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The First Results of the Pilot Project on Complex Diagnosing Earthquake Precursors on Sakhalin

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Abstract—The results of the first stage of the pilot project on the complex monitoring of the atmospheric and ionospheric parameters, conducted on the instructions of the Russian Federation Government in order to decrease risk of destructive earthquakes in the Far East, are presented. The experiment was performed before and during a strong ($M = 6.3$) earthquake that occurred on August 2, 2007, on Sakhalin. The meteorological data (relative humidity and temperature), cloudiness anomalies according to the TERRA and AQUA satellite data, thermal anomalies of outgoing IR radiation according to the NOAA satellite data, variations in the total electron content according to the GPS data, and tomographic reconstructions of the ionosphere vertical structure according to the TRANSIT satellite data have been analyzed. The indications, typical of earthquake preparation and previously presented in the publications devoted to studying earthquake precursors, have been detected in all analyzed parameters. Synchronism and localization of the anomalies, registered using different methods in different geophysical fields, make it possible to assume that these anomalies have a common source, which could be the earthquake preparation process that is explained using the developed complex model of the lithosphere–atmosphere–ionosphere coupling (LAIC).

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1. INTRODUCTION

Recent studies evidently demonstrated that specific variations in the atmospheric and ionospheric parameters are observed before strong earthquakes ($M > 5$) in the region of earthquake preparation, the dimensions of which are defined by the formula $R = 10^{0.43M}$, where R is the radius of the earthquake preparation region, and M is the earthquake magnitude [Dobrovol'skii, 1991].

The appearance and main morphological characteristics of these variations as well as the interrelation between atmospheric and ionospheric anomalies are explained based on the recently developed LAIC model [Pulinets and Boyarchuk, 2004; Pulinets et al., 2006a; Pulinets, 2007]. Activation of tectonic structures in the preparation region results in an increased gas (including radon) emission onto the surface.

Alfa particles with an energy of about 5.8 MeV, emitted by radon, ionize air molecules. These newly produced ions become condensation centers of water vapor, which is always present in the atmosphere. Condensation (or rather attachment of water molecules to ions: ion hydration) makes these ions stable since a high dipole moment of water molecules prevents ions from recombination.

Ionization and hydration result in a number of effects that can be identified as atmospheric and ionospheric precursors of earthquakes. Condensation leads to a decrease in the number of water vapor free molecules in the air, which can be registered as a decrease in humidity at a sufficient intensity of the process. When water molecules are attached to ions, their phase state changes from free to bound, which is accompanied by a release of the latent evaporation, which is the physical constant ($Q = 40.683$ kJ mol^{-1}) heat into the ambient space. Anomalous fluxes of the latent evaporation heat were registered for a number of the last strong earthquakes [Dey and Singh, 2003].

Energy release into the atmosphere leads to an increase in air temperature. In spite of the fact that the radon concentration in the air is very insignificant, the energy effectiveness of the ionization process is so high (more than 10^8) [Pulinets and Boyarchuk, 2004] that these variations result in variations in the atmospheric parameters registered using both ground-based meteorological equipment and satellite remote sounding methods [Pulinets et al., 2006b]. The extension of an earthquake preparation region is the second factor of

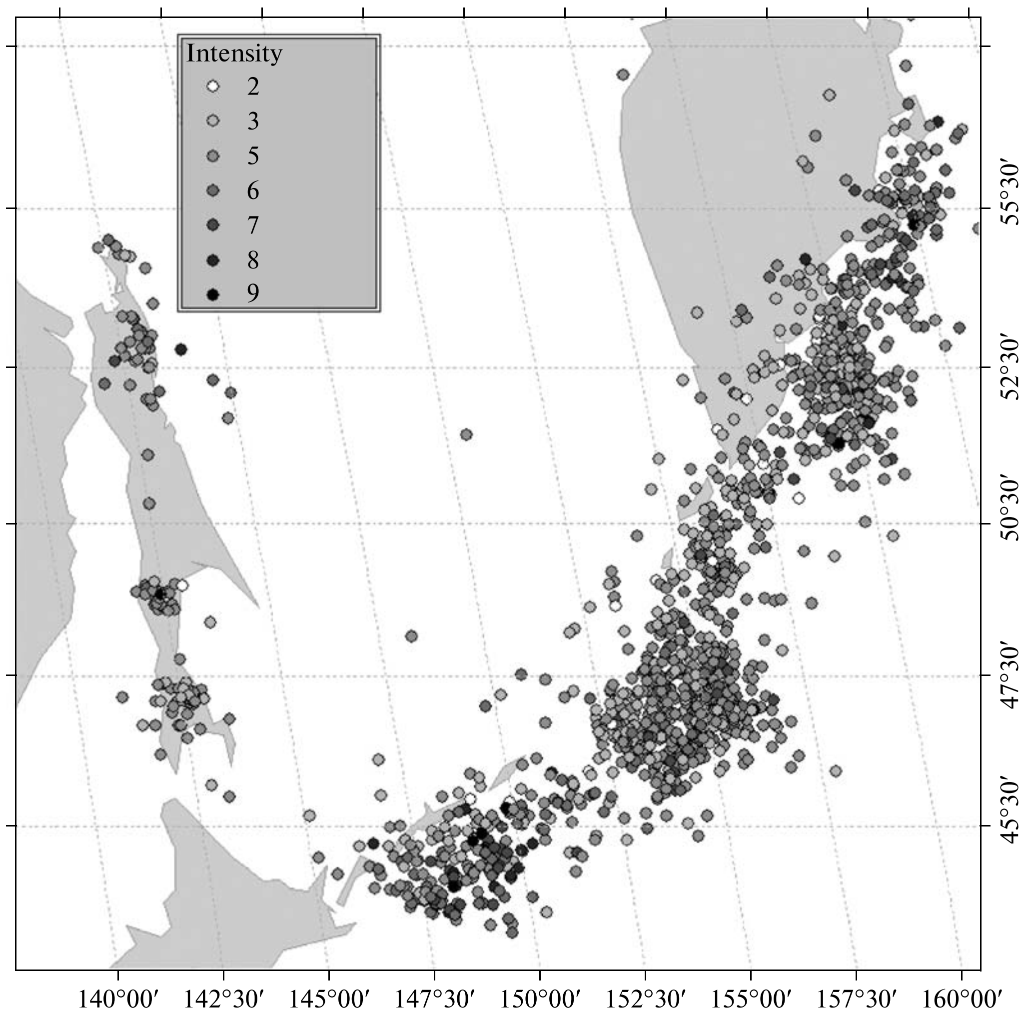

Fig. 1. Distribution of earthquakes in the Sakhalin region in 1994–2006.

no small importance. For strong earthquakes ($M \approx 7$), the preparation region area is about several hundreds of thousand kilometers squared. This is confirmed by not only the estimates by Dobrovol'skii and other authors but also by the direct measurements using the satellite remote sounding methods [Genzano et al., 2007; Ouzounov et al., 2006]. A change in the near-Earth conductivity in such wade areas leads to an upset of the balance in the global electric circuit. Since the vertical resistance of the boundary atmospheric layer (the first 5 km) accounts for 70–90% of the resistance of the entire column to ionospheric heights of about 60 km [Hoppel et al., 1986], resistance variations lead to changes in the vertical gradient of the atmospheric electric field and in the ionospheric potential above the region of impending earthquake.

Heat release in the near-Earth atmosphere and an increased electric potential gradient result in a removal of hydrated ion clusters into the upper layers, where these clusters become condensation centers for formation of clouds above active tectonic faults [Morozova, 2001].

A change in the ionospheric potential results in the generation of horizontal compensating electric fields, which cause drift of ions and formation of ionospheric inhomogeneities [Pulinets, 2007]. In addition to the formation of large-scale electron density inhomogeneities, the horizontal electric field induced in the ionosphere, will result in the generation of the current in the dynamo region, heating, and generation of acoustic gravity waves [Hegai et al., 1997].

The aim of the present experiment was to complexly register the atmospheric and ionospheric parameters described by the presented model. Precisely the complex approach, rather than the registration of any one indication, can finally result in the development of methods of reliable short-term prediction of earthquakes.

2. EXPERIMENTAL PROGRAM

More than 500 seismic events of different intensity (Fig. 1) occurred during ten years in the Far East, which is the most seismically active region of Russia.

In 2007 it was decided to perform a complex experiment at the first stage of the pilot project on a trial operation of equipment samples, using the data of the Russian and foreign navigation systems intended for diagnosing precursors of strong earthquakes. This project was first of all aimed at selecting of the most complete data on variations in different parameters of the lithosphere–atmosphere–ionosphere system in the seismically active Far East region of the Russian Federation.

The main aim of the complex experiment was to experimentally confirm the scientific principles of a complex diagnosis of earthquake precursors [Pulinets and Boyarchuk, 2004; Pulinets et al., 2006a; Pulinets, 2007] in the seismic region (Sakhalin and adjacent zones) based on the data of remote sounding the Earth from the space; the methods and algorithms of selection, processing, and distribution of monitoring information including data from existing Russian and foreign navigation, meteorological, and resource satellites; and the heliogeophysical data.

To achieve these aims, we had to solve the following problems during the experiment:

(1) to mobilize the special-purpose equipment (the universal tomographic facility in Yuzhno-Sakhalinsk and the GLONASS/GPS MRK-33 receiver in Yuzhno-Sakhalinsk and Nevelsk) in the seismic region and to support functioning of the mobilized tomographic chain (Nogliky–Poronaisk–Yuzhno-Sakhalinsk);

(2) to collect complex heliogeophysical characteristics of the heliosphere–atmosphere–lithosphere system in order to diagnose earthquake precursors on the Sakhalin territory, the Far East region, Russia according to the program of studies;

(3) to complexly study the obtained experimental characteristics of the heliosphere–atmosphere–lithosphere system and to detect anomalies corresponding to seismic activity;

(4) to adapt the available methods and algorithms for processing data on the environmental state and to develop special-purpose methods;

(5) to analyze, systematize, and classify the obtained results;

(6) to develop the method for diagnosing earthquake precursors, based on a complex analysis and joint processing of atmospheric–ionospheric–magnetospheric data with seismometric information, and the base of algorithms for precursor phenomena;

(7) to assess the information capacity of the available space-borne and ground-based instrumentation, to form requirements to promising technologies, and to develop proposals concerning the creation of the regional system of earthquake precursor complex monitoring.

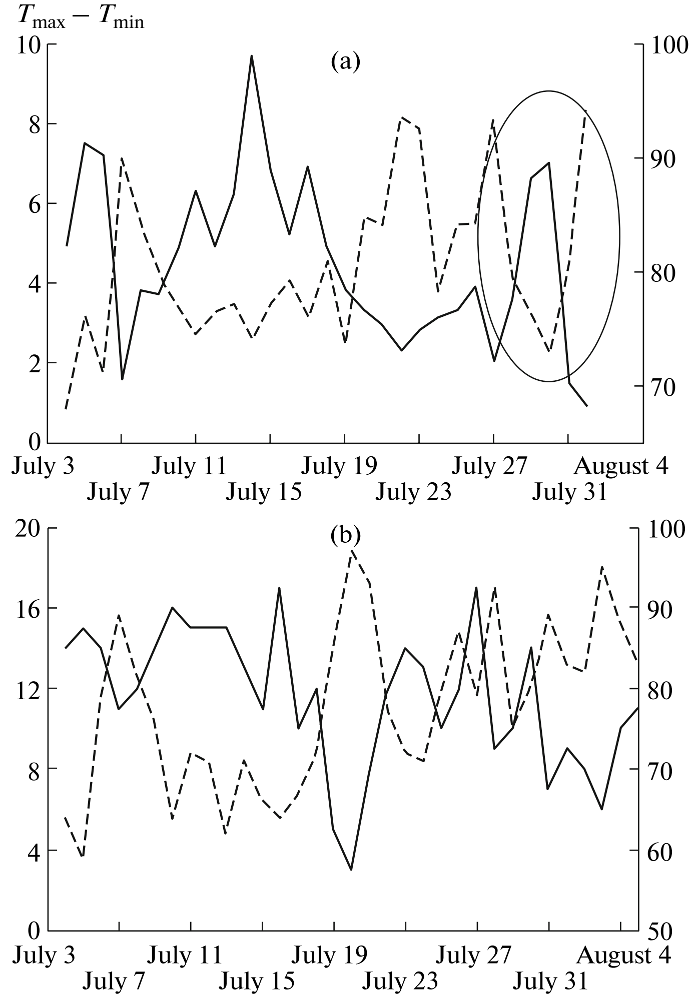

Fig. 2. Daily variations in the temperature (solid line) and humidity (dashed line) before the Nevelsk *M*6.3 earthquake (Sakhalin) of August 2, 2007, in (a) Nevelsk and (b) Khabarovsk.

In the scope of the experimental works, it was assumed not only to select new data on precursors of strong earthquakes, which manifest themselves in variations in the LAIC system parameters, but also to profoundly analyze the experimental data on strong earthquakes obtained previously.

For August–September 2007, we analyzed the temperature and humidity variations, the satellite data on anomalous cloud structures (obtained on the TERRA and AQUA satellites), and the outgoing flux of the long-wave IR radiation (OLR) in the range 10–12 μm according to the NOAA satellite data. We performed the vertical reconstruction of electron density, using the meridional chain of tomographic stations on Sakhalin [Urlichich et al., 2006], and calculated the total electron content (GPS TEC) for four Far East stations.

(a) (b)

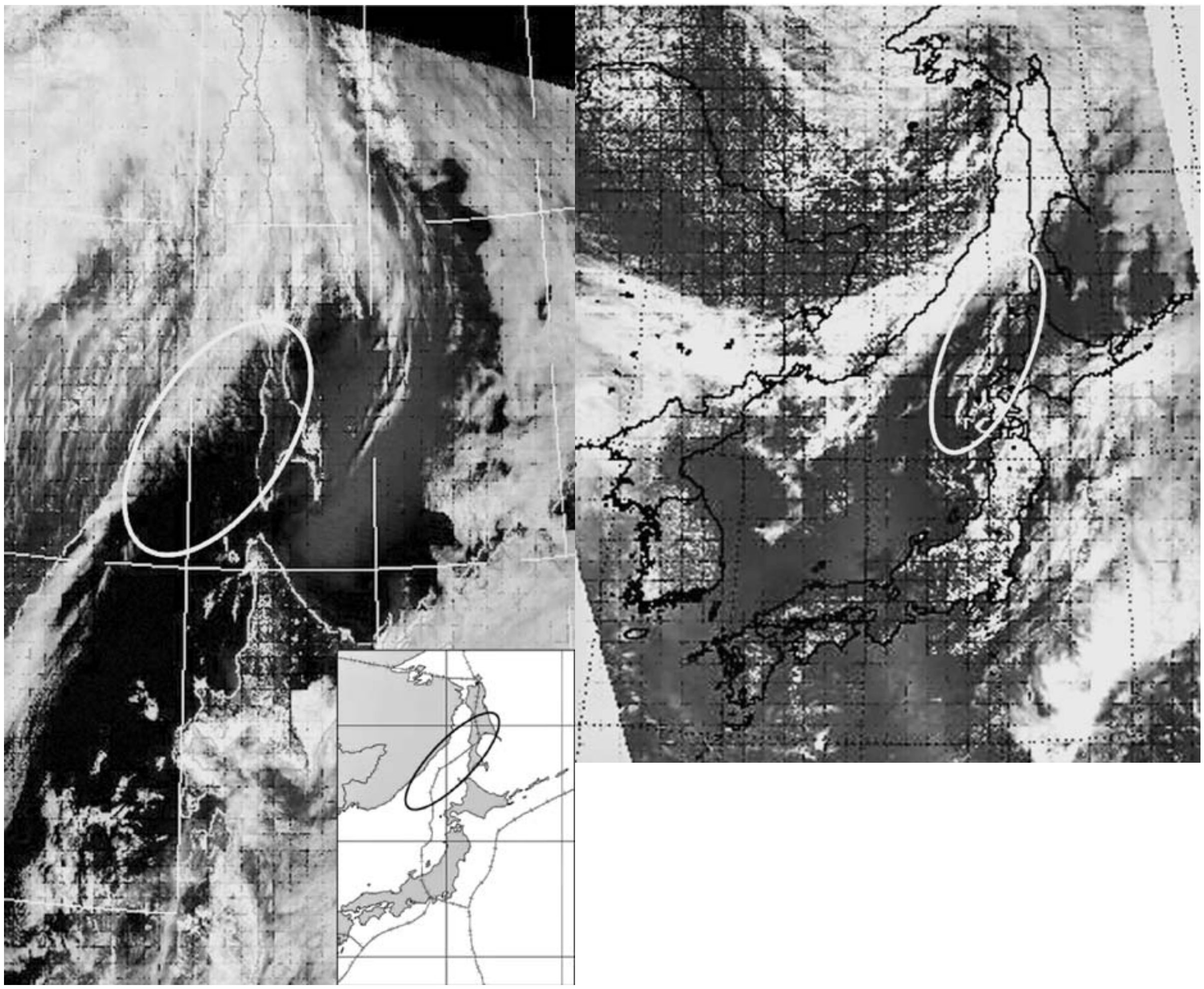

Fig. 3. Anomalous cloud structures on (a) July 30, 2007, and (b) July 31, 2007, according to the TERRA and AQUA spacecraft data.

3. VARIATIONS IN METEOROLOGICAL AND ATMOSPHERIC PARAMETERS

A stochastic analysis of the meteorological data for strong earthquakes in Central Asia indicated the temperature and humidity were anomalous during a month (or even during a season) when an earthquake was registered in the areas of several hundreds of kilometers squared [Mil'kis, 1986]. A detailed analysis of the meteorological data for a number of the last strong earthquakes [Pulinets et al., 2006a, 2006b] made it possible to reveal the time dynamics of such anomalies. It was indicated that a daily temperature range (a difference between the maximal and minimal temperatures during a day) is the most sensitive parameter. This parameter reaches its local maximum approximately five–seven days before an earthquake and subsequently decreases up to the earthquake instant. In this case the maximum of the temperature daily variations coincides with the relative humidity minimum. These variations are far outside the limits of the average monthly variations for several earthquakes and correspond to the average monthly values for some earthquakes; however, the shape of parameter variations before an earthquake remains unchanged. Therefore, the shape of temperature and humidity time variations rather than their absolute values can be considered as the main indication. A more detailed analysis, performed for the network of meteorological stations in Mexico before the catastrophic Michoacan earthquake of September 19, 1985, indicated that there exist the zones where the variations in the meteorological parameters are opposite in phase [Pulinets and Dunajecka, 2007], and the boundaries of the zones with different variation signs correspond to those of the tectonic plates and active tectonic faults. Such a behavior corresponds to the concept presented by Utkin [2000], who revealed the zones of increased and decreased radon flux from the Earth's crust before

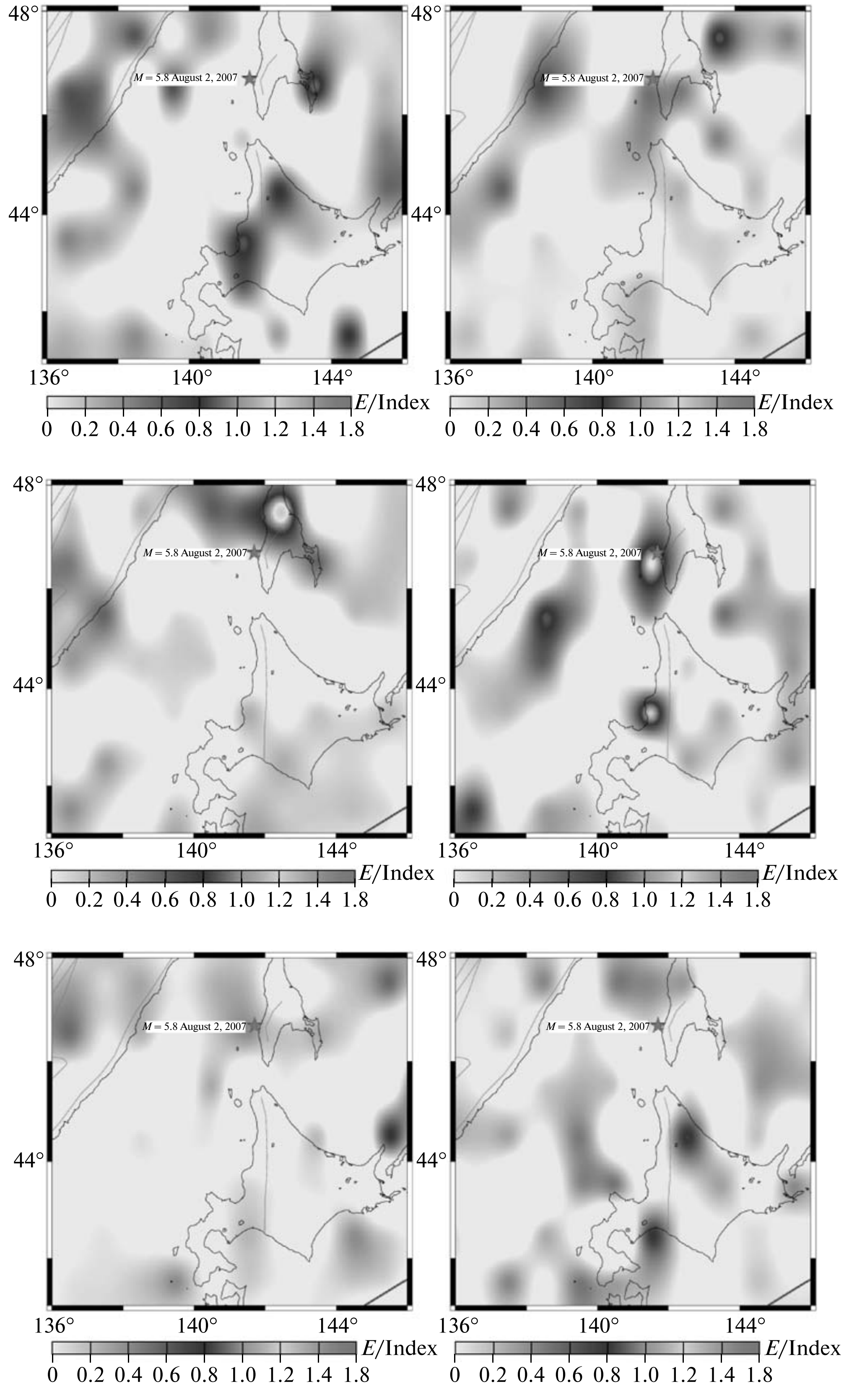

Fig. 4. The OLR distribution dynamics according to the AIRS AQUA data. The rms deviation (σ) of the OLR zonal index from the average monthly value for July 20, 23, 26, and 29; August 2 and 5, 2007, averaged over three days, is indicated.

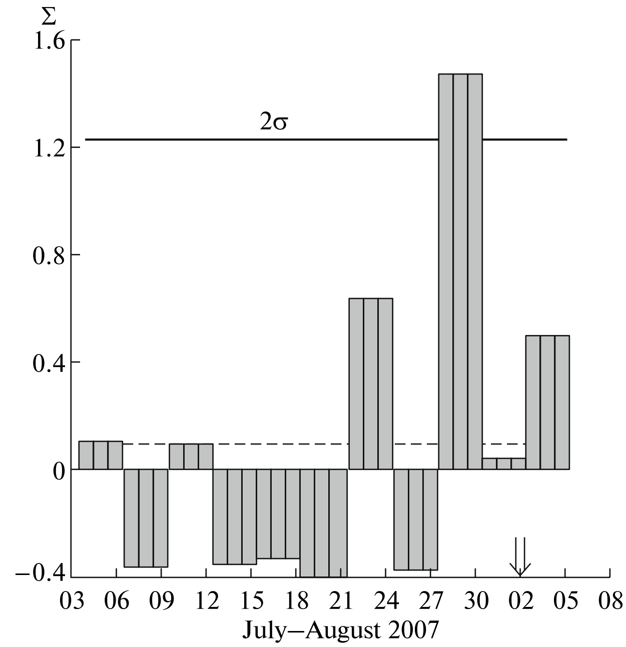

Fig. 5. Variations in parameter Σ from July 3 to August 8, 2007. An arrow marks the earthquake instant. A dashed line shows the average values of parameter Σ; a thick line, the doubled value of the standard deviation (2σ).

the earthquake (which apparently correspond to the zones of tension and compression in the Earth's crust) by analyzing the spatial distribution of the radon concentration in California. An increased or decreased radon concentration as compared to the undisturbed level affects variations in atmospheric parameters.

Figure 2a shows the variations in the daily range of the temperature and humidity in Nevelsk for July–August 2007. We can see that neither the range of temperature nor humidity demonstrate anomalous values and are within the monthly variations, but the shape of variations before the earthquake corresponds to the shape typical of other earthquakes (as well as the timescale of the appearance of the maximum in the daily range and the minimum of humidity four days before the earthquake). We should note that the variations in Khabarovsk (Fig. 2b) are almost in antiphase with the variations in Nevelsk, which corresponds to the conclusions on the positive and negative zones of radon emanation drawn in [Pulinets and Dunajecka, 2007]. Note that the maximum in the daily temperature variations falls on July 29–30; the minimum, on July 30.

The next analyzed parameter was the cloud structures formed above the earthquake preparation region. The linear structures, related to the system of active faults and tectonic plate boundaries, were distinguished on the photographs from the American remote sounding satellites. The structure of the tectonic plate boundaries near Sakhalin is shown in the right lower corner of Fig. 3a, and the TERRA satellite photograph for July 30 occupies the remaining part of Fig. 3a. It is evident that cloudiness is cut off along the tectonic boundary crossing Sakhalin (the registered features are located within an oval). Figure 3b demonstrates the AQUA satellite photograph for July 31. It is clear that a filamentary cloud touch upon an almost epicenter of the future earthquake (outlined by an oval). The extensions and location of the cloud structures indicate the scale of intensification of tectonic processes before the earthquake and confirm the conclusion that activity increases not only near the epicenter but also at the boundaries of the tectonic plate with the epicenter of the future earthquake [Pulinets

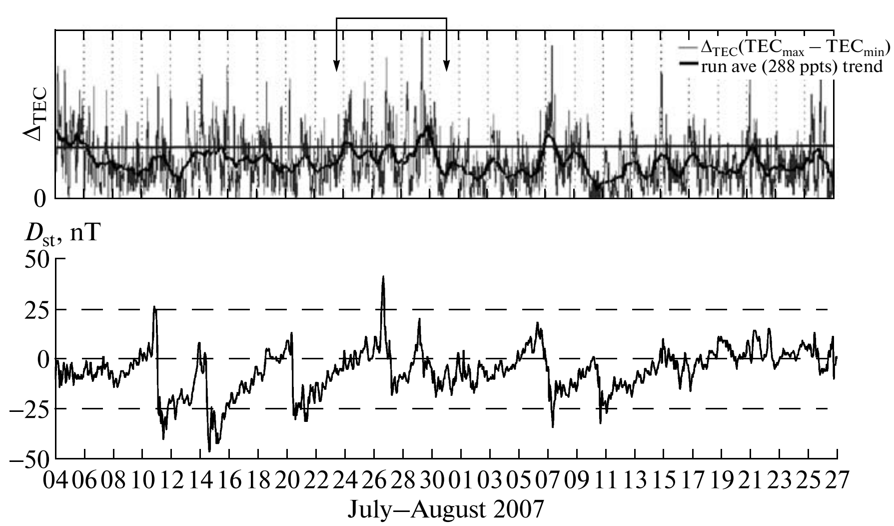

Fig. 6. The regional ionospheric variability index (the upper panel) according to the data of GPS receivers in the Sakhalin region (July–August 2007) and the global index of geomagnetic activity *Dst* (the lower panel).

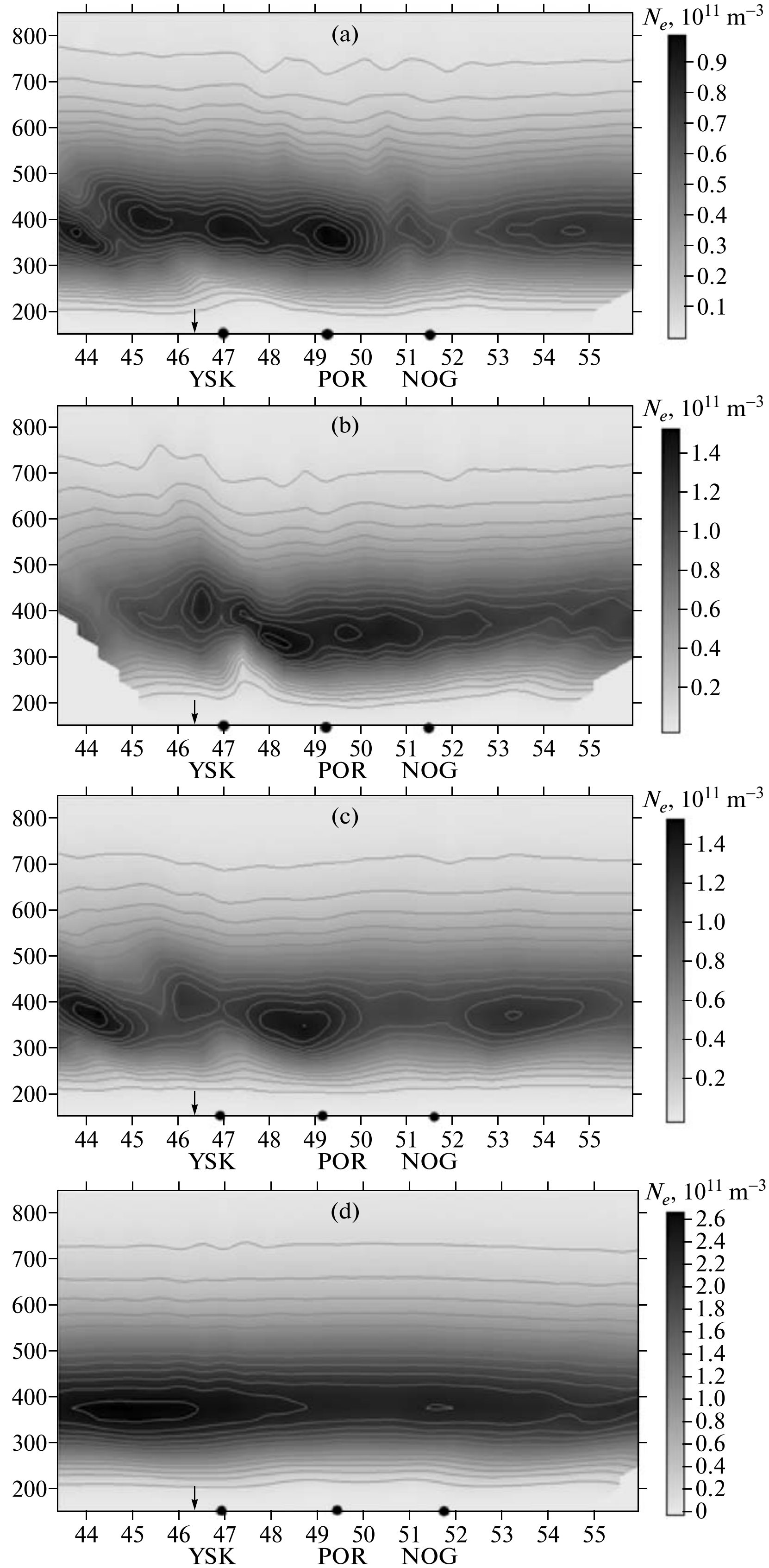

Fig. 7. The electron density vertical distribution, obtained using the data of the Russian low-orbiting navigation satellites. The registration was performed on (a) July 24, 2007; (b) July 28, 2007; (c) July 30, 2007; (d) July 27, 2007.

and Dunajecka, 2007]. This example is an evidence of one more factor of no small importance: gases emanate from tectonically active structures into the atmosphere not only on the land but also in the ocean, and short-term precursors of earthquakes can also be successfully registered above the water surface.

This is also confirmed by an analysis of OLR in the band 10–13 μm based on the data of radiometers installed on the remote sounding satellites [Ouzounov et al., 2007]. Owing to the existence of a transparence window, emission is not absorbed by a cloud cover precisely in this frequency range, and the existent data processing technology makes it possible to measure emission at a height of about 12 km above clouds. Figure 4 presents the dynamics of the OLR distribution over Sakhalin according to the data obtained using the AIRS device during the AQUA night passes. Each map shows the rms deviation (Σ) from the average monthly values of the OLR zonal index averaged over three days. It is evident that a thermal anomaly was formed on July 26 and 29 and moved from the beginning of the fault to the earthquake epicenter. In this case the anomaly was located above the ocean on July 29. Neither thermal water, proposed as a source of thermal anomalies before the earthquake, nor heat released from the Earth's crust can evidently explain the observed phenomenon since the anomaly is located above water (we examined the data on the ocean temperature and did not find any rise of the surface temperature). Only the latent heat, released immediately in the atmosphere as a result of ionization, can be such a source.

The time dynamics of the Σ parameter immediately above the earthquake epicenter (a point with the coordinates 46.5° N and 141.5° E) is shown in Fig. 5. As in the case illustrated in Fig. 4, the data were averaged over three days. The Σ parameter maximum, observed on July 30, substantially exceeds the doubled rms deviation (2σ) shown by a thick line in Fig. 4.

4. IONOSPHERIC DATA ANALYSIS

The variations in the total electron content according to the GPS data for July–August 2007 were calculated for four Far East stations (Petropavlovsk-na-Kamchatke, Yuzhno-Sakhalinsk, Khabarovsk, and Shintotsukava (Japan). An analysis of geomagnetic disturbances (the *Dst* index, the lower panel of Fig. 6) indicates that substantial disturbances were absent during both months. Insignificant disturbances (the largest of which was not more than –50 nT) were observed on July 12–14. Nevertheless, we detected possible seismoionospheric variations using the method for calculating the index of regional ionospheric variability [Pulinets et al., 2007], which makes it possible to detect such variations even under the conditions of magnetic disturbance. Taking into account that Petropavlovsk-na-Kamchatke is located at higher latitudes rather far from the epicenter, we calculated the index for only three lower-latitude stations. The result is presented in Fig. 6 (the upper panel), which indicates that the seismic activity index increased (the current average (a thick line) demonstrates this increase) during a week before the seismic shock (from July 24 to July 31, shown by arrows). The second maximum is related to aftershocks, which were observed for a long time after the main shock. We should note that the index variations are not very significant, which indicates that the radon concentration was low in this region.

The variations in the ionospheric variability index, obtained based on an analysis of signals from the global navigation system, show three clearly defined local maximums before the seismic event: on July 24, 28, and 30. An analysis of the tomographic reconstructions of the vertical ionospheric structure indicated that the anomalies in the electron density distribution were observed precisely on these days. Figure 7 presents these anomalies, reconstructed using the method of phase difference tomography, during the nighttime satellite passes on July 24, 28, and 30 (Figs. 7a–7c, respectively). The tomographic reconstruction for the undisturbed state of the ionosphere is presented in Fig. 7d. The reconstruction for July 24 can be interpreted as a horizontal wave disturbance with a wavelength of about 200 km. This disturbance can be an acoustic gravity wave generated by an electric field anomaly according to the procedure described in [Hegai et al., 1997]. The reconstruction for July 30 can be interpreted as a ring structure with a minimum above the future earthquake epicenter.

5. CONCLUSIONS

In 2007 the precursor phenomena were diagnosed in the scope of the unique complex experiment, using the data obtained based on the methods and equipment for remote sounding the Earth from the space.

The scientific program of the complex experiment, performed in the scope of the pilot project on the trial operation of equipment samples, using the data of the Russian and foreign navigation systems intended for automatic diagnosis of strong earthquake precursors, was mainly fulfilled.

The data on the state of the atmosphere and ionosphere were selected and analyzed, and the anomalies of the following parameters of the lithosphere–atmosphere–ionosphere system, confirming the interaction model presented in [Pulinets and Boyarchuk, 2004; Pulinets et al., 2006a; Pulinets, 2007], were revealed.

The character of the simultaneous temperature and air humidity variations in the near-Earth atmosphere in Nevelsk and Khabarovsk corresponds to the conclusions [Utkin, 2000] on the radon emanation zones and humidity and temperature variations in 1985 in Michoacan, Mexico) is analyzed.

The distribution of integral OLR in the studied region during July 2007 indicates that a significant anomaly was registered over the tectonic fault zone. The character of the revealed OLR features indicates that it is necessary to continue processing (calculating the OLR dynamics before the earthquake) more thoroughly analyzing the results.

The ionospheric variability index variations, confirmed by the vertical electron density distribution in the ionosphere according to the data of the low-orbiting navigation satellites, correspond to the revealed index anomalies before the earthquake that occurred on Sumatra in 2004 and are significant even against a background of strong magnetic storms previously observed in the Far East region of Russia.

We should note that the time coherence is observed in the manifestation of all registered anomalies, which were observed during a week (from August 24 to August 31) before the seismic shock of August 2.

Based on gathered information and on an analysis presented in this work, we can conclude that the morphology of the detected variations in the atmospheric and ionospheric parameters before the earthquake that occurred on Sakhalin on August 2, 2007, completely corresponds to the indications detected previously for other strong earthquakes.

This indicates that the physics of the process is common. At the same time, we should note that the amplitude of the registered variations in the atmospheric and ionospheric parameters is rather small. This can most probably be explained by the regional geology, which is responsible for a low radon concentration in the Earth's crust.

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