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Nature of the Sunrise Effect in Daily Electric Field Variations at Kamchatka: 2. Electric Field Frequency Variations

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Abstract—The power spectra of time variations in the electric field strength in the near-Earth's atmosphere and in the geomagnetic field horizontal component, which were simultaneously observed at the Paratunka observatory (φ = 52°58.3′ N; λ = 158°14.9′ E) in September 1999, have been studied. The periods of the day (including sunrise, sunset, and night) have been considered. It has been indicated that oscillations with periods $T \sim 2.0$–2.5 h are present in the power spectra of these parameters during the day. The intensity of these oscillations increases noticeably and the oscillations in the band of periods $T < 1$ h increase simultaneously in the field strength power spectra at sunrise. The variations in the argument of the cross-spectrum of these parameters indicated that oscillations in the 2.0–2.5 h period band are caused by sources that are located above the ionospheric dynamo region; at the same time, oscillations in the 0.5–1 h period band are caused by sources in the lower atmosphere. A possible mechanism by which these oscillations are generated, related to the vortex motion of convective cells that originate at sunrise in the boundary atmospheric layer, is proposed.

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1. INTRODUCTION

It is known that the solar terminator (ST) is an effective source of waves in the Earth's atmosphere (see, e.g., (Somsikov, 1991)). By definition, the ST is a transition region that separates the atmosphere from the total dark to the region illuminated by the full solar disk. The horizontal temperature gradient originates, and other geophysical parameters (pressure and density of the medium) vary as a result of a change in solar radiation in this region. This region has a finite width, which varies depending on the latitude, altitude, and geophysical conditions and coincides with the sunrise and sunset periods. Atmospheric waves are generated at different altitudes in a wide range of periods as a result of the ST motion at the Earth's rotation velocity. These waves were initially detected using different radar methods mainly at ionospheric altitudes in a band of periods varying from several minutes to several hours and belong to the range of acoustic gravity waves (AGWs) (Somsikov, 1991).

Many theoretical and experimental data on the ST effects have been accumulated by now. The present-day state of this problem is most completely reviewed in (Somsikov, 2012). Unfortunately, the works devoted to studying the ST effects in the lower and middle atmospheres are insufficiently presented in this review. Antonova et al. (1988) analyzed in detail the AGW spectra, detected in spatiotemporal variations in the light backscatter coefficient using a laser method, for the middle atmosphere ($h \sim 20$–25 km). We should note here that the laser method, which is used at lidar facilities, makes it possible to determine the vertical distribution of the atmospheric temperature, aerosols, ozone concentration, etc., in the stratosphere and upper troposphere, i.e., at altitudes of 15–60 km. Only one work (Kuznetsov and Cherneva, 2008), where the daily variations in the electric field strength (EFS) at the Paratunka observatory were considered, was cited in the review for the lower atmosphere. The sunrise effect as a baylike increase in the EFS value superposed by short-period variations is clearly defined in the records under fair-weather conditions. The authors visually (without a detailed spectral analysis) estimated the period of these oscillations (~1 h) and attributed them to the ST effect at ionospheric altitudes.

In the present work, we performed a detailed spectral analysis of time variations in the EFS and the geomagnetic field in order to determine the nature of the short-period oscillations in these fields, which are simultaneously observed at sunrise. We used the records of the electric and geomagnetic fields in September 1999 at the IKIR DVO RAN Paratunka observatory (φ = 52°58.3′ N; λ = 158°14.9′ E), where these geophysical parameters have been regularly observed for more than ten years. This work continues the stud-

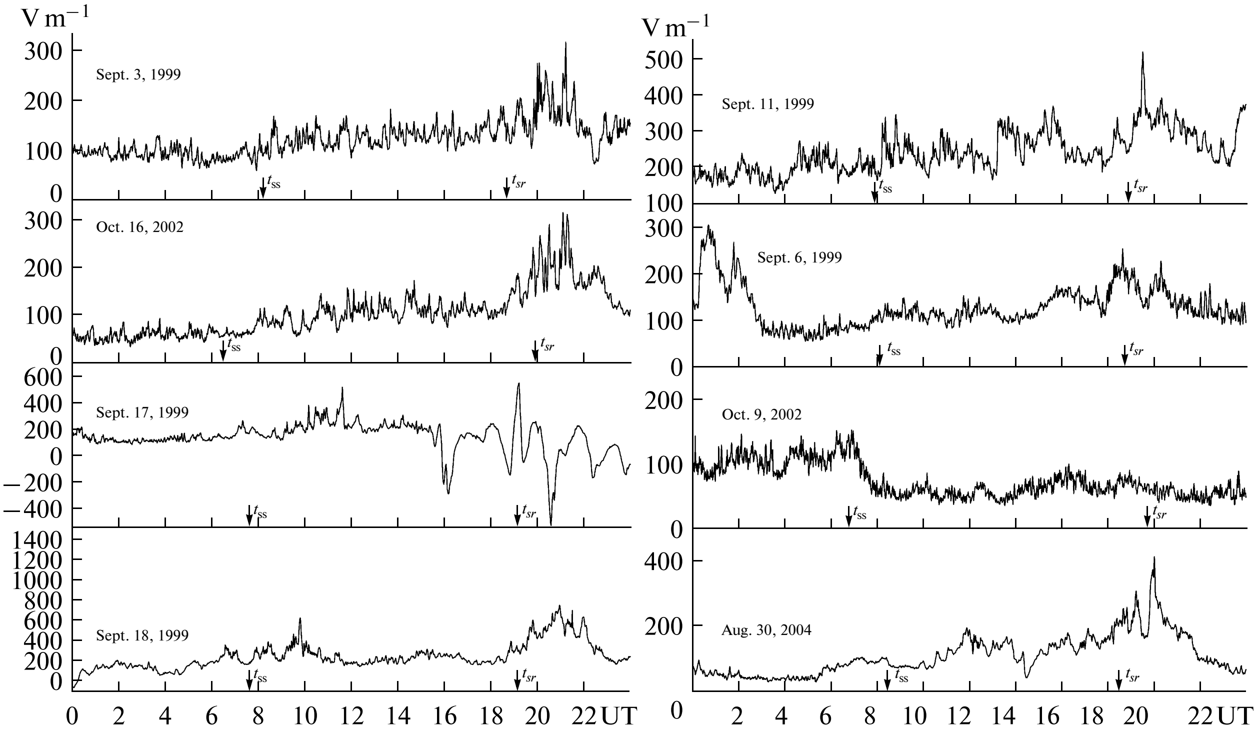

Fig. 1. Daily variations in the EFS under different geophysical conditions: fair weather conditions on September 3, 1999, and October 16, 2002; an anomaly before an earthquake on September 17, 1999; an earthquake at 2128:33 UT on September 18, 1999; $\varphi = 51.21°$ N; $\lambda = 157.56°$ E; $h = 60$ km; $M = 6.0$; cloudiness with weak precipitation on September 11, 1999; an earthquake at 1504:52.81 UT on September 6, 1999; $\varphi = 52.10°$ N; $\lambda = 159.15°$ E; $h = 33$ km; $M = 5.0$; strong abrupt wind, the lower level of stratus–rainy clouds (~10 points) but without precipitation on October 9, 2002; an earthquake at 1223:21.60 UT on August 30, 2004; $\varphi = 49.38°$ N; $\lambda = 157.42°$ E; $r = 40$ km; $M = 6.0$.

ies of the sunrise effects in time variations in the EFS in the near-Earth's atmosphere at Kamchatka, the results of which were previously published in (Smirnov et al., 2012).

2. INITIAL EXPERIMENTAL DATA AND PROCESSING METHOD

A Pole-2 device, the output signal of which was recorded on a personal computer hard disk at an interval of 1 min, was used to measure the EFS. The meteorological parameters for detecting the so-called fair-weather conditions, i.e., days without precipitation, thunderstorms, and fog and when the wind velocity is lower than 6 m/s, a level lower than the point-2 level of stratus–cumulus clouds is present (Reiter, 1992; RD 52.04 ..., 2002), and the geomagnetic and seismic activities are low ($Kp \leq 4$ and $M < 4$, respectively), were simultaneously recorded. Figure 1 shows typical records of the daily EFS variations, observed under different meteorological conditions before earthquakes and under fair-weather conditions.

We also used simultaneous records of the geomagnetic field horizontal component at the Paratunka (HP) and Barrow ($\varphi = 71.3°$ N; $\lambda = 203.4°$ E) (HB) observatories (the latter records were obtained from the Internet using the SPIDR (WDC) system) in order to complexly process the experimental data. Figure 2 illustrates simultaneous records of these parameters for three days: September 1–3, 1999.

The spectral processing method is shown using the record for September 14, 1999 (Fig. 3), as an example for the period including sunrise (12–24 UT). The method includes the following procedures. The average value for the considered period (fragment 1) was eliminated from (a) the initial EFS record and (b) HP, and the resultant curve (fragment 2) was completed with zeros up to 2048 points without loss of analysis accuracy (Kharkevich, 1957). The FFT algorithm was used to estimate the amplitude spectrum of this curve (a thick line in fragment 4 in the dependence on frequency with the left ordinate axis and in the dependence on the $T = 1/f$ period on the left-hand side in fragment 5). Then we used a filter in order to separate the spectrum in the 0.5–3 h band of periods (a dashed line in fragment 4 with the right ordinate axis and on the right-hand side in fragment 5 in the dependence on the period). The separated band of periods includes internal gravity waves (IGWs). Using inverse FFT, we determined the time dependence of the filtered signal (fragment 3). This signal was subsequently used for spectral processing, specifically, in order to estimate

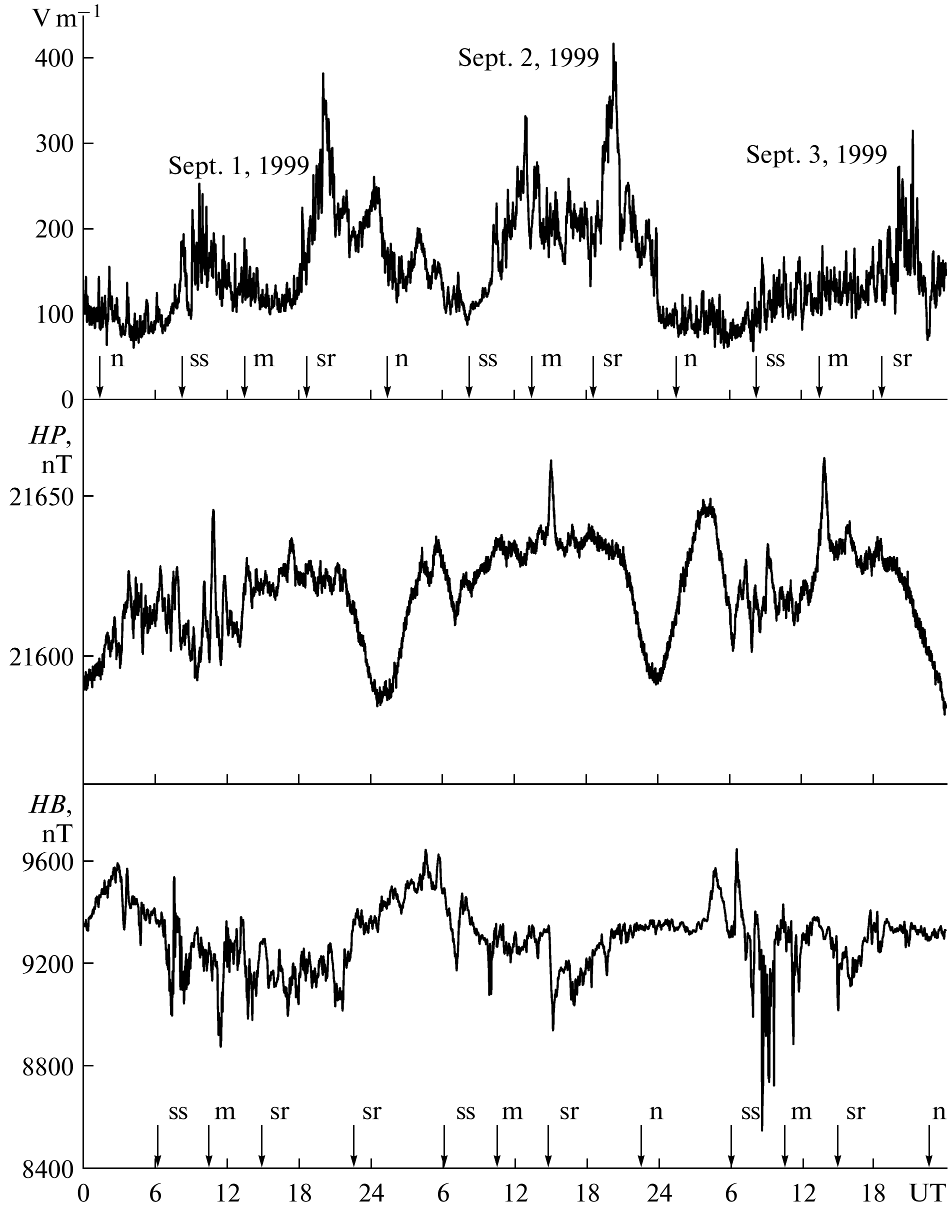

Fig. 2. Example of simultaneous records of the EFS (E) and the geomagnetic field horizontal component at the Paratunka (HP) and Barrow (HB) observatories during three days: on September 1–3. The sunrise (sr), sunset (ss), noon (n), and midnight (m) times are shown with arrows on the abscissa.

the auto- and cross-spectral power density (for brevity, power spectra) in a band of 0.5–3 h periods, with the help of the modified periodograms method (MPM) (Welch, 1967). According to this method, the initial record was divided into n short segments with $t_i = 6$ h (overlapped by a half of the 3-h segment). For each segment, we estimated the modified periodogram by introducing a time window of the $0.5(1 - \cos^2(t/t_i))$ type at $0 < t \leq t_i$. To calculate the spectra in more detail with respect to the frequency, we completed the spectrum with zeros up to 2048 points on this t_i interval. We determined the resultant power spectrum of the initial record by averaging the spectra calculated for short segments. It is known that the MPM decreases the power spectrum estimation variance at a specified duration of the initial record, increases it, and makes more stable, simultaneously decreasing the spectral frequency resolution (compare the spectrum in fragment 5 on the right and curve *5* in Fig. 3c). In our case, we selected $t_i = 6$ h in order to separate the harmonic with $T \sim 3$ h; in such a case, number n on the initial record with a duration of 12 h is equal to 3. To search for the relationship between the wave processes at different atmospheric altitudes and determine the location of their sources, we estimated the auto- and cross-spectral power densities by the MPM. The cross-spec-

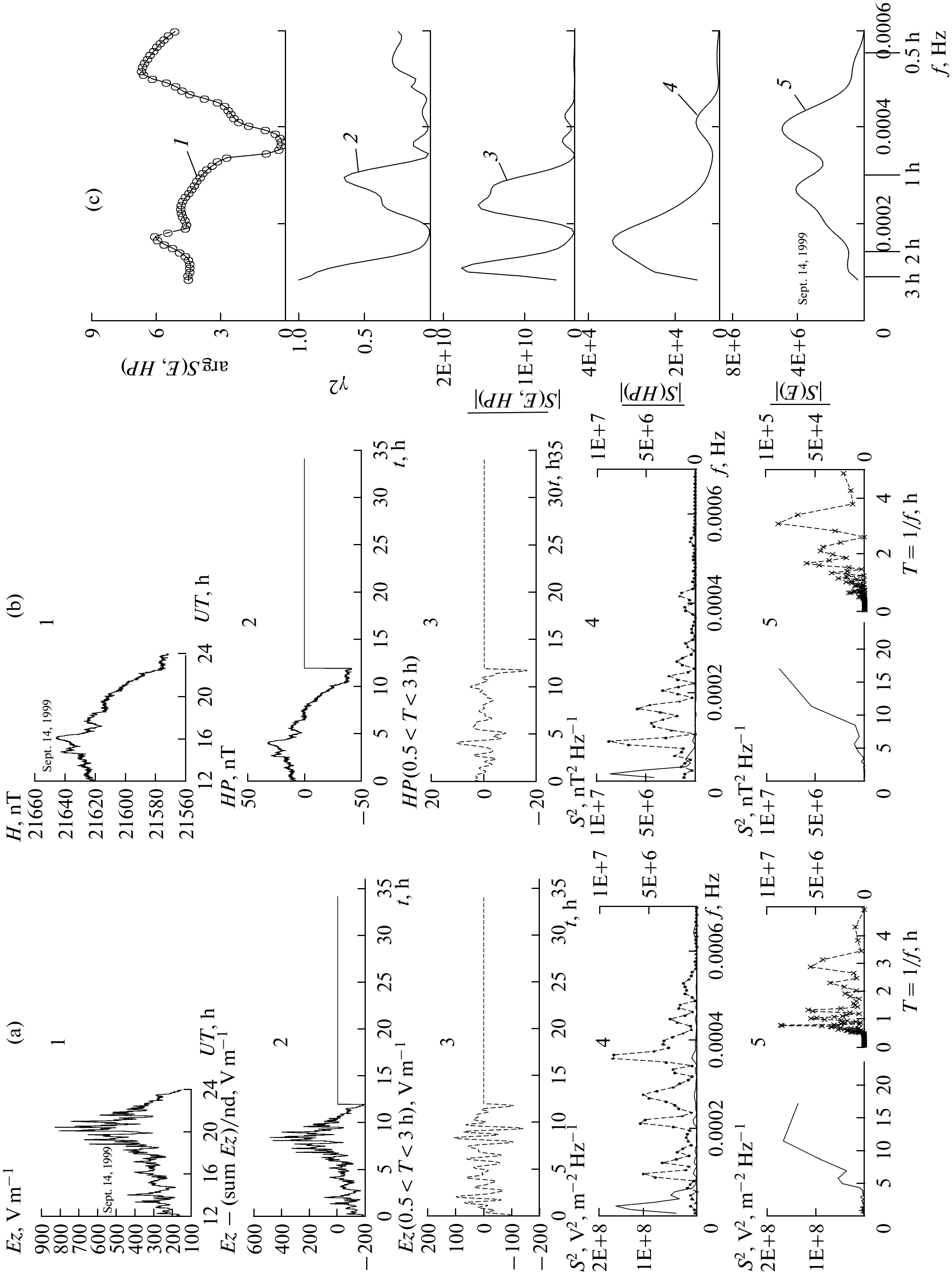

Fig. 3. Example of the spectral processing of simultaneous EFS records (E) and the geomagnetic field horizontal component (HP) in the 12–24 UT time interval, including sunrise (for more detail, see text).

trum of two processes (Bendat and Piersol, 1986) is determined as $Sxy(f) = |Sxy(f)|\exp(-j\theta xy(f))$, where the magnitude $|Sxy| = (\mathrm{Re}Sxy^2 + \mathrm{Jm}Sxy^2)^{1/2}$ and the argument $\theta xy = \arctan(\mathrm{Jm}Sxy/\mathrm{Re}Sxy)$. The cross-spectrum magnitude characterizes the contribution of individual sources to the cross-process, and its argument makes it possible to determine either one process is late or ahead of another one. In relative units, the relationship between two wave processes is characterized by the value of the coherence function squared: $\gamma^2(f) = |Sxy(f)|^2/(Sxx(f)Syy(f))$. The $\gamma^2(f)$ value is similar to the normalized correlation function squared at a given frequency. This value is small when the ratio of the useful signal to noise is small, two processes are not linearly related, and the second process (Y) depends not only on the basic process (X) but also on other sources (Bendat and Piersol, 1986). An example of the proposed method for processing initial records of the EFS and the HP component for the 12–24 UT period, including sunrise, is shown in Fig. 3c.

We accepted EFS oscillations as basic process X and HP and HB oscillations as process Y. It is clear that the oscillations in the $T < 1$ h and $T \sim 1$ h bands of periods, the intensity of which is substantially higher than that of oscillations with $T \sim 2$–2.5 h, predominate in the $S(E)$ autospectrum. At the same time, oscillations in the $T \sim 2$–2.5 h band of periods with weak oscillations at $T \sim 0.7$ h on the contrary predominate in the $S(HP)$ autospectrum. In the $S(E, HP)$ cross-spectrum, the latter oscillations are pronouncedly suppressed, and the coherence value is $\gamma^2 \sim 0.1$, which indicates that there is no relationship between the wave processes in the dynamo region and the near-Earth's atmosphere. Consequently, the source of EFS oscillations is located in the lower atmosphere.

Two other maximums in the cross-spectrum at $T \sim$ 2–2.5 and ~ 1 h with coherence coefficients of $\gamma^2 \sim 0.9$ and 0.6, respectively, indicate that the processes in the lower atmosphere and in the ionospheric dynamo region are correlated. The character of the cross-spectrum argument curve indicates that the source of these oscillations is located above the dynamo region in the first case (the argument is almost constant) and in the lower atmosphere in the second case (the cross-spectrum phase indicates that the process in the dynamo region is late of the process in the near-Earth's atmosphere).

3. MAIN RESULTS

The described spectral method was used to process simultaneous EFS, HP, and HB records at sunrise, sunset, and night. The resultant auto- and cross-spectra, averaged over several fair weather days in September 1999, are presented in Fig. 4: we used (a) 14 days at sunrise, (b) 7 days at sunset, and (c) 12 days at night. The rms deviations as a square root of the estimated variances are shown with vertical bars on the curves. An analysis of these spectra indicated the following:

The IGWs power in the {$S(E)$, $S(HP)$, $S(HP)$} auto- and {$S(E, HP)$, $S(E, HB)$} cross-spectra is mostly located in a band of 1.5–3 h periods with a pronounced maximum at $T \sim 2$–2.5 h. The presence of this oscillation band in the $S(E, HP)$ and $S(E, HB)$ cross-spectra with the coherence coefficients varying from 0.3 to 0.9 indicates that the processes in the lower atmosphere and at altitudes of the dynamo region are correlated but the source of these wave processes is located above the dynamo region according to an analysis of cross-spectra argument curves. The EFS power spectra (the lower curve in Fig. 4) represent the only exception. In addition to the oscillation band near 1.5–2 h, we distinguished here weaker oscillations with maximums at periods of $T \sim 0.8$ and 0.6 h, which are almost absent on the $S(E, HP)$ and $S(E, HB)$ cross-spectra. This indicates that the source of these oscillations is located in the near-Earth's atmosphere but their energy is insufficient for propagation to altitudes of the ionospheric dynamo region. For the maximum, which is present in the $S(E, HP)$ and $S(E, HB)$ cross-spectra near $T \sim 1$ h with the coherence coefficient varying from 0.2 to 0.7, the source of oscillations in the EFS spectrum was determined insufficiently with confidence. The cross-spectrum argument varies complexly (this is possibly related to the low-frequency resolution of the MPM) and points to either a remote source above the dynamo region or to a source in the lower atmosphere.

At night (08–14 UT), when the optical solar radiation is switched off but the corpuscular radiation is preserved, the character of the EFS auto-spectra slightly varies in shape, but the distinguished maximums are less intense than such maximums with periods of 12–24 h and, especially, at periods of $T \sim 0.6$ and 0.8 h. The $S(HP)$ and $S(HB)$ autospectra change more substantially during this period, increasing at $T \sim$ 1 h. This is possibly related to the appearance of substorm bursts, which are clearly defined in time variations in the geomagnetic field horizontal components, especially at $\varphi = 71°$ N (Barrow) (see Fig. 2).

At sunset (00–12 UT), one maximum at $T \sim 1.5$ h is clearly defined and the oscillations during periods shorter than 1 h are strongly suppressed on the EFS autospectra. This period more corresponds to daytime conditions in the atmosphere since the noon times at the Paratunka and Barrow observatories correspond to 0145 and 2205 UT, respectively (see Fig. 2). After noon, solar radiation becomes less intense and the air temperature correspondingly decreases. Figure 2 indicates that the character of time oscillations in the EFS and in the geomagnetic field horizontal components at $\varphi = 53°$ N and 71° N differs essentially. This is also observed in the auto- and cross-spectra of these oscillations. The character of oscillations in the $S(E, HP)$ and $S(E, HB)$ cross-spectra argument indicates that

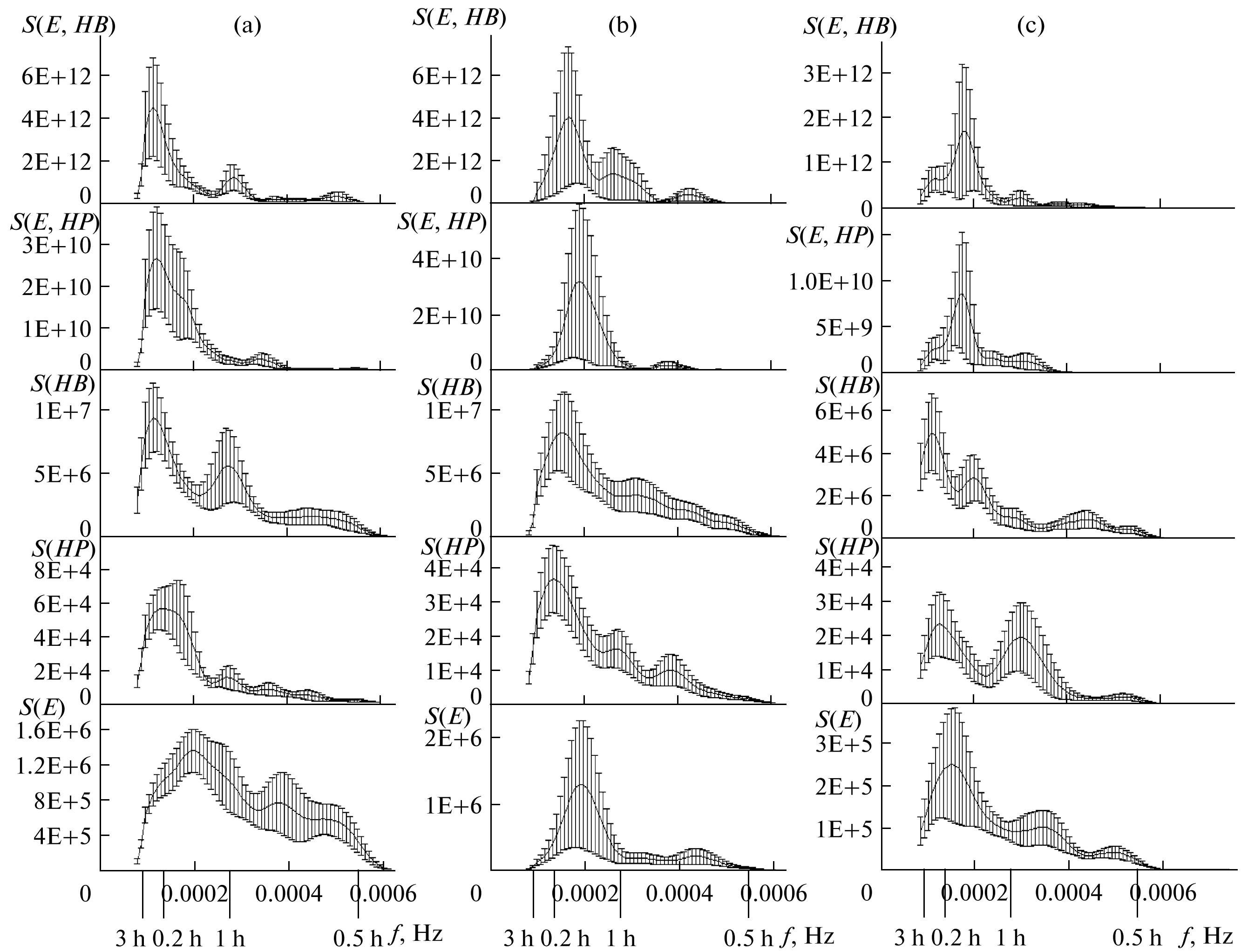

Fig. 4. Average power auto- and cross-spectra at (a) sunrise, (b) sunset, and (c) night. The vertical bars on the curves show the rms deviation.

the oscillations at $T \sim 2$–2.5 h are caused by a remote source, whereas the oscillations at ~1–1.5 h, which are present in the $S(HP)$ and $S(HB)$ auto-spectra and are absent in the EFS auto-spectrum, are caused by a source in the dynamo region or above it. However, the waves do not propagate into the lower atmosphere since they are weak.

Thus, an analysis of the auto- and cross-spectra of the EFS power in the near-Earth's atmosphere and the geomagnetic field horizontal component at $\varphi = 53°$ N and 71° N indicated that oscillations with $T \sim 2$–2.5 h are caused by a remote source, whereas oscillations with $T \sim 1$ h, which are detected in the lower atmosphere at night and sunrise, are possibly caused by the source in the dynamo region or higher. Oscillations with $T < 1$ h, which are only detected in the lower atmosphere, slightly penetrate to the dynamo region's altitudes.

When the neutral gas concentrations ([O] and [N_2]) were measured on the DE-2 satellite (Lizunov and Skorokhod, 2010), it was detected that a constant source of continuous AGWs is present at polar latitudes. These oscillations in the horizontal component at the Barrow observatory are actually more intense than at the Paratunka observatory (see Fig. 2).

4. DISCUSSION OF RESULTS

The sunrise effect in daily EFS variations is observed as a power spectrum extension toward shorter periods ($T < 1$ h) with considerable weakening of these oscillations in the evening and at night. This effect is insignificant in the HP and HB autospectra and in the EFS and geomagnetic field cross-spectra at latitudes of 53° N and 71° N, which indicates that IGWs slightly propagate to the dynamo region's altitudes at sunrise. At the same time, oscillations in the $T \sim 2$–2.5 h band, the intensity of which is maximal at sunrise, are constantly observed in the auto- and cross-spectra of the considered parameters during the

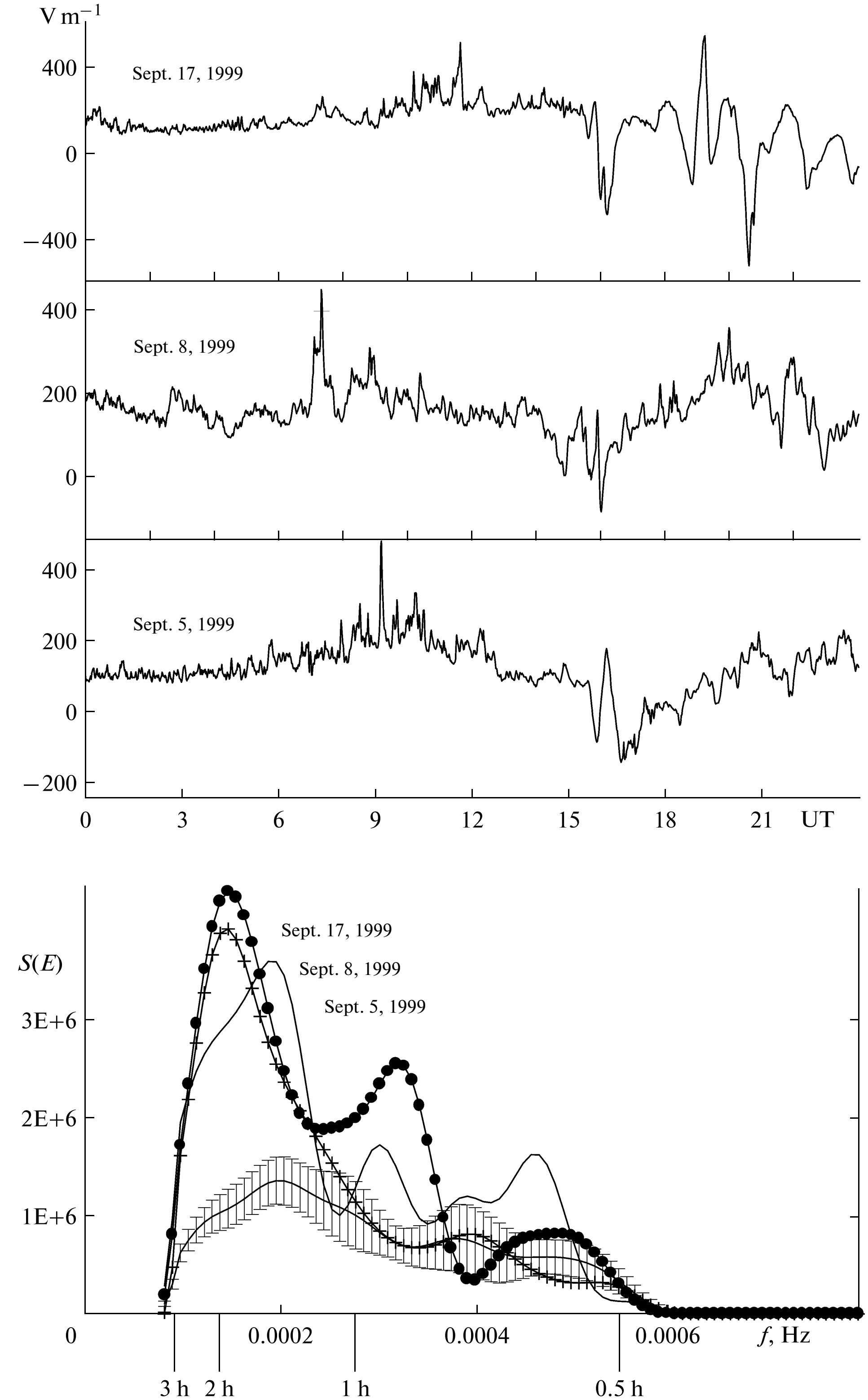

Fig. 5. Daily variations in the EFS with anomalies before the following earthquakes:
September 6, 1999 1504:52.81 UT $\varphi = 52.10°$ N; $\lambda = 159.15°$ E; $r = 55$ km; $M = 5.0$
September 9, 1999 1402:01.59 UT $\varphi = 47.51°$ N; $\lambda = 154.33°$ E; $r = 33$ km; $M = 5.6$
September 18, 1999 2128:33.17 UT $\varphi = 51.21°$ N; $\lambda = 157.56°$ E; $r = 60$ km; $M = 6.0$
(the top fragment) and their autospectra together with the averaged autospectrum at sunrise (the bottom fragment). The right ordinate axis corresponds only to the curve for September 17, 1999.

day. These oscillations were formerly observed in quasi-periodic variations in other geophysical parameters, e.g., in atmospheric pressure fluctuations, and at altitudes of the ionospheric *D* and dynamo regions (Mikhailov et al., 2008; Mikhailova et al., 2008). These oscillations are possibly caused by global oscillations in the Sun, which can affect the Earth's atmosphere through corresponding oscillations in solar radiation in the optical and corpuscular fluxes. A comparatively long time ago, it was detected (Severnyi, 1983) that oscillations in the Sun, such as a sphere with $T \sim 160$ min, are actually observed. This work indicated that such oscillations increase at sunrise.

As was indicated in the work, oscillations in the power spectra of the considered parameters near $T \sim 1.5$ h are caused by sources in the dynamo region or higher. Aleksandrov et al. (1992) indicated that these oscillations are caused by natural radial oscillations in the ionosphere with $T \sim 85.8$ (*D* region), 86.8 (*E* region), 87.6 (*F*1 layer), and 89.5 min (*F*2 layer). These oscillations manifest themselves in periodic compressions and expansions of the entire gas sequence and are expressed in a change in the gas density, pressure, and temperature.

The oscillations in the EFS power spectra in the $T < 1$ h band of periods include the range of the Earth's natural oscillations: $T \sim 57$ min (Garmash et al., 1989). These oscillations in the EFS variations at Kamchatka, which intensified during the earthquake preparation period, had been formerly detected in (Mikhailova et al., 2008). Moreover, it was indicated that intensified IGWs can propagate to altitudes of the *D* and dynamo regions but only during strong earthquakes (with a magnitude of $M \geq 6$). Therefore, it was interesting to compare the IGW intensity at sunrise and before an earthquake. For this purpose, we selected three earthquakes that occurred at Kamchatka in September 1999 at distances $r \sim 150–250$ km from the Paratunka observatory. The upper fragment in Fig. 5 presents the daily EFS variations before these earthquakes. It is clear that the EFS anomalies related to the earthquakes coincide with the sunrise periods (see Fig. 1, $t_{sr} \sim 18.7–19$ UT). At the same time, the individual auto-spectra of these variations, presented in the lower fragment of Fig. 5 together with the average autospectrum at sunrise, are in close agreement with each other. Specifically, a predominant maximum in the 2–2.5 band of periods and additional less intense maximums at periods $T \leq 1$ h are present in all spectra. According to the intensity, these maximums are of the same order of magnitude for sunrise and earthquakes with the $M < 6$ magnitude (the left scale), the energy of which was insufficient for propagation to altitudes of the dynamo region (Mikhailova et al., 2008b). This result makes it possible to conclude that IGWs oscillations, which are generated in the lower atmosphere at sunrise, also cannot penetrate to higher altitudes. This fact is confirmed by the absence of oscillations in the geomagnetic field spectra, observed at the Paratunka and Barrow observatories at sunrise. We assume that these oscillations in the lower atmosphere are caused by oscillations in the meteorological parameters at sunrise, i.e., by oscillations in the atmospheric temperature and pressure as a result of their modulation by solar radiation variations. The result achieved in the work disagrees with the conclusions drawn in (Kuznetsov and Cherneva, 2008). The oscillations at periods shorter than 1 h, detected by us, can probably be generated by the vortex motion of originating convective cells, which carry volume charges upward in the boundary atmospheric layer when the air temperature increases at sunrise. However, other sources of these oscillations are also possible.

5. CONCLUSIONS

The following phenomena were found in the power spectra of the quasi-static electric field strength in the Kamchatka near-Earth's atmosphere (Paratunka observatory) at sunrise:

1. The oscillations in the 2–2.5 h band of periods intensified.

2. The oscillations in the $T < 1$ h band of periods, the intensity of which is comparable with those of the IGWs intensity before weak earthquakes with magnitudes $M < 6$, intensified insufficiently for propagation to the ionospheric dynamo region's altitudes.

3. The oscillations in the argument of the EFS cross-spectra and the geomagnetic field horizontal component, which were simultaneously observed at the Paratunka and Barrow observatories, made it possible to establish that the sources of these oscillations are located in the lower atmosphere.

4. These oscillations can be caused by vortex motions of convective cells originating in the atmospheric boundary layer, which carry volume charges upward when the air temperature increases at sunrise. However, other sources of these oscillations are also possible.

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