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Interdependent Perturbations of the Earth's Surface, Atmosphere, and Ionosphere

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Abstract—The results of original experiments performed with a ground-based geophysical laser interferometer and a GPS-based satellite ionospheric profilometer are given. Synchronous growth was recorded for deformations of the Earth's surface and variations in the atmospheric pressure and in the level of spatiotemporal modifications of the electron content within the ionospheric *F*2 layer with characteristic space scales of 10^2–10^3 km and periods of 10^2–10^3 s. The relationship between the revealed phenomena and the Earth's seismic activity is analyzed.

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1. INTRODUCTION

Many years' parallel studies of nonstationary processes in the upper layers of the Earth's crust and in the Earth's atmosphere, which were performed in different years by many researchers using various geophysical instruments, indicate that there is a deterministic relationship between atmospheric and lithospheric phenomena in a wide frequency band (Trubitsyn and Makalkin, 1976; Lyubushin et al., 1992; Dubrov et al., 1998; Volkov et al., 2001). Apart from the purely meteorological factors (wind, precipitation, and heat and mass exchange), a characteristic feature of the observed dynamical interaction between these adjoining geospheres is the presence of sporadic waves and other anomalous processes that are simultaneously observed in both lithosphere and atmosphere of the Earth. As a rule, these anomalous phenomena are accompanied by seismic activity enhancement and, often, by strong earthquakes (*Deformational* ..., 1989; Volkov et al., 1999; Aleshin et al., 2003). At the same time, it has long been noted experimentally that, before strong earthquakes, the intensity of nonstationary dynamical processes in the ionosphere grows and the perturbations of the Earth's electric and magnetic fields increase (Belov et al., 1974; Gogatishvili, 1984; Liperovskii et al., 1992; Ponomarev et al., 2003). A substantial progress in studying seismic ionospheric phenomena was achieved with the application of methods for the radiophysical sensing of the Earth's ionosphere based on using satellite navigation systems. The activities in this area that began in our country with the participation of one of the authors of the works (Andrianov and Smirnov, 1993; Smirnov, 2001a, 2001b) were then developed by many groups of researchers from both our country and abroad. The use of the branched network of GPS and FORMOSAT satellite systems appeared to be especially effective for studying ionospheric variations in the *F*2 layer (see, e.g., (Hsiao et al., 2009; Namgaladze et al., 2009) and references therein). As a result, it has been established that ionospheric perturbations (expressed as modifications of the ionospheric electron content over territories that are connected directly with a future earthquake epicentre) are observed for a period of time from tens of hours to several days before particularly strong earthquakes (Pulinets et al., 2005; Smirnov and Smirnova, 2008; Namgaladze et al., 2009). In this regard, it was especially interesting to compare directly seismic ionospheric variations, registered using radio engineering methods, with the measurement results of the Earth's surface deformations and atmospheric processes, which were obtained using independent ground-based devices (Lyubushin et al., 1992; Dubrov et al., 1998), including those in periods preceding strong earthquakes (Dubrov, 2006; Liperovskii et al., 2008). This work is devoted to the investigation of the interdependence between the indicated phenomena and to their collation with the Earth's seismicity. A comparative analysis of the dynamical processes that were recorded during experiments simultaneously in three media—the Earth's crust, atmosphere, and ionosphere—is conducted for the first time if being based on published works.

2. EARTH'S CRUST DEFORMATIONS AND ATMOSPHERIC PRESSURE VARIATIONS: DEFORMATIONAL–BARIC INTERACTIONS

While taking exact measurements of the Earth's surface deformations and atmospheric pressure variations, we can often observe cases of sporadic occurrence of wavelike synchronous deformations of the

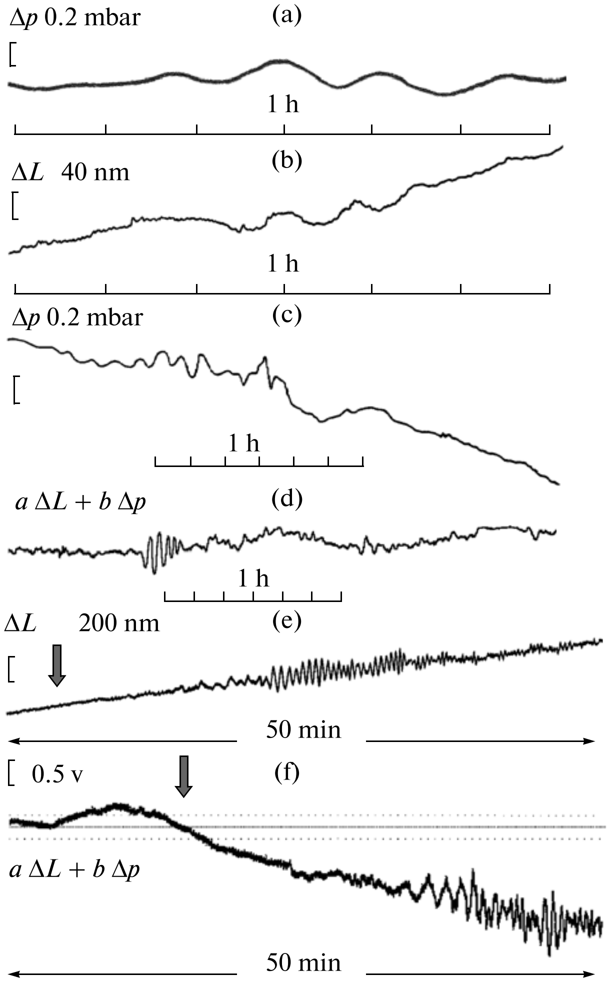

Fig. 1. Baric and deformational variations registered in Fryazino with (a) an optical microbarograph on September 25, 1973; (b) a 10-m laser deformograph on June 19, 1983; (c) a photoelectrical microbarograph on January 14, 1994; (d) a 100-m laser deformograph on September 23, 2001; (e) a 100-m equal-arm laser deformograph on September 7, 1974; and (f) a 300-m wideband laser deformograph on March 20, 2008. Along the vertical axis, characteristic scales of variations in Δp (in millibars) and in ΔL (in nanometers) are indicated.

ground and atmospheric pressure oscillations (Dubrov et al., 1998). These dynamical perturbations, which are mainly recorded under windless weather conditions, are of a quasi-wave type with oscillation periods from several minutes to several hours and days (Volkov et al., 2001; Aleshin et al., 2003). We do not consider here chaotic microdeformations of the Earth's surface and atmospheric pressure micropulsations connected with deteriorations of weather conditions (wind strengthening and precipitation) and other manifestations of stochastic atmospheric activity. These oscillations have their own distinctive properties (Dubrov et al., 1998) and are of a random noise nature, while their periods are within a range from several seconds to tens of seconds.

Characteristic examples of the sporadic quasi-wave perturbations, which we recorded in different periods of time by means of various instruments, are shown in Fig. 1. The presented results were obtained in the course of observations that were conducted using optical and photoelectrical microbarographs (Figs. 1a, 1c) and 10- and 100-m laser deformographs (Figs. 1b, 1d). The duration of the recorded fragments varies from one to several hours, and the characteristic periods of quasi-wave perturbations are 5–60 min. In this case, both comparatively short-period processes with periods from several minutes to tens of minutes (see Figs. 1a, 1b) and oscillations with longer characteristic periods from several tens of minutes to several hours stand out on individual records. In a number of cases, e.g., in Figs. 1c and 1d, wave processes of both types are observed simultaneously.

For comparison, the same figure presents examples of deformations (Figs. 1e, 1f) caused by seismic waves from remote earthquakes that were recorded by laser interferometers at the light-guide facility (underground test laboratory) of the Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Fryazino (Dubrov et al., 1998, 2007). When the distance from an earthquake epicenter is $D = 10^3$–10^4 km, the fastest (volume) seismic waves reach the point of recording in 10–20 min after the foreshock (its moment is shown in Fig. 1 with a vertical arrow), while the slowest (surface) waves are recorded by seismic instruments with a much larger delay of 30–50 min. The record given in Fig. 1e for an earthquake on September 7, 1974 (Island of Java, the magnitude $M = 7.2$), is performed in Fryazino using a 100-m equal-arm interferometer that is insensitive to baric perturbations Δp; the surface waves stand out clearly enough. An earthquake was recorded on March 20, 2008 (China, $M = 7.4$), by a 300-m wideband unequal-arm laser interferometer, which is sensitive to Δp variations; apart from seismic ΔL waves, which reached their maximum amplitude in 30–35 min after the beginning of the earthquake (see Fig. 1f), a bell-shaped deformational–baric perturbation is observed on the record, which takes a lead of the foreshock by 5–10 min.

To reveal the relationship between the Earth's quasi-wave surface oscillations and atmospheric pressure variations with the indicated characteristic periods (from several minutes to several hours), as well as to study their spatial propagation, a special technique (Dubrov et al., 1998; Volkov et al., 2001; Volkov et al., 1999) was developed and applied. The observation results of the Earth's surface motion at three points near Moscow were used. Measurements of deformations (laser deformographs in Fryazino (Dubrov et al., 1998)), tilts and variations in the gravity force (tiltmeters and gravimeters in Obninsk and in the territory of the Institute of Physics of the Earth in Moscow (Volkov et al., 2001)) were taken. The distances between the observational points were within 45–140 km. As a result of a parallel analysis of the obtained data, the connection between atmospheric pressure microvariations and the recorded geophysical fields at spaced observation points was investigated. It has been established that dynamical perturbations in the atmosphere have a wave microstructure and are accompanied by the Earth's surface movements in the form of a sufficiently complex superposition of deformations, tilts, and vertical displacements. These perturbations also have a clearly outlined phase composition and propagate along the ground–atmosphere interface at a speed of 30–50 km/h (Volkov et al., 1999).

By means of simultaneously operating and spatially separated instruments, simultaneous growth in the intensity of quasi-wave deformational–baric perturbations and the Earth's seismic activity was revealed. For example, the processes of increase in the atmosphere–lithosphere coupling, which we detected for the first time during the period March 21–23, 1998, that preceded a series of strong earthquakes in the southern part of the Pacific Ocean (in a sector restricted by the coordinates 0.4–63° S and 99° E–75° W), are characterized by the following features. Earthquakes occurred at an interval of 3–4 days: March 25, 1998, Balleny Islands, the magnitude $M_{PLP} = 7.5$; March 29, 1998, Tonga Islands, $M_{PLP} = 6.9$; two more earthquakes on April 1, 1998, with $M_{PLP} = 7.5$ (Indonesia and near the southern coast of Chile). No stronger earthquakes were recorded by world seismic services during a period of more than 70 days; from February 20, 1998, to May 2, 1998.

The maximum intensity of deformational–baric processes was recorded by our instruments during March 22–23, 1998: 4- to 5-h oscillations in atmospheric pressure with a value of 0.8–0.9 mbar were accompanied by the Earth's surface deformations $\Delta L = 0.3$–0.5 μm on the baseline $L = 10$ m, by tilts of 0.005 arcsec, and by vertical variations in the gravity force of 8.6 μGal with the same characteristic periods (Volkov et al., 2001). We did not record any more similar perturbations lasting for more than 50 h during the entire cycle of observations mentioned above. The described processes are similar in the form of their manifestation and look like a dynamical interaction between two adjoining media—two geospheres (in this case, these are the Earth's surface and atmosphere).

An interesting opportunity to record processes of this type is provided by a laser deformograph with a measuring air-filled arm that is partially connected to the outer atmosphere (Dubrov, 1977). The ΔU signal change recorded by this instrument can be represented as

$$\Delta U = a\Delta L + b\Delta p, \tag{1}$$

where U is the voltage, e.g., in volts, at the output of the recording system of the interferometer–deformograph; ΔL and Δp are the measured variations in the instrument's baseline length L and atmospheric pressure p, respectively; and a and b are the scale (or calibration) coefficients. The a coefficient value

$$a = \partial U/\partial L \tag{2}$$

defines the interferometer sensitivity to the Earth's surface deformations and can be on average equal to several volts per micrometer for instruments with the length $L = 10$–100 m. The absolute value and the sign of the coefficient b

$$b = \partial U/\partial p$$

express the dependence of a recorded signal on atmospheric pressure variations and are determined by the degree of airtightness of the protective pipeline in the measuring arm of the interferometer: $b_1 = \pm(3$–$30)$ mV/mbar for an absolutely airtight (or vacuum-processed) interferometer, and $b_2 = \pm(3$–$30)$ V/mbar for an interferometer the arm of which is freely connected to the atmosphere. In the later case, both summands in expression (1) are values of the same order. It is this variant that is implemented in schemes of laser interferometers-deformographs, records from which are given in Figs. 1d and 1f.

When compared with the results of water level observations (Lyubushin and Malugin, 1993), studies performed with the application of the proposed technique showed that the Earth's hydrosphere is also involved in the above-described mechanism of coupling between the lithosphere and atmosphere. Moreover, both deformational–baric and hydrobaric excitations of the mentioned geospheres are observed (Dubrov et al., 2007). Recording examples of this coupling of geophysical fields during the above-indicated period of increase in the Earth's seismic activity (March 21–25, 1998) are given in (Aleshin et al., 2003; Dubrov et al., 2007), respectively. If the influence of lithospheric deformations on variations in the level of underground water, which many authors consider as action "from below," is physically justified, then it is possible by analogy to speak about action "from above," i.e., not only the above-lying layers of the atmosphere (troposphere and thermosphere) but also the Earth's ionosphere and magnetosphere are involved in the total geodynamical process (Yomoto, 2010).

3. DEFORMATIONS OF THE EARTH'S CRUST AND VARIATIONS IN THE IONOSPHERE'S ELECTRON CONTENT: SEISMIC IONOSPHERIC PHENOMENA

The connection between seismic and electromagnetic processes in the Earth's crust and in adjoining geospheres (atmosphere and ionosphere) was noted long ago by many authors (Belov et al., 1974; Gogatishvili, 1984; Liperovskii et al., 1992; Ponomarev et al., 2003). The possibility of detecting the Earth's seismic-activity effects using devices installed onboard satellites and orbital stations stimulated in many respects the utilization of space technology for solving problems of earthquake prediction based on ionospheric precursors (Liperovskii et al., 1992). One of the most effective variants of this utilization is based on studying seismic ionospheric effects using global navigational satellite systems (GPS, GLONASS, etc.). Stable radio signals, emitted by satellites of these systems and received on the Earth, are used as sensing signals, when the ionosphere's parameters are determined using the radio translucence method (Andrianov and Smirnov, 1993; Smirnov, 2001a, 2001b). The presence of a branched network of ground-based stations that receive navigation system signals and the possibility of using radio engineering measurement methods for determining the ionosphere's physical parameters make it possible to carry out continuous satellite monitoring of ionosphere modifications related to the Earth's seismic activity, which is based on the already detected and newly discovered ionospheric effects.

In this section of the work, we give a comparison of two types of experimental data, obtained simultaneously by ground-based and satellite devices, namely, the measurement results and quantitative estimates of the following:

—deformational–baric variations recorded by laser interferometers-deformographs with an extension of 100 and 300 m at the test site of the Kotel'nikov Institute of Radio Engineering and Electronics in Fryazino (Dubrov et al., 1998, 2007);

—spatiotemporal modifications of the electron content in the Earth's ionosphere calculated from GPS data using the radio translucence methods and algorithms described in (Smirnov, 2001a, 2001b; Smirnov and Smirnova, 2008).

To analyze variations in the total electron content (TEC) in the ionosphere, the processing results of data received by local stations (at a distance of 100–300 km from deformographs) and by remote GPS stations situated at a distance of 2000 to 7000 km from the site where the deformographs are installed were used. As a result of these measurements, spatiotemporal TEC variations are actually determined in a region which is mainly located in the *F*2 ionospheric layer at altitudes of up to 400 km. When a GPS satellite moves along its trajectory (the orbit height is ~20000 km), this region in space and its projection onto the Earth's surface (subionospheric point) are also displaced with respect to the receiving station. Thus, by selecting the GPS satellite and station number, it is possible to check the ionosphere's variations above different regions, including the area of a future earthquake epicentre.

With the use of the described technique, tens of earthquakes were analyzed, including some regional earthquakes, i.e., those that occurred at distances of up to 100–300 km from the observation point. Some examples of the analyzed seismic events and recorded variations in parameters are given in Table 1. Significant variations in parameters that can be qualified as true precursors were obtained for almost all earthquakes (more than 90%) with the magnitude $M > 5$, which were considered by the authors. An analysis of the ionospheric state showed an increase in the electron content for 4–5 days with its subsequent substantial decrease for 1–3 days before a forthcoming earthquake (Smirnov, 2001b; Bondur and Smirnov, 2005; Smirnov and Smirnova, 2006, 2008). This behavior of variations in the electron content was observed at all stations located near an epicenter. In this case, not only a decrease in the electron content occurs, but also the "violation" of its spatiotemporal behavior with respect to the previous days takes place. In more than 50% of cases, wavelike variations are noted for events with periods of 10–90 min, which are similar to those shown in Fig. 1.

While performing a comparative analysis of laser deformographic observations and seismic ionospheric variations obtained by processing GPS satellite signals, we revealed a correlation between wavelike deformational–baric oscillations of the Earth's surface and atmospheric pressure within a frequency range of 1–10 mHz, as well as synchronously recorded spatiotemporal TEC variations. Figure 2 displays the results of this experiment carried out using a 100-m laser deformograph (installed at the underground light-guide test laboratory of the Kotel'nikov Institute of Radio Engineering and Electronics in Fryazino) and four GPS stations. We used data from local stations situated in Zvenigorod and Mendeleevo (Moscow region) and from remote regions situated southward (in Sofia and Ankara) when the distance from the laser deformograph was larger by an order of magnitude (Dubrov and Smirnov, 2004). We studied the recording fragments, obtained by a laser deformograph that records the Earth's surface motion, and the calculation results of the TEC change rate in the ionosphere during the period September 22–24, 2001. In Fig. 2 and further, temporal TEC variations are expressed in standard units: TEC units per second (1 TECU/s = 10^{16} el m^{-2} s^{-1}).

The results of comparing the recorded deformations of the Earth's surface and ionospheric variations indicate that there is a correlated excitation of wavelike deformational oscillations of the Earth's surface and variations in the electron content in the ionosphere. A comparison of recording fragments for deformations (Fig. 2a) and ionospheric variations (Figs. 2b, 2c) for the considered 3-day period of time demonstrates a simultaneous increase in perturbations on September 23, 2001, for all recording channels; at the same time, the behavior of the observed quantities is almost stationary on September 22 and 24 (see the corresponding tracks in Fig. 2). In this case, the characteristic periods of anomalous TEC variations of the ionosphere, obtained as a result of processing signals from satellite no. 6, are 5–10 min for local stations (see Fig. 2b) and 20–40 min for remote stations (see Fig. 2c). At the same time, the laser deformograph

Table 1. Earthquake parameters, recording conditions, and periods of observed variations

Date	Epicenter point, magnitude	GPS station	Mean distance, km:		Registered period of variations, min
			to the station	to the subionospheric point	
Aug. 17, 1999	Turkey, $M = 7.7$	ANKR (Ankara)	300	100–400	70–90
		ZECK (Zelenchukskaya)	1100	700–1400	–
Oct. 16, 1999	Hector Mine, California $M = 7.1$	COSO (Coso Junction, United States)	300	400	–
		AMC2 (Colorado Springs, United States)	1200	1300	–
Sept. 23, 2001	Greece, $M = 4.7$	SOFI (Sofia)	500	300–600	20–40
		MDVJ (Mendeleevo)	2000	2000	5–10
Dec. 22, 2003	Central California, $M = 6.5$	USLO (San Luis, United States)	70	50–500	–
		AMC2 (Colorado Springs, United States)	1500	1500	–
Sept. 21, 2004	Kaliningrad region, $M = 4.8$ and $M = 5.0$	RIGA (Riga) MDVJ (Mendeleevo)	300	200–400	70–80
Oct. 08, 2005	Pakistan, $M = 7.6$	SELE (Almaty)	800	600–900	–
		IISC (Bangalore, India)	2500	2100–2900	–
May 07, 2008	Honshu Island, $M = 6.6$	TSKB (Tsukuba, Japan)	200	50–1000	40–60 10–20

recorded on the track both short- (5–10 min) and long-period (20–40 min) oscillations on September 23.

An interesting feature of the observed wave perturbations is that they had arose 1–2 h before an earthquake in the Ionian Sea near the Greece coast (2116:13.7 GMT, 37.75° N, 20.98° E, $M = 4.7$, $h =$ 33 km), which was the nearest regional seismic event during the considered 3-day interval (Table 2) (*Operative* ..., 2001). The earthquake moment is marked with a vertical arrow in Fig. 2. In this case, the energy level of the seismic event that was the nearest in time (no. 2658, 2241:04, West Iran, $M = 4.0$) was lower by an order of magnitude, while stronger earthquakes ($M = 4.9$–5.8) occurred at distances from the epicenter exceeding the distance from the above-mentioned earthquake (no. 2657) near the Greek coast by 3–7 times (see Table 2).

The experimentally established fact that the simultaneous dynamical excitation of the Earth's lithosphere, atmosphere, and ionosphere exists in a frequency region of 0.01–0.0004 Hz is indirectly confirmed by the comparison results of our recorded processes with perturbations of the Earth's magnetic field according to data from the Moscow geomagnetic observatory, Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation (IZMIRAN) (Zaitsev and Odintsov, 2005), for the same period of time. Figure 3 displays variations in the Z component of the magnetic field and a spectral–temporal diagram of these variations recorded during September 22–24, 2001. Growth in geomagnetic perturbations (from a level of background fluctuations of 0.1–0.2 nT to values of 1–2 nT with characteristic periods of 15–150 min) occurs synchronously with our recorded sporadic wave perturbations in the Earth's lithosphere and ionosphere (see Fig. 2), and the observed process is as a whole correlated with the increase in the regional seismic activity. The growth in geomagnetic perturbations noted by the IZMIRAN observatory for other days of September 2001 also corresponds by time to the increase in the seismic activity in the Eastern Mediterranean.

The presented analysis of the obtained results is evidence that the sporadic wave phenomena that we recorded simultaneously in three adjacent geospheres cannot be ascribed to a random coincidence of three independent physical processes. However, for revealing their connection with growth in the Earth's local seismic activity, experimental data and their statistical analysis are required.

Let us consider the data-processing results obtained for other earthquakes that were stronger and farther apart. Figure 4 presents the calculation results of temporal TEC variations for the period from September 22 to 28, 2003, for satellite no. 24 according to the data of the Tsukuba GPS station (Japan). A series of great earthquakes occurred in this period, the strongest of which were two earthquakes in Japan (September 25, 2003, Hokkaido, $M_S = 8.3$ at 1950:08 and $M_S =$ 7.2 at 2108:00) and two earthquakes in Altai (Septem-

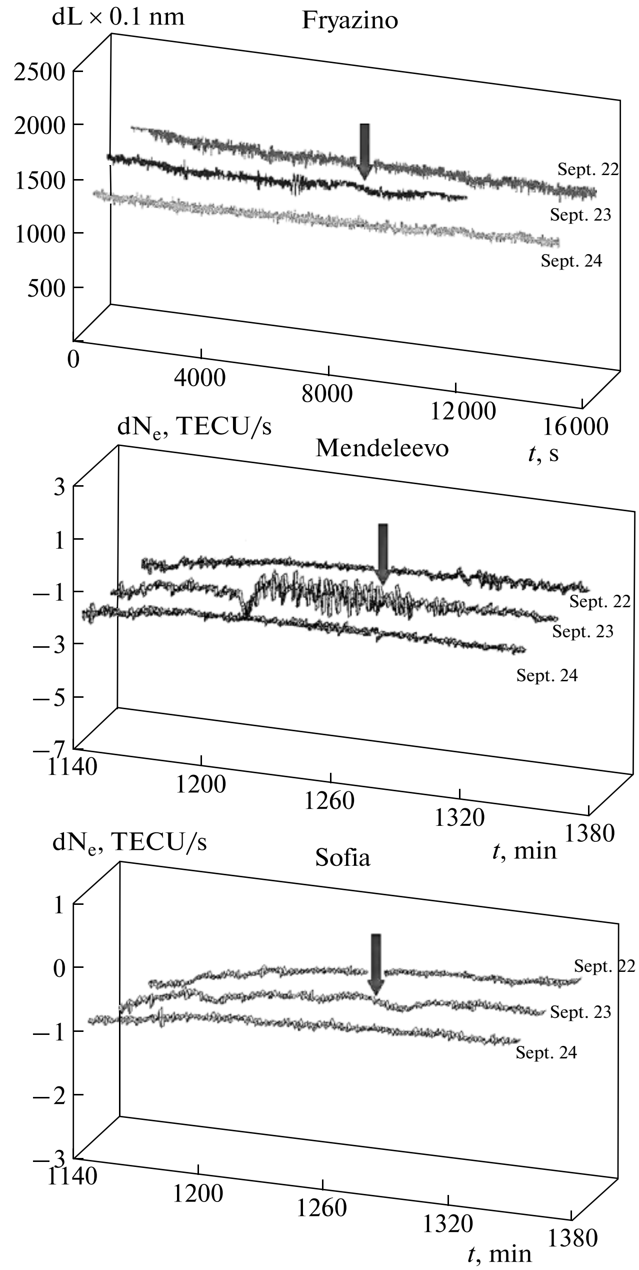

Fig. 2. Deformational–baric and ionospheric variations on September 22, 23, and 24, 2001, according to the data of (a) a 100-m laser deformograph, Fryazino, (b) satellite no. 6, Mendeleevo station, and (c) satellite no. 6, Sofia station. The moment of an earthquake on September 23, 2001, at 2116:15 with $M = 4.7$ (Greece) is indicated with an arrow.

ber 27, 2003, Kazakhstan–Xinjiang, $M_S = 7.3$ at 1133:26 and Gorny Altai, $M_S = 6.7$ at 1852:47).

Apart from a pronounced anomalous behavior and temporal variations in the TEC for days and hours before the indicated earthquakes, an extraordinary high absolute value of the TEC growth rate is observed at the final leg of the trajectory on September 24, 2003 (around 2300 UTC), which exceeds by 2–3 times the

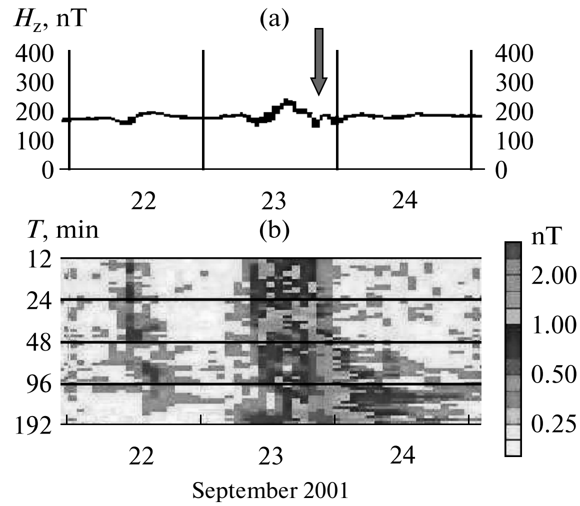

Fig. 3. Perturbations of the Earth's magnetic field for September 22–24, 2001, according to data from the IZMIRAN Moscow geomagnetic observatory (Zaitsev and Odintsov, 2005): (a) variations in the Z component of the geomagnetic field; (b) the a spectral–temporal diagram of variations in a range of periods from 10 to 190 min.

appropriate values of this rate before and after the earthquakes, i.e., on September 22 and 28, 2003. A remarkable feature of the TEC behavior curve for September 25, 2003, is the presence of contrasting and substantial (in amplitude) variations from 2005 to 2015, i.e., 15 min after the first strongest seismic event with the magnitude $M_S = 8.3$. Similar variations also stand out on the record from a 100-m laser deformograph in Fryazino (see the bottom record in Fig. 5).

In addition to the standard volume and surface seismic waves, deformational–baric variations are present on the interferometer's record which are similar in shape to the ionospheric response but stretched in time by several times: its period is ~40–50 min. The delay in the time of its arrival at Fryazino can be estimated with the same value. From here, it follows that the propagation velocity of the marked perturbation is within the limits from 8400 to 10500 km/h or 2.3–2.9 km/s, which corresponds to the propagation velocities of surface seismic waves. Probably, the same nature is inherent in the earlier-noted large-scale variations with periods of 20–40 min, which were recorded at a distance of ~2000 km between a deformograph and GPS stations during the period of an earthquake near the Greek coast (Section 3.1).

Ionosphere monitoring from two stations located most closely to the epicenter of the Altai seismic events of 2003 was conducted in the period from September 24 to 28. Figure 6 presents the altitude profiles of the electron content distribution, which were obtained using observations of the URUM GPS station. The station was located approximately at the same longitude as the epicenters of the earthquakes at a distance of ~600 km from them.

Table 2. Earthquakes on September 22–24, 2001 (*Operative* ..., 2001)

No.	Day	Time in the epicentre hh:mm:ss	Latitude (deg)	Longitude (deg)	Depth, km	Magnitude, M_{PSP}	Region
2641	22	0323:37	3.97 N	75.88 W	169	5.8	Colombia
2642	22	0648:06	55.81 N	154.49 W	33	5.3	Alaska
2643	22	0831:54	37.42 N	141.39 E	33	4.2	Honshu Island
2644	22	1042:04	18.57 S	174.70 W	33	5.0	Tonga Islands
2645	22	1329:20	37.08 S	179.91 E	33	4.9	New Zealand
2646	22	1334:16	30.29 N	50.38 E	33	4.4	Iran
2647	22	1457:32	56.20 N	114.83 E	14	4.0	Lake Baikal
2648	22	2225:01	13.39 N	90.62 W	33	4.7	Guatemala
2649	23	0114:04	39.55 N	49.44 E	39	4.3	The Caspian Sea
2650	23	0248:30	37.17 N	71.65 E	130	4.0	Afghanistan
2651	23	0641:21	5.95 S	147.47 E	33	4.6	New Guinea
2652	23	0806:11	13.05 N	120.50 E	33	4.6	Mindoro Island
2653	23	0830:16	8.00 S	155.60 E	33	4.3	Solomon Islands
2654	23	1225:41	12.19 N	95.30 E	33	4.2	Andaman Islands
2655	23	1447:56	24.43 N	94.80 E	33	4.3	Myanmar–India
2656	23	1516:47	46.48 N	149.74 E	166	4.1	Kuril Islands
2657	23	2116:13	37.75 N	20.98 E	33	4.7	The Ionian Sea (Greece)
2658	23	2241:04	32.56 N	49.14 E	33	4.0	Western Iran
2659	24	0129:10	0.03 S	35.91 E	33	4.9	Kenya
2660	24	0449:58	40.37 S	175.97 E	33	5.0	New Zealand
2661	24	0531:25	36.87 N	71.49 E	118	4.0	Afghanistan
2662	24	1555:37	44.81 N	147.25 E	138	4.0	Kuril Islands
2663	24	1715:39	2.02 N	128.08 E	129	4.6	Halmahera Island
2664	24	1805:49	34.32 N	102.49 E	33	4.3	China
2665	24	1815:49	14.92 S	166.86 E	33	4.6	New Hebrides
2666	24	1935:15	36.41 N	140.19 E	82	4.6	Honshu Island
2667	24	1957:27	36.40 N	140.20 E	79	5.0	Region of Honshu Island
2668	24	2244:55	18.51 N	146.75 E	35	4.3	Mariana Islands

It can be seen that a substantial decrease in the electron content occurred on September 27 (on the day of the earthquakes) for a period of 0–3 h (the electron content values for this period of time on September 25–26 were nearly equal). It was established by the processing results of signals of other satellites that a reduction in the electron content as a whole was observed on September 27 up to 0600–0700 UT.

The decrease in the electron content on September 25–26 was ~20% with respect to its maximum value for September 24. The further reduction in the morning hours of September 27 (on the day of the earthquakes) reached 30% of the electron content value for September 26 or more than 40% with respect to the value for September 24.

Before the mentioned Altai earthquakes, a laser deformograph in Fryazino recorded a microseismic precursor that lasted for ~8 h in the form of an amplitude fading for narrow spectral peaks within a frequency band of 1–3 Hz, which were separated using high-resolution spectroscopic methods. Spectral–temporal diagrams demonstrating this process are presented in Fig. 7. The amplitudes of the most intensive peaks in this band at frequencies of 1.94 and 2.79 Hz, which are ~64 units before the precursor development rate (Fig. 7a), reduce by more than sevenfold during the "calm" period and almost do not stand out against the random noise background in Fig. 7b. The maximum amplitudes of the spectral background components do not exceed 9–10 units here (the limiting amplitude of deformations is on the order $\Delta L/L = 10^{-11}$–10^{-12}). According to a commonly used classification, the observed process can be regarded as a seismic precur-

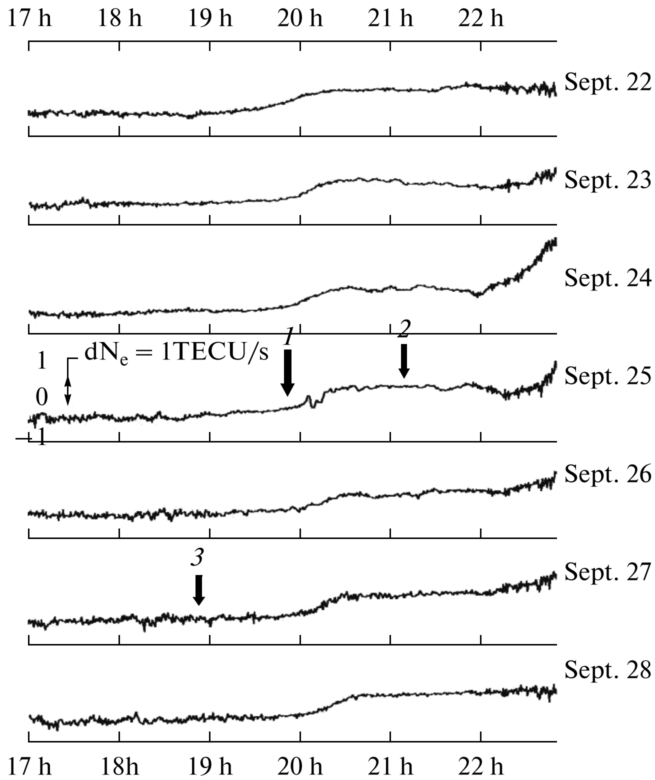

Fig. 4. Variations in the total electron content (in TEC units) for September 22–28, 2003, from satellite no. 24, Tsukuba GPS station (Japan). The arrows indicate earthquakes in Hokkaido with $M_S = 8.3$ (*1*) and 7.2 (*2*) and in Gorny Altai with $M_S = 6.7$ (*3*).

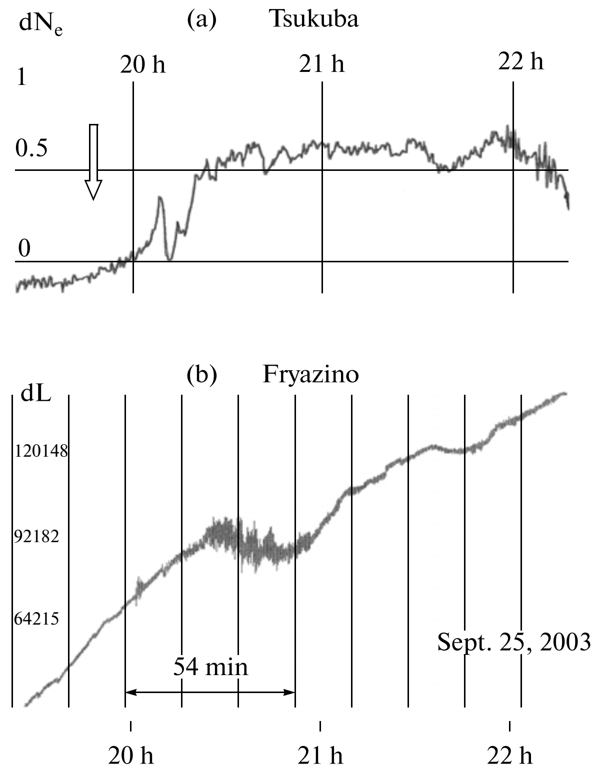

Fig. 5. Synchronous recording of perturbations of the ionosphere and the Earth's surface on September 25, 2003, according to data from (a) satellite no. 24, Tsukuba station, and (b) a laser deformograph (Fryazino). The arrow indicates the earthquake time (1950:08), Hokkaido, $M_S = 8.3$.

sor that manifests itself in the form of a "calm" seismic period (Sobolev and Ponomarev, 2003).

4. DISCUSSION OF RESULTS

The presented experimental data indicate a correlation between dynamical processes occurring in the Earth's atmosphere and ionosphere and simultaneously recorded movements of the Earth's surface within a wide range of time periods and space scales.

Laser–interferometer measurement methods of the Earth's surface deformations and atmospheric pressure variations, supplemented with data of the Earth's ionosphere radio translucence, using signals from orbital systems of navigational positioning, allow one to reveal a number of features of the observed geophysical phenomena.

The detected processes of perturbation development in three adjoining geophysical media represent synchronous growth in the Earth's surface deformations, atmospheric pressure variations, and the level of spatiotemporal modifications of the electron content in the ionosphere's *F*2 layer with prevailing periods from 5–10 to 20–50 min at distances between observation points from 100 to 7000 km, respectively. The noted phenomena anticipate and/or accompany seismic events of a regional scale, as well as remote earthquakes with magnitudes $M = 7$–8.

The existing physical models describing the regarded atmospheric–lithospheric and seismic ionospheric interactions have so far remained very debatable. Our supposition consists in the fact that the observed wave phenomena are not local; i.e., they are not only characteristic of the Earth's surface and lower layers of the atmosphere (Volkov et al., 1999), but also involve other adjacent geospheres, including the Earth's ionosphere. The interdependence between the factors participating in the considered processes can be established as a result of a comparative analysis of experimental and computational data.

The above-obtained estimates of spatiotemporal scales of 10^2–10^3 km and 10^2–10^4 s for the revealed perturbations make it possible to draw conclusions on the nature of the observed effects. According to independent data of synchronous measurements of the Earth's surface deformations and variations in the level of underground water (Dubrov et al., 2007), the estimate of the spatial scale for comparatively short-period hydrobaric perturbations is 90–100 km with a characteristic time of perturbations of 20–30 min. It is significant that the epicentre of a forthcoming earthquake with the magnitude $M \sim 7$ has the same spatial

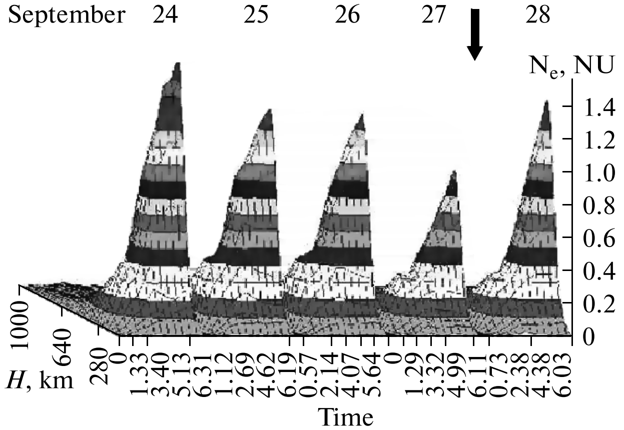

Fig. 6. Altitude profiles of electron content N_e in the ionosphere for September 24–28, 2003 (satellite no. 14, URUM station). Altitude is indicated in kilometers along the H axis; 1 NU = 2×10^6 el cm^{-3}.

scale (Sobolev and Ponomarev, 2003), while a range of characteristic velocities, obtained from the mentioned spatiotemporal scales ($V \sim (10^2–10^3$ km$)/(10^2–10^4$ s$) \sim 10^2–10^3$ m/s), includes characteristics of the atmosphere and ionosphere, such as the maximum velocities of displacement ($\sim 10^2$ m/s) of air masses in the zone of tropical cyclones, the velocities of displacement of medium (150–200 m/s) wave packets in the E and F regions of the ionosphere, as well as of the large-scale (~1000 m/s) ionospheric soliton-like perturbations (Afraimovich et al., 2004). The results of our measurements (see Fig. 5) demonstrate that seismic ionospheric perturbations can propagate still faster by the order of magnitude, at the velocities of propagation of seismic waves in the solid Earth.

Probably, only complex researches of a wide spectrum of dynamical processes in all interacting geospheres with the application of high-precision instrumental methods will make it possible to come closer to the creation of an adequate physical model of the observed effects and, based on it, solve such an important problem as prediction of seismic hazard.

5. CONCLUSIONS

Based on laser–interferometer observations of the Earth's surface deformations and atmospheric pressure variations supplemented with data of the Earth's ionosphere radio translucence, it is shown that there is a correlation between processes recorded simultaneously in these three media and the development of the Earth's seismic activity.

Dynamical processes with characteristic spatiotemporal scales of $10^2–10^3$ km and $10^2–10^4$ s, respectively, have been registered. A connection between the observed effects and regional seismic events, as well as remote earthquakes of magnitudes $M = 7–8$, is considered.

The revealed peculiarities of the dynamical coupling of the Earth's lithosphere, atmosphere, and ionosphere can be used for the development of technology of early detection of earthquake precursors and other natural hazardous phenomena. Studying the possible response of monitored geospheres to the anthropogenic effect also seems important, including the application of the developed methods during geophysical and geoecological monitoring.

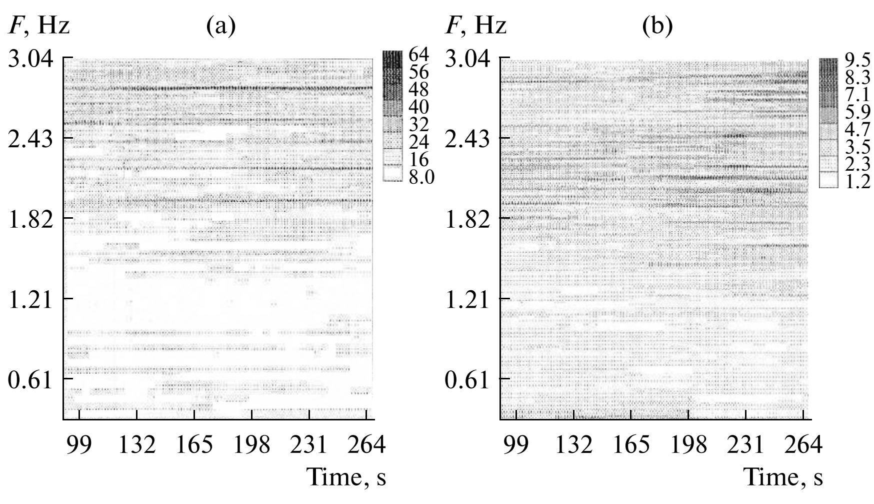

Fig. 7. Microseismic background within a band of 1–3 Hz (Fryazino) (a) under usual conditions and (b) during a "calm" period on September 26, 2003. The amplitudes of spectral components are displayed according to the brightness scale on the right-hand side of each diagram.

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