pressure Gradients

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The influence of large-scale gradients of the atmospheric pressure on the preparation of some strong earthquakes including the earthquake in Sumatra on December 26, 2004, with a magnitude of $M \sim 9.0$ was studied on the basis of detailed geomechanical models of the Earth's crust and data obtained using satellite navigation systems.

METHOD

The influence of atmospheric processes on seismic activity was demonstrated in theoretical calculations and direct instrumental observations [1–3]. However, either the structure of the Earth's crust in these investigations was not specified or only the large-scale inhomogeneity of the land–ocean type was taken into account.

In this work, we developed computer models for the study regions to analyze the influence of the atmospheric pressure on the stressed state of the Earth's crust. The distributions of distortions in the Earth's crust to a depth of 100 km determined at four levels were used as the basis of the model: layer 1 0–20 km; layer 2 20–40 km; layer 3 40–60 km; and layer 4 60–100 km. The distortions were obtained from the quantitative analysis of the distributions of fractures and lineaments in the studied regions on the basis of the method for processing satellite images suggested in [4]. Three-dimensional models of the distortions in the Earth's crust including tectonic faults of different ranks were developed using this method.

Distortion of the medium is characterized by the inhomogeneity function $g(x_s)$, which ranges from 0 to 1. The $g(x_s)$ function was approximated with splines. All mechanical parameters were specified as

$$\Pi(x_s) = \Pi^0[1 - \kappa g(x_s)], \tag{1}$$

where Π^0 is the homogeneous initial value of the parameter for an undisturbed medium and $\kappa \leq 1$ is the parameter of smallness.

The mechanical properties of the Earth's crust parameterized using this method were taken into account in the calculation of stresses related to tectonic processes at the boundaries of the volumes studied in this work. The models of relative motion of tectonic plates were used to estimate these stresses. These models were obtained from the data of the modern GPS, SLR, and VLBI methods of satellite geodesy combined with the International Terrestrial Reference Frame ITRF 2005. Detailed distribution of boundary stresses was obtained from the comparison of the named tectonic models with regional GPS observations in the original regions [5, 6].

The primary regional compression was estimated on the basis of the given initial parameters. The secondary regional compression was determined from the conditions of restricted compression. The calculations were performed using the FLAC^{3D} programming code, which realizes the explicit finite difference scheme for solving the problems of continuous media mechanics.

RESULTS

Let us consider as an example the Sumatra earthquake ($M = 9.0$), which occurred on December 26, 2004, within the Philippine and Soenda island arcs and generated a giant tsunami. Its epicenter was located at coordinates 3.3° N, 96.0° E. The parameter of distortion was obtained as a result of quantitative processing of the distribution of fractures and lineaments in the studied region of the Indian Ocean within coordinates

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20.0° S–20.0° N and 65.0° E–125.0° E, which corresponds to a rectangular region with size 6649.5 by 4595.5 km. The space geodesy data made it possible to distinguish the orientation of the principal regional compression at an angle of 12° to the meridian [5, 6].

The further calculations were performed in two stages. First, the initial stressed state of a uniform parallelepiped was calculated under the influence of dead weight forces. Next, the layer was loaded with regional stresses and the stress–strain state was calculated.

The calculations demonstrated that the material was at the state of strength limit in a number of zones only in layers 3 and 4 (depths from 40 to 100 km). These zones were adjacent to the source of the earthquake studied. The distribution of the main tangential stresses reached their maximum precisely in this region in layer 4 (depths from 60 to 100 km) (Fig. 1).

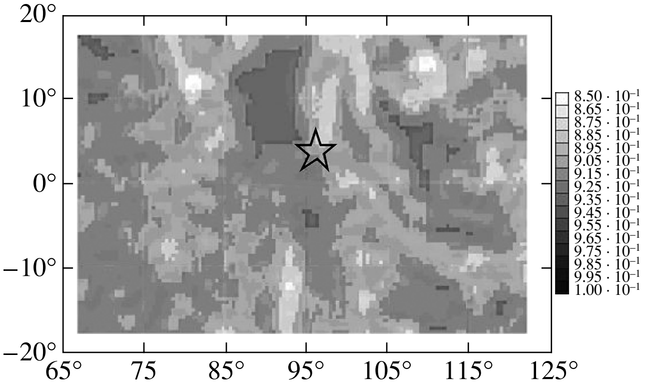

Fig. 1. Distribution of main tangential stresses in layer 4 (depths from 60 to 100 km).

Thus, the computer simulation made it possible to outline energetically saturated and highly stressed regions of the Earth's crust, which coincided with the epicenter of the Sumatra earthquake considered here.

At the next stage, we studied the influence of the atmospheric pressure on the distorted Earth's crust. It was important to understand whether the Earth's crust approached the strength limit or receded due to pressure. The distribution of parameter R, which characterizes the deviation of the stressed state from its position with respect to the ultimate strength, was studied to solve this problem. If parameter $R < 0$, the Earth's crust recedes from the limit state. If $R > 0$, the crust approaches the limit.

It should be noted that the variations in the atmospheric pressure over a seismoactive region can be judged either from the results of the immediate observations of this parameter or from indirect measurements of the variations in the ionospheric density. We know of investigations that revealed a high correlation between synchronous variations in the mean surface pressure and ionization of the F ionospheric layer [7]. Thus, if direct observations of the variations in surface pressure are absent, it is possible to use the results of measurements of the total electron content (TEC) in the ionosphere based on radio signals of the GPS or GLONASS navigation systems.

Figure 2 presents results of the wavelet analysis of TEC variations (from day 350 to day 365) in the range of periods $T \sim 2$–5 days (vertical axis) based on the data of ten land-based stations of the GPS system located in the Sumatra earthquake region (Fig. 3). It follows from Fig. 2 that the maximal intensity of these variations was recorded at stations Samp, Ntus, Bako, and Coco, which are located close to the epicenter (Fig. 3), and a much weaker intensity was recorded at station Dgar during the last 10 days before the earthquake (day 362). At more distant stations, the variations in TEC were practically absent. However, the magnetic activity was low over the entire period studied (from mid-November to December). The mean value of geomagnetic activity was $K_p \leq 2$, and the maximum was $K_p < 4$.

Figure 3 shows spatiotemporal distributions of the regions of maximal variations in the TEC corresponding to the regions of increased atmospheric pressure distinguished 30, 20, and 10 days before the seismic event on December 26, 2004. It is seen that intense TEC variations were recorded in the ionosphere before the earthquake in the regions within coordinates 20.0° S–20.0° N and 65.0° E–125.0° E. The largest of them started to form approximately 30 days before the earthquake and existed for 10 days. Later, the second anomaly was recorded over five days. Finally, the third anomalous region was formed 10 days before the earthquake.

We also obtained similar TEC distributions for the series of subsequent Sumatra earthquakes (July 5 and 24, $M = 7.3$ and $M = 6.7$, respectively) and to the Pakistan earthquake (October 8, 2005, $M = 7.7$), and other very strong earthquakes.

DISCUSSION

Local intensification of TEC variations on a scale of a few days (planetary waves range) cannot correspond to the direct propagation of these atmospheric waves into the ionosphere because of their comparatively low vertical velocity (~5 km/day or less). Therefore, the distinguished TEC variations can be attributed to the interaction between the planetary waves with the atmospheric internal waves propagating into the ionosphere [8]. The wind system of planetary waves modulates spreading of internal waves to the ionospheric altitudes. However, internal waves can be generated by the baric formation in the surface atmospheric layer (for example, a gradient of the atmospheric pressure related to the propagation of an atmospheric front) or the epicentral region of a preparing earthquake, where the internal wave can be generated due to intensification of degassing before a seismic event [9].

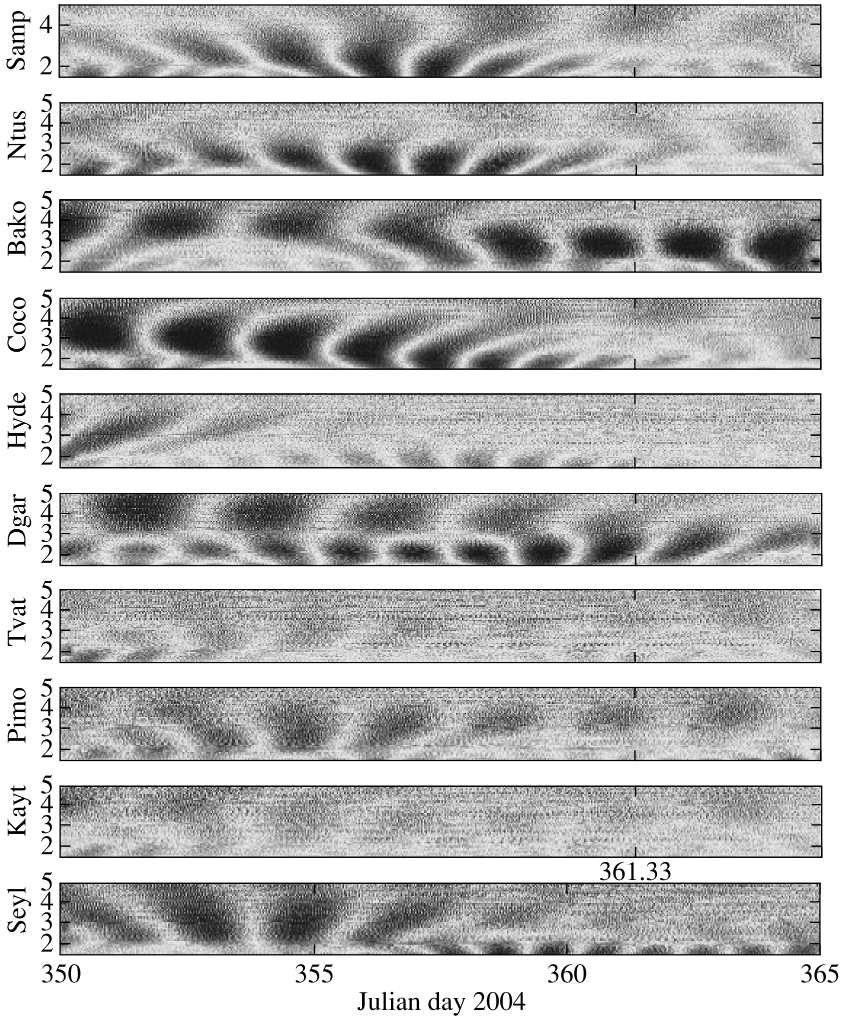

Fig. 2. Results of wavelet analysis of the TEC variations at $T \sim 2–5$ days based on the data of ten land-based GPS stations located in the Sumatra earthquake region ($M = 9.0$, December 26, 2004).

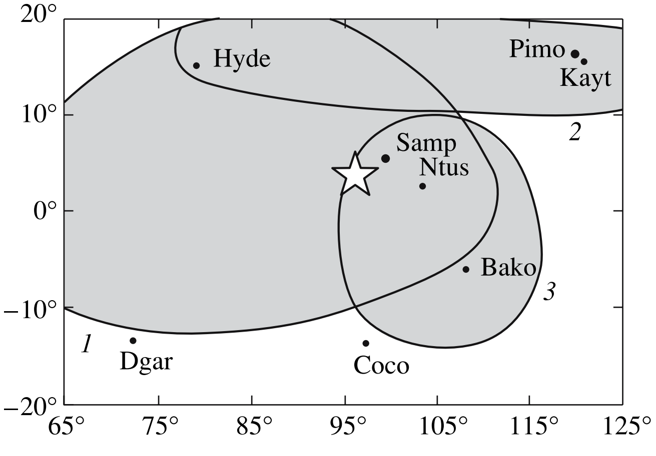

Fig. 3. Regions of anomalous spatiotemporal TEC variations based on the GPS data: (*1*) 30 days before the earthquake; (*2*) 20 days before the earthquake, and (*3*) during 10 days before the earthquake in Sumatra on December 26, 2004.

Figure 4 shows the calculated distribution of parameter R in the case of the influence of the third anomalous region (Fig. 3), which is associated in the model with the atmospheric pressure gradient. In our calculations, we assumed that pressure on the Earth's crust is only transferred in the regions not covered by the oceans. The maximal value of the excess pressure is not greater than 1% of the mean atmospheric pressure. Figure 4 shows that the upper layer 1 (0–20 km) recedes from the strength limit in the pressure anomaly zone, while the layer approaches this limit in the deeper layers 2, 3, and especially 4. Hence, the atmospheric pressure excess approaches these zones to the strength limit and thus can provoke the trigger effect. The first and second anomalous regions act similarly (Fig. 3).

It is worth noting that crustal regions in the source zone can be located at any distance from the strength limit during the earthquake preparation.

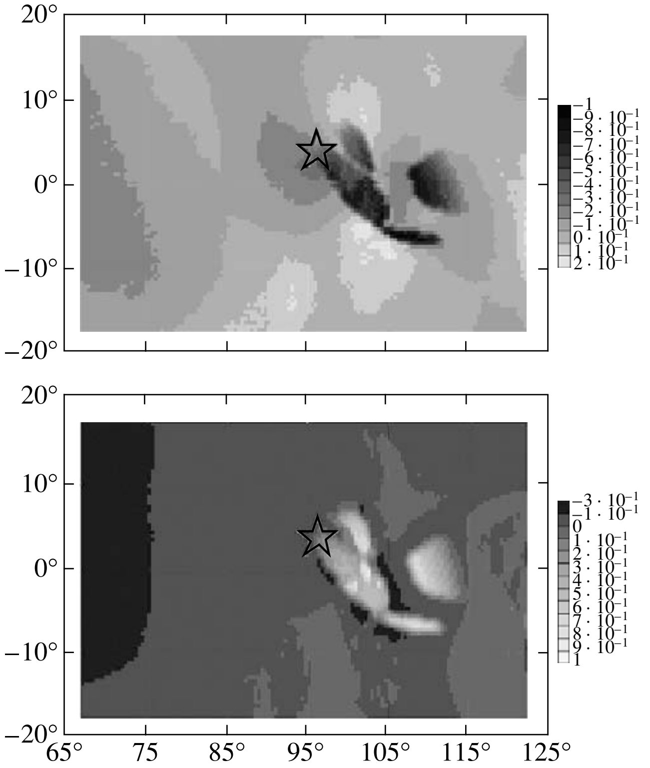

Fig. 4. Distribution of parameter *R* for anomaly *3* in layer 1 (0–20 km) (upper panel) and in layer 4 (80–100 km) (lower panel).

Thus, although tectonic earthquakes and large-scale variations in the atmospheric pressure develop according to their specific laws, their correlation (within the approximation considered here) is very likely starting from a certain time moment.

The analysis performed in this work suggests the following conclusion. Modeling of the nearly realistic stress–strain state of the Earth's crust and its variations related to minor external forces makes it possible to scrutinize the regions of seismic hazard. Recording of variations in the atmospheric pressure and total electron content in the ionosphere can play an important role in the monitoring of future seismic events.

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