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Variations in the Quasi-Static Electric Field in the Near-Earth's Atmosphere during Geomagnetic Storms in November 2004

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Abstract—The effects of the geomagnetic storms of November 8 and 10, 2004, in variations in the strength and power spectra of the electric field in the near-Earth's atmosphere in Kamchatka were studied, together with the meteorological and geophysical phenomena observed simultaneously. A sequence of strong solar flares was shown to cause an anomalous increase in air temperature and humidity. This resulted in the excitation of anomalously strong thunderstorm processes in the atmosphere during the storm of November 8 and made it impossible to distinguish the effects associated with cosmic rays on this background. During the storm of November 10, on the background of weak variations in meteorological parameters, an increase in the strength and intensity of power spectra of the electric field on the day before the storm of November 10 was detected; it was followed by an attenuation of these parameters on the date of the storm. These effects were supposed to be associated with the action of cosmic rays on currents of the global electric circuit. It was shown that the influence of the Forbush effect of galactic cosmic rays in the power spectrum of the electric field first of all shows as the amplification of the component with the period $T \sim 48$ h; in variations in humidity, the effect shows as the amplification of the component with $T \sim 24$ h. Cause-and-effect relationships between variations in the electric field strength and the horizontal component of the geomagnetic field were shown to be absent both under the conditions of "fair weather" and during the storm of November 10. A diurnal negative-difference atmospheric pressure was detected on the second day after the geomagnetic storms of November 8 and 10.

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1. INTRODUCTION

The literature on the effects of solar activity and associated geomagnetic storms on the atmospheric electricity of high and middle latitudes is rather voluminous (see, e.g., (Apsen et al, 1988)). We are interested in the effects of powerful solar flares accompanied by geomagnetic storms with the Forbush effect of galactic cosmic rays (GCRs) in the near-Earth's atmospheric layer at middle latitudes over the continent. Unfortunately, these results are limited and rather contradictive. This can be connected not only with the particularities of the physical processes in the near-Earth's atmosphere for individual geomagnetic storms but also with the choice of, e.g., detection location, zero day in the method of superposed epochs, intervals of data averaging (from minutes to days), as well as with the state of the atmosphere before a storm and after it. The proposed possible mechanisms of these effects are contradictory to the same extent. Some results of these investigations are briefly presented below.

For example, in (Markson, 1981; Markson, 1982), a hypothesis of the influence of solar activity on atmospheric electricity was proposed for the first time. The concept of the hypothesis is that the conductivity of the global electric circuit (GEC) varies under the action of cosmic rays (which is one of the main ionizers of the atmosphere). The global electric circuit is a closed current system in which, according to the spherical capacitor model, tropical thunderstorms (the Global Thunderstorm Generator, GTG) are the main generator. Currents of this generator go through the resistance of air above it to the lower ionosphere and are closed via the nondisturbed remote atmosphere and the Earth's surface. These currents provide the charge of the spherical capacitor, the upper wall of which is under electric potential V_1 with respect to the zero potential of the Earth. In the lower part of this circuit at heights of up to ~2 km, the atmosphere is mainly ionized by the natural radioactivity of the soil; at heights of ~15–20 km (the maximum in the distribution of galactic cosmic rays), by GCRs. Penetrating into the lower stratosphere and upper troposphere, rays are able to cause ionization, which leads to the amplification of GEC currents. It is the reason for the use of simultaneous observations of atmospheric electricity and GCR parameters either in mountains or on isolated islands with equipment on boards of aircrafts or aerostats, i.e., above the exchange atmospheric layer, in which variations in the electric field strength are significantly affected by local convective and turbulent processes. Under such conditions, a positive correlation between the electric potential of the lower ionosphere and GCR intensity was detected in (Markson, 1981). At the same time, a negative correlation of these parameters was detected in other experiments carried out in a mountainous area (Krechetov and Filippov, 2000).

The results obtained in experiments carried out in flatlands are also contradictory. In a series of works by the group led by V.M. Sheftel' (Sheftel' and Chernyshev, 1991, 1992a; Sheftel' et al., 1992b), it was shown that the field strength increases with respect to the background level 5–6 h before the beginning of a GCR decrease. This phase of positive disturbance of the field continued up to the instant of the maximal depth of the Forbush effect and was followed by a longer negative phase of the field disturbance. The authors associated the positive-phase lead with respect to the beginning of the Forbush effect with the action of solar protons; the effect of the positive disturbance phase itself at the deepening stage was associated with the action of the penetrating GCR muon component upon the atmosphere. The component reaches the sea level and determines the contribution of protons to atmospheric conductivity at the place where the electric field was detected.

A similar result was obtained in (Marcz, 1997): a ~2% positive phase of the disturbance of the electric field strength was observed on the day of the maximal depth of the Forbush effect during strong geomagnetic storms. This was followed by a long negative phase with the gradual recovery of the electric field strength during ten days. According to the author, the effect is caused by a change in the GEC conductivity under the action of GCRs. Model calculations that were performed in (Makino and Ogawa, 1984) for the response of determining the electric field and density of the conduction current in the GEC with variations in the conductivity profile during the Forbush effect at a constant GTG current demonstrated a negative correlation between these parameters and GCR intensity.

During strong geomagnetic storms, including the storm of October 30, 2003 (Nikiforova et al., 2005; Kleimenova et al., 2008), negative bays of the electric field potential were detected at the Swider station. The coincidence of their durations with those of riometer absorption bursts in the subauroral zone permitted the authors to suppose that negative values of the gradient of the electric field potential can appear due to an increase in the conductivity of the upper atmosphere caused by the penetration of energetic electrons into subauroral latitudes (Nikiforova et al., 2005).

At the Borok observatory, during the main phase of the storm of March 28–31, 2000, a positive bay of the electric field strength was observed. The author supposed that the penetration of fields of a magnetospheric–ionospheric source into the midlatitude lower atmosphere served as a mechanism of the effect (Anisimov, 2007).

When studying the connection between the electric field strength and GCR Forbush effect at the Paratunka observatory, an almost simultaneous decrease in the electric field strength and in the GCR flux was detected (Kuznetsov and Cherneva, 2008). The maximal value of the negative phase of the electric field disturbance was ~5–10% and followed by the recovery of the field during 5–10 days. The electric conductivity of positive and negative light ions in the near-ground atmosphere was also measured at the observatory. It turned out that the electric conductivity of negative ions decreased simultaneously with the effect in the electric field. This permitted the authors to propose the following mechanism of the observed phenomena: since field magnitude Ez is determined by the surface density of negative charges on the Earth's surface, it is natural that, if the total density of the Earth's charges in the near-ground atmospheric layer decreases, then quantity Ez also decreases (Kuznetsov and Cherneva, 2008).

The results presented above were obtained at different points, mostly under the conditions of the so-called "fair weather" (Reiter, 1992; RD 52.04.168 ..., 2002).

At the same time, literature presents another group of works devoted to studying the relation between atmospheric parameters (temperature, pressure, and wind) and geomagnetic activity, in particular, geomagnetic storms. On the second day after the onset of a storm, daily differences in atmospheric pressure were detected. Their magnitude and sign turned to be dependent on the region and season (Mustel' et al., 1977; 1979; Chertoprud et al., 1979; Pudovkin and Babushkina, 1990). At large temporal scales, a relation between temperature and pressure variations of the atmosphere and corpuscular fluxes from the Sun was also detected experimentally in (Bucha, 1980). The reviews (Laštovička,1996; Avdyushin and Danilov, 2000) present additional data on the effects of geomagnetic storms in variations in atmospheric parameters, in particular, in variations in the index of the vorticity area in the troposphere at a level of 500 hPa (h ~ 5 km). This index in fact characterizes the behavior of planetary-scale waves at these heights. The reviews also present possible mechanisms of the effect of geomagnetic storms upon the troposphere: these are the electric mechanism associated with the global electric circuit, CR penetration into the atmosphere, and the optical mechanism associated with variations in atmospheric transparency and the chemical composition of the stratosphere under the action of the shortwave radiation of the Sun and GCRs. However, in a later and extended review (Danilov and Laštovička, 2001), the authors prefer the uniquely possible mechanism of the effect of geomagnetic storms upon tropospheric processes via variations in parameters of the global electric circuit under the action of CRs.

In contrast to earlier works, to study the effects of geomagnetic storms (November 2004) in the electric field in the near-Earth's atmosphere in Kamchatka (Paratunka observatory, $\varphi = 52.9°$ N, $\lambda = 158.25°$ E), we used a wider set of different geophysical and meteorological parameters observed simultaneously. Choosing these storms was caused by extreme events on the Sun; their manifestation was considered in detail in the behavior of many geophysical processes in the magnetosphere and ionosphere of the Earth (Yermolaev et al., 2005). At present, however, as far as we know, information on the effects of these solar events in simultaneously observed variations in the electric field strength and meteorological parameters in the near-Earth's atmosphere is absent both in Russian and foreign publications. This gap is filled in this work. Earlier, we considered the effects of weaker geomagnetic activity only in variations in the electric field strength (Mikhailova et al., 2009).

2. INITIAL DATA AND MAIN RESULTS

It is suitable to consider the response of the electric field in the near-Earth's atmosphere to a powerful geomagnetic storm by the method of superposed epochs in a complex with processes occurring on the Sun and near the Earth's surface. In connection with this, Fig. 1 presents the results of observations of different geophysical and meteorological phenomena during the period November 4–15, 2004.

Curve *1* are the strength of the quasi-static electric field (the *Ez* component) measured with a Pole-2 device with an accuracy of 0.3 V/m and in time steps of 1 min, as well as the values of the *Dst* index (nT) determined in time steps of 1 h.

Curves *2–5* are pressure (*P*, hPa), temperature ($T°$, C), atmosphere humidity (%), and the wind velocity (*V*, m/s), respectively, measured every 10 min at the Paratunka observatory. (The magnitude of the velocity exceeded the dynamic range of the device during the period November 9–12.) The work additionally involves observation data on the state of cloudiness and precipitation at the local meteorological station. Unfortunately, the results of actinometrical measurements and the electric conductivity of positive and negative light ions in the near-Earth's atmosphere were absent for this period.

Curve *6* is the horizontal component of the geomagnetic field (HP) measured at the Paratunka observatory with a FRG-601G fluxgate magnetometer with an accuracy of 0.01 nT and in time steps of 1 min.

Curve *7* is the sequence of solar flares measured on the GOES 12 satellite (http://goes.ngdc.noaa.gov/data/avg).

Curve *8* is the three-hour values of the *Kp* index.

Curve *9* is the flux of galactic cosmic rays (*N* is the number of particles per minute) measured by a neutron monitor in time steps of 1 min at the Stekol'nyi observatory, Institute of Cosmophysical Research and Radiowave Propagation, Far Eastern Branch, Russian Academy of Sciences.

The table complements this figure with a more detailed chronological sequence of these events. The sequence was comprehensively described in (Yermolaev et al., 2005). As is seen in Fig. 1 and in the table, during the period November 4–5, the solar (*M*-ball X-ray radiation or weak optical radiation with *F* and *SF* intensities) and geomagnetic ($Kp < 3$) activities were relatively quiet and the meteorological conditions corresponded to "fair weather." However, before this, i.e., on November 6, three powerful flares occurred on the Sun. They were accompanied by three X-ray radiation flares—*M*9.3/2*N* (0011 UT), *M*5.9 (0044 UT), and *M*3.6 (0140 UT)—as well as by an anomalous optical 2*N* flare. The flares were accompanied by coronal mass ejections (CMEs) at 0131, 0206, and 0242 UT, respectively. As a result, a strong geomagnetic storm was observed on the Earth (the data on *Dst* variations) with a sudden commencement on November 7 at 0257, 1052, and 1827 UT. Its intensity maximum ($Dst = -373$ nT) was reached on November 8 at 0700 UT. The duration of the main phase of this storm was 13.5 h. Then, at the recovery phase on November 9 and 10, another two powerful flares occurred on the Sun, They were accompanied by the *M*8.9/2*N* (1659 UT) and *X*2.5/3*B* (0159 UT) X-ray radiation and by radiation amplification in the optical range up to 3*B*. A sudden commencement of a storm was detected November 9 at 0930 UT. The storm reached its maximum ($Dst = -289$ nT) on November 10 at 1000 UT. The duration of the main phase of this storm was 8 h. Two strong GCR reductions were observed simultaneously with these storms.

According to the GOES-12 satellite data (Yermolaev et al., 2005, Fig. 16), the value of proton fluxes in the north polar cap with energy $E = 1–5$ MeV during the period November 4–5 was $N \sim 1/\mathrm{cm}^2$ s sr. With an increase in solar activity on November 6, proton fluxes in this energy band increased by approximately a factor of 10; on November 7, by a factor of 100; and on November 8–9, by a factor of 1000. The maximal proton energy fluxes were observed on November 8 in a range of 14–26 MeV.

Let us consider in detail the processes that occurred in the near-Earth's atmosphere at the Paratunka observatory during this period of observations. On November 4–5, at weak geomagnetic activity ($Kp \le 3$), the solar activity in the optical range of the spectrum

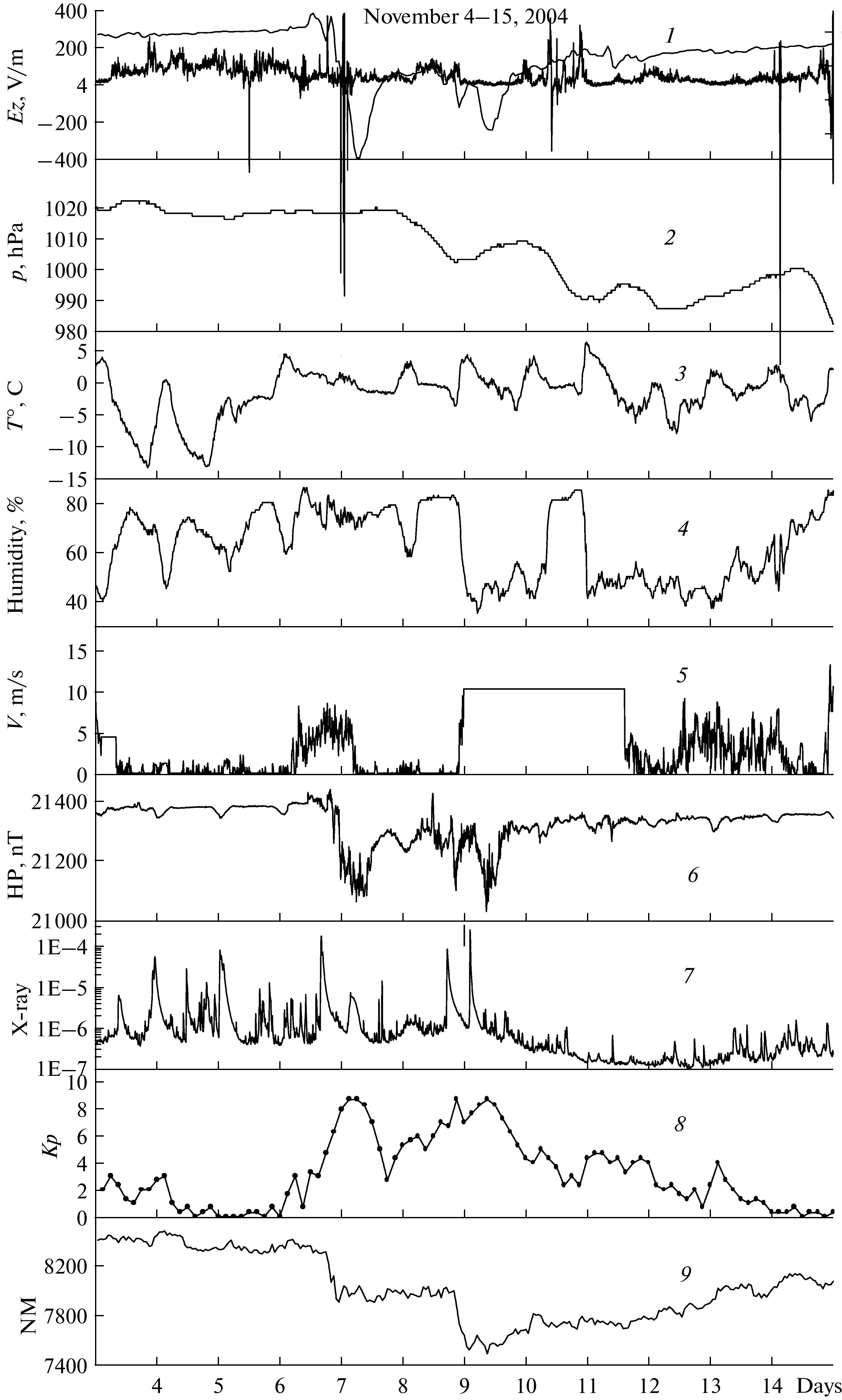

Fig. 1. Diurnal variations in the electric field strength and meteorological, geophysical, and solar parameters during the period November 4–15, 2004.

Flare events in AO 10696 in the period November 4–5, 2004, and their manifestations in the circumterrestrial space (Yermolaev et al., 2005). The *Dst* data were taken from http://spidr.ngdc.noaa.gov/spidr/; the *Kp* data, from http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/kp-cgi

Date	Flare		*S*; UT	*Dst*, nT	*Kp*	SCL; *E*, MeV; *P*, $cm^{-2} s^{-1} sr^{-1}$	GCR, %; *Rc* = 10 GV	Main phase of the storm
	Time, UT; Duration, min	Units						
04	0845; >79	C6.3/SF		–18	2+	1–5 1		
04	2142; >131	M2.5/SF		–10	3–	″		
04	2253	M5.4/1N		–8	3–	″		
05	1123; >10	M4.0/1F		–8	1–	″		
05	1910	M1.2/SF		–6	1–	″		
06	0011; 157	M9.3/2N		–3	0	1–5 10		
06	0044	M5.9		–3	0	″		
06	0140–0208	M1.4		–1	0	″		
07	1542–1615	X2.0/2B	02:57	1	2	10 100	0.6	
07	>33		10:52	20	3+	″	0.4	
07			18:27	–29	6+	″		1830; 07; –
08	07			–373	8+	14–26 1000	7.3	0700; 08;
08	1543–1552	M2.3/1N		–151	3–	″		τ = 12.5 h
09	1700 90	M8.9/2N	09:30	–110	6	″		
10	0200 76	X2.5/3B		–146	8–	–	8.1	0200–
10	1000			–289	8+	–	″	1000; τ = 8 h

was weak (SF). Under these conditions, the diurnal range of atmospheric temperature (Fig. 1, curve *3*) varied regularly, i.e., the temperature maximum $T = +4$°C occurred during the local midday (0130 UT) and the minimum $T = -13$°C took place before sunrise. Correspondingly, in the opposite phase with temperature, air humidity was ~40 and ~75%. In the absence of cloudiness and precipitation (according to the local meteorological service), atmospheric pressure varied insignificantly and the wind velocity was less than 2 m/s, i.e., the conditions of the so-called “fair weather” were satisfied. Under these conditions, the electric field strength shown on a magnified scale in Fig. 2 had a typical diurnal range with a typical increase at sunrise and sunset (Smirnov et al., 2012). Later, at t = 0100 UT on November 6, a solar flare, in the optical spectrum of which brightness increased to 2*N*, took place. At the same time, the diurnal behavior of temperature and atmospheric humidity was sharply distorted: at noon, the temperature increased from 0 to +4°C; at night, from –13 to –(5–2)°C. Small amounts of cloudiness with clear spells took place in the absence of wind; it distorted the diurnal behavior of the field strength (Fig. 2). On November 7 at t ~ 1600 UT, the next powerful flare took place (*X*2.0/2*B*); it resulted in a further increase in temperature at noon to +5°C and in humidity to 85%, as well as in an increase in the wind speed to ~7 m/s. It is well-known that such sharp variations of atmospheric processes in the lower layer of the atmosphere can be accompanied by the amplification of turbulent and convective air flows and lead to the formation of continuous cloudiness and precipitation. Indeed, according to the local meteorological service, continuous cloudiness with clearings was observed during the period November 7–10; on November 8–9, even snow fell. Moreover, thunderstorm processes can be formed under such meteorological conditions. Indeed, as seen in Figs. 1 and 2, large-magnitude sign-alternating oscillations (±800 V/m) typical of thunderstorm processes were

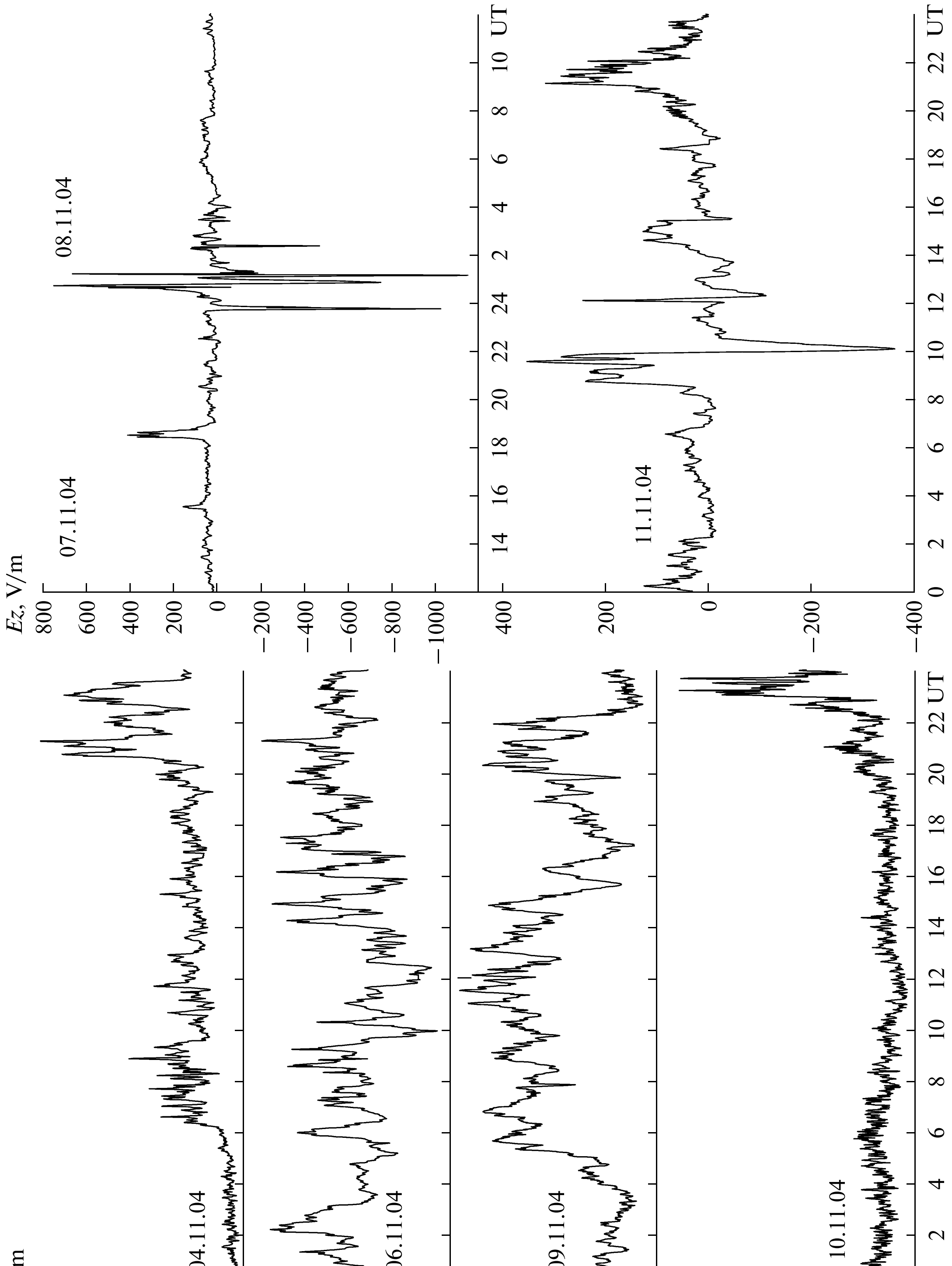

Fig. 2. Diurnal variations in the electric field strength in selected intervals of observations.

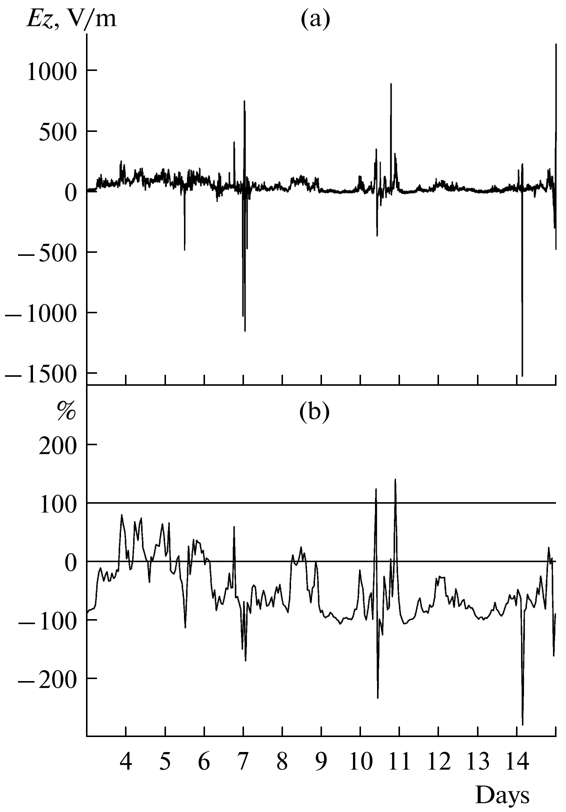

Fig. 3. Observed electric field strength variations: (a) measured in time steps of 1 min and (b) averaged values for 1 h.

observed at noon on November 8 in variations in the electric field strength (Mikhailova et al., 2010). This thunderstorm phenomenon coincided in time with the main phase of the geomagnetic storm of November 8 (Fig. 1, curve *1*); its onset coincided with the beginning of the GCR Forbush effect (Fig. 1, curve *9*).

Such a phenomenon was not observed during the geomagnetic storm of November 10 at relatively high air temperature but low humidity. However, on November 11, at high air temperature, air humidity increased to 90%, which also resulted in the generation of thunderstorm processes in the atmosphere and the appearance of strong sign-alternating variations in the electric field strength (Fig. 2).

In addition, a negative difference of diurnal pressure ΔP (on the order of 20 hPa) was observed on the second day after the onset of the geomagnetic storms (Fig. 1, curve *2*).

Figure 3 presents curves of (a) the initial values of the electric field strength in time steps of 1 min and (b) averaged values for 1 h for comparing the observed variations in the field strength with the results of other investigations. Beginning from November 7 (the beginning of the first Forbush effect), plot (b) shows negative disturbances of the electric field with oscillations $\delta E \sim 90\%$ with respect to the average level under the conditions of "fair weather" on November 4–5. The sign of the disturbance is preserved up to November 15 with a further decrease in the GCR flux intensity. During the main phases of the geomagnetic storms coinciding with the sharp decrease in the GCR intensity, the behavior of variations in negative disturbances of the electric field is different: during the storm of November 8, as a result of the appearance of thunderstorm processes in the atmosphere, the negative disturbance visibly decreased in magnitude; during the storm on November 10, it somewhat increased.

3. VARIATIONS IN THE POWER SPECTRAL DENSITY OF THE ELECTRIC FIELD AND METEOROLOGICAL PARAMETERS

In the sequence of events on November 4–15, phenomena with individual features are distinguished in variations in the electric field strength and meteorological parameters: these are the days of "fair weather" (November 4–5); days with an anomalous behavior of temperature and atmospheric humidity (November 7 (1200 UT)–November 8 (1200 UT)); the period of the storm on November 10; and the period of developing thunderstorm processes in the atmosphere (November 11).

It was interesting to study the wave processes in the near-Earth's atmosphere in these periods. For this purpose, a spectral analysis of diurnal variations in the electric field strength was carried out by the following scheme. The spectral power density (for the sake of brevity, power spectra) in the band of periods of thermal tidal waves with $T = 4–24$ h (TTWs) was estimated using the periodogram method with a rectangular temporal "window" with the duration $t = 24$ h. Components in the band of periods of internal gravitational waves with $T = 5$ min–3 h (IGWs) for preliminarily filtered data were separated using the method of modified periodograms (Welch, 1967) with the following parameters: segment duration $t_i = 8$ h with segment overlapping at 4 h so that there are in total five segments in an interval of 24 h. The spectrum of each segment was estimated using the cosine temporal window. Components of the power spectra in the band of periods of planetary-scale waves with $T > 24$ h (PSWs) were separated using the periodogram method with a rectangular temporal "window" with the duration $t_i =$ 2 days; the window was shifted by one day along the time series of the data during the period November 4–15. The choice of such a duration of the "window" was caused by two aspects: first, the condition of "fair weather" was preserved on November 4 and 5; second, as is seen in Fig. 1 (curve *8*), the duration of periods of high geomagnetic activity was about 48 h.

The resulting power spectra of the Ez component of the field for curves presented in Fig. 2 are shown in Fig. 4. They were constructed separately in the TTW (4–24 h) $SE1$, IGW (0.5–3 h and 6–30 min) $SE2$, and PSW (4–48 h) SE bands. The first digits near the PSW

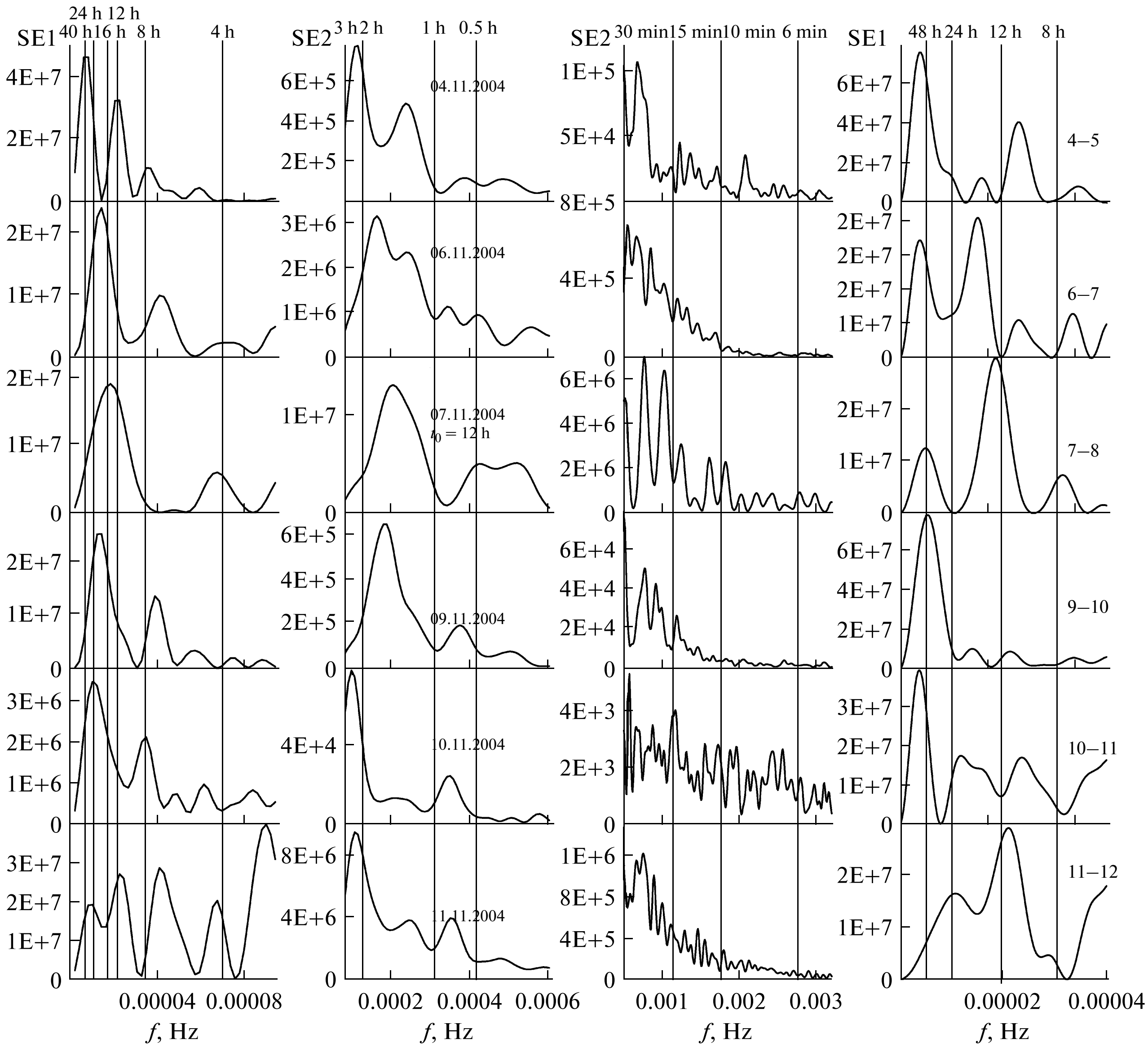

Fig. 4. Variations in the power spectral density of thermal tidal waves ($T \sim 4$–24 h), internal gravitational waves ($T \sim 30$ min to 3 h and 5–30 min), and planetary-scale waves ($T \sim 4$–48 h) in diurnal variations in the electric field strength presented in Fig. 2. The vertical solid lines highlight the periods of spectral components.

curves correspond to the first date of the temporal "window." On November 4, as is seen in the figure, the main component with $T \sim 24$ h and harmonics decreasing with respect to intensity with $T \sim 12$, 8, and 4 h are distinguished in the TTW spectrum; in the IGW spectrum, one can distinguish components with $T \sim 1.5$ and 2.5 h. Their intensity is lower by almost two orders of magnitude than in TTW components. In the band of PSW periods, the component with the period $T \sim 48$ h prevails. A similar character of the power spectra of the electric field under the conditions of "fair weather" was observed in Kamchatka, e.g., in September 1999 (Mikhailova et al., 2009). On November 6, as a result of a powerful solar flare accompanied by an anomaly in diurnal variations in temperature and humidity of the atmosphere, the following changes in the power spectra took place: the periodicity of the components with $T = 8$ and 12 h was broken, and the intensity of the component with $T \sim 24$ h decreased by almost a factor of 2; at the same time, the spectrum intensity in the IGW band increased by almost an order of magnitude. In addition, the PSW spectrum became more complicated due to the amplification of the component with $T = 24$ h. During the period from 1200 UT on November 7 to 1200 UT on November 8, which included the main phase of the storm of November 8 and strong thunderstorm processes, the components with $T \sim 8$, 12, and 24 h in the TTW merged into a single wide maximum with their following attenuation as compared to "fair-weather" conditions. The spectrum components in the IGW band were in fact amplified by two orders of magnitude. In the PSW band, the component with a period $T \sim 12$ h prevails and the component with $T \sim 48$ h is strongly suppressed. In the pause between two storms on November 9, the character of the spectra closely coincides with the spectra under the conditions of "fair weather" both in the shape and intensity of maximums. On November 10, during the second storm, the character of the spectra in the TTW and IGW bands closely coincides with the spectra of November 9 in the shape but is lower by an order of magnitude in the intensity of maximums. The component with the period $T \sim 48$ h prevails in the PSW spectrum. Finally, on November 11 (a day with thunderstorm activity but weaker than on November 8), a full spectrum of components with almost similar intensity and coincidence in magnitude with the spectra of November 4 was distinguished in the TTW spectrum. At the same time, however, the intensity of the spectra in the IGW band increased by an order of magnitude as compared to the spectra of November 4. A similar character of the spectra was also observed during thunderstorms in Kamchatka in September 1999 (Mikhailova et al., 2010). Comparing the power spectra in the band of the TTW and IGW periods on November 7–8 and 10–11, one can conclude that the main contribution to the electric field spectrum during the main phase of the storm of November 8 was made by the simultaneously observed thunderstorm processes.

To analyze the interactions between different processes in the near-Earth's atmosphere and solar and geomagnetic phenomena, Fig. 5 presents a sequence of power spectra in the band of periods of 4–48 h for all the parameters considered here. The designations of the spectral curves correspond to those in Fig. 1. For a further analysis of the power spectra, we exclude from consideration days with thunderstorm activity and only consider November 4–5 (days with "fair weather") and November 9–10 with the storm of November 10. As is seen in the figure, components with the periods $T \leq 8$, 12, and 48 h with prevailing intensity at $T \sim 48$ h are distinguished in the power spectrum of the electric field on November 4–5. As this takes place, components with $T \sim 48$ h also prevail in all spectra (*SP*, *SN*, and *SD*), except the spectra of temperature (*ST*), humidity (*SV*), and the horizontal component of the geomagnetic field (*SH*). During the period November 9–10, only the component with $T \sim 48$ h prevails in the power spectrum of the electric field; in the spectra of humidity, pressure, and GCRs, the intensity of this component increased by almost two orders of magnitude as compared to "fair-weather" conditions. Beginning from November 9, the maximal intensity of the temperature spectrum (*ST*) component decreased by an order of magnitude at $T \sim 48$ h. A similar character of the power spectrum of the electric field in this band of periods was observed in Kamchatka during the geomagnetic storm of September 22, 1999 (Mikhailova et al., 2009).

The strong difference in the composition of the components and their intensity in the power spectra of the electric field (*SE*) and the horizontal component of the geomagnetic field (*SH*) both under the conditions of "fair weather" and during the geomagnetic storm of November 10 indicates the absence of cause-and-effect relationships between these parameters. The GCR effect on the electric field in the near-Earth's atmosphere shows only at periods $T \sim 48$ h, when the intensity of this component increases by two orders of magnitude and shows in the amplification of the intensity of this component by two orders of magnitude as compared to "fair-weather" conditions. In the absence of thunderstorm events and at weak geomagnetic activity (but at high solar activity) in the optical spectrum range (curves *6*–*7*), the electric field is affected to the largest extent by variations in air humidity which amplify the component with the period $T \sim 24$ h in the field spectrum.

4. DISCUSSION OF RESULTS

As is seen in Fig. 1, the effects of the geomagnetic storms of November 8 and 10 in variations in the electric field strength in the near-Earth's atmosphere were developed on the background of strongly changed meteorological parameters (curves *3*–*5*), i.e., in the absence of "fair-weather" conditions. Under the action of a series of powerful solar flares (curve *7*) that occurred in the period November 6–10, anomalous changes in the diurnal behavior of temperature and humidity resulted in the formation of cloudiness and snow precipitation, which in turn led to a decrease in the electric field strength and strong variations in its magnitude (Fig. 3). On this background, thunderstorm processes took place on November 8; they also distorted the diurnal behavior of the field strength (Fig. 2) and made it impossible to separate the GCR effect in them. Nevertheless, this turned out to be possible on November 10 under a relatively weak influence of meteorological parameters. A considerable attenuation of the field strength as compared to the previous day was observed with the simultaneous amplification of planetary-scale waves with $T \sim 48$ h both in temporal variations of the field strength (Fig. 2) and in variations in the power spectrum of November 10 (Figs. 4, 5). This result coincides with the results of other investigations, demonstrating the attenuation of the electric field strength in the near-Earth's atmosphere during the Forbush effect and the amplification of planetary-scale waves (see Introduction).

To explain the observed effects in temporal variations in the electric field strength, let us consider the action of the global electric circuit in the context of the spherical-capacitor model. The main electrodynamics equations describing the GEC imply a general expres-

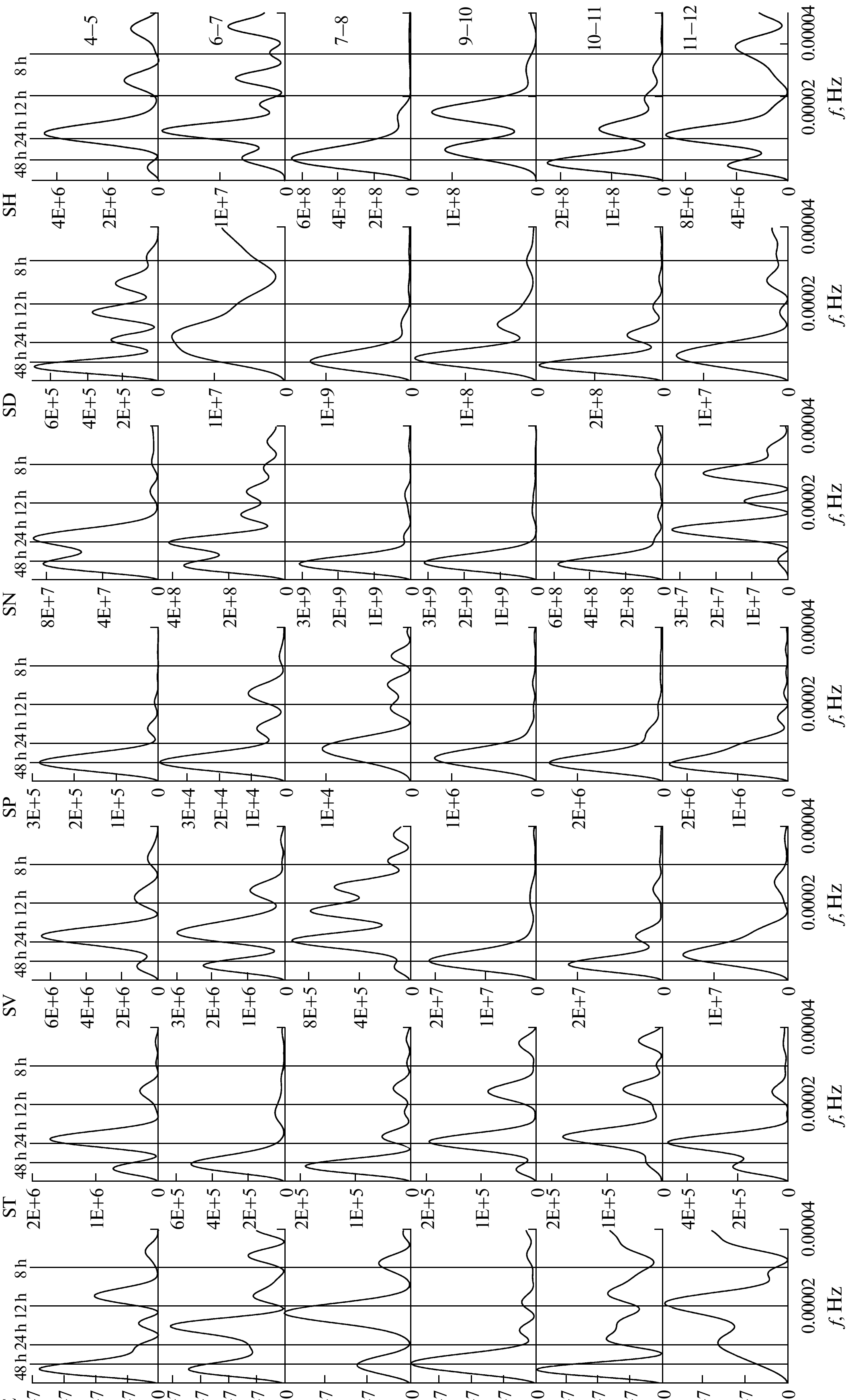

Fig. 5. Sequence of curves of the power spectral density of the electric field and parameters presented in Fig. 1 for the events on the days highlighted in Fig. 2.

sion for the current density in the form (Atmosfera, 1991)

$$J = \lambda E + \rho V + D_\tau \nabla \rho + \sum J_s,$$

where λ is conductivity; E is the electric field strength; ρ is the charge density; V is the velocity of the moving medium; D_τ is the turbulent diffusion coefficient; and $\sum J_s$ is the total current density of S sources. The first summand is the atmospheric conduction current caused by the global thunderstorm generator. The second and third summands take into account the local currents (caused by the convective generator) in the atmospheric exchange layer. The last summand includes possible sources of both local and global scales. The first of them can include cloudiness, precipitation, local lightning discharges, and underground radioactive gases (in November, radioactive sources have practically no effect upon the conductivity in the exchange layer due to low air temperatures). Cosmic rays are an additional global source of the current. At midlatitudes at a height of about 15–20 km, as was shown in (Stozhkov et al., 2001), a linear connection between the current density and a CR flux can be observed. Under quiet geomagnetic conditions, the coefficient of correlation between annual values of these parameters is 0.77 ± 0.10. At heights above 35 km in the high-latitude atmosphere, the main contribution to GEC currents is made by SCRs. In the considered period, as follows from (Yermolaev et al., 2005, Fig. 16), solar proton fluxes in the energy range 1–5 MeV increased by three orders of magnitude on November 9 as compared to the fluxes of November 6. The boundary of their penetration into the atmosphere lowered to invariant latitudes of ~55°–60° (Yermolaev et al., 2005, Fig. 30). The penetration of solar protons into stratospheric heights could cause an increase in the ionization of the atmosphere and the amplification of currents in the GEC. At the deep lowering of GCR fluxes during the storm of November 10, an inverse effect took place (Fig. 3). The formed anomalously powerful thunderstorm process during the main phase of the magnetic storm of November 8 suppressed the Forbush effect both in the diurnal behavior (Fig. 2) and in the power spectra of the Ez component of the field (Figs. 4, 5). At the recovery phase of GCR fluxes on November 10–15, a linear connection between the electric field strength and the fluxes was absent due to the strong influence of meteorological processes upon the electric field. In spectral characteristics, the influence of the Forbush effect on the electric field manifests itself in the period of planetary-scale waves when the intensity of the component with $T \sim 48$ h in the spectra of cosmic rays and the electric field increases by two orders of magnitude as compared to "good-weather" conditions.

The temporal and frequency variations in the electric field strength in the observed period can be qualitatively explained by the influence of cosmic ray fluxes (emission of underground radon-saturated gases is perceptibly reduced at low air temperatures); in contrast to this, a variation in meteorological parameters under the considered conditions is difficult to explain even qualitatively. At present, several possible physical mechanisms of the connection between meteorological parameters and solar and geomagnetic activities are proposed in published works. Their short list and discussions were presented in surveys (Tinsley, 2000; Danilov and Laštovička, 2001) (see Introduction). A comprehensive discussion and comparisons of these mechanisms with the experimental results obtained in this work are beyond the scope of this paper. We only note that actinometrical measurements of direct solar radiation in the optical range that are necessary, e.g., for verifying the optical mechanism proposed in (Pudovkin, 1996), were absent at the observatory. The verification of the mechanism proposed in (Tinsley, 2000; Molodykh et al., 2007) to explain the influence of the quasi-static electric field's strength upon cloudiness and, correspondingly, upon the temperature regime in the troposphere needs simultaneous measurements of the volume charge distribution over height and of the electric field strength.

At the same time, the following changes in the meteorological parameters were found in the considered period:

(1) A small level of cloudiness with clear spells (as an attribute of slowly ascending air flows) appeared from the beginning of the active phase on the Sun observed on November 6. In proportion to the level of solar activity on November 7, it transformed into continuous cloudiness with the formation of convective clouds, generating thunderstorm events on November 8 (snow). These processes did not occur continuously; the cloudiness with clear spells observed on November 9 was transformed into solid convective clouds on November 11. The dynamics of the cloudiness development indicates the amplification of ascending flows of warm air. This in turn indicates the ingress of addition heat flows into the atmosphere;

(2) An anomalous increase in air temperature at night in the presence of a continuous cloudiness from –13 to –2° with a less considerable increase in the afternoon (from 0 to +5°);

(3) Amplification of wind from 1 to 8 m/s which is caused by the enhancement of the turbulent exchange between the Earth's surface and enhancement of planetary-scale waves associated with the exchange.

These facts coincided in time with the beginning of the active phase on the Sun and developed on the background of solar activity enhancement. This suggests that they were caused by an additional heat inflow into the lower atmosphere as a result of a solar thermal flare which is also indicated by the enhancement of radiation brightness in the Hα line from SF up to $3B$ units. Unfortunately, there are no published data on the radiation intensity enhancement in the IR wave range (the radiation must increase (as UV radiation) under thermal flares (Fletcher et al., 2011)).

The negative diurnal difference in pressure of ~20 hPa that we detected on the second day after both geomagnetic storms agrees with a similar effect that was observed in other works (see Introduction), the authors of which associate it with the action of corpuscular fluxes from the Sun.

The experimental fact of a sharp change in the atmospheric temperature during the period November 6–8 under quiet variations in the GCR intensity, i.e., up to the instant of the appearance of the Forbush effect, provide grounds to doubt that this association takes place. This conclusion agrees with the results in (Wolfendale et al., 2009). Moreover, the component with the maximal intensity in the period $T \sim 24$ h prevails in the power spectrum of temperature during the storm of November 10; in the GCR spectrum, the component in the period $T \sim 48$ h.

5. CONCLUSIONS

Studying variations in the strength and power spectra of the quasi-static electric field and meteorological parameters in the near-Earth's atmosphere in Kamchatka during solar events in November 2004 demonstrated the following:

(1) A sequence of strong solar flares accompanied by radiation enhancement in the optical range of the solar electromagnetic radiation was accompanied by an anomalous increase in the temperature and humidity of the atmosphere, which led to the excitation of powerful thunderstorm processes during the geomagnetic storm of November 8;

(2) The formation of cloudiness and precipitation from the instant of the solar flare of November 6 led to a decrease in the general background level of the electric field as compared to "fair-weather" conditions;

(3) An enhancement of the strength and intensity of power spectra of the electric field was detected on the commencement of the geomagnetic storm of November 10, followed by the attenuation of these parameters on the day of the storm. This effect can be qualitatively explained by the action of cosmic rays on global electric circuit currents capable to change the ionization of the atmosphere in different parts of the circuit (solar protons at heights of ~50 km and GCRs at heights of ~15–20 km);

(4) It was shown that the enhancement of the intensity of atmospheric planetary-scale waves ($T \sim 48$ h) was observed simultaneously in the GCR and electric field power spectra;

(5) It was shown that, under quiet geomagnetic conditions, the electric field in the near-Earth's atmosphere is affected to the largest extent by atmospheric humidity variations amplifying the component with the period $T \sim 24$ h in its spectrum;

(6) Cause-and-effect connections between variations in the electric field strength and the horizontal component of the geomagnetic field were shown to be absent both under "fair-weather" conditions and during the storm of November 10;

(7) A negative diurnal difference of atmospheric pressure was detected on the second day after both geomagnetic storms. The cause of this is unclear;

(8) The coincidence in the time of the beginning of the active phase on the Sun with the break of regular meteorological processes in the lower atmosphere made it possible to suppose that these effects are caused by heat flares in the optical range of the wave radiation of the Sun.

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