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Influence of Meteorological and Wave Processes on the Lower Ionosphere during Solar Minimum Conditions According to the Data on Midlatitude VLF–LF Propagation

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Abstract—The statistical characteristics of the intensity of VLF–LF radio signals transmitted from the mid-latitude radio stations and recorded by the receiver at the Mikhnevo geophysical observatory (54.94°N, 37.73°E; Institute of Geosphere Dynamics, Russian Academy of Sciences) in 2007–2010 are analyzed. The experiments revealed strong variations in the intensity of radio signals during the deep solar minimum conditions, when the medium does not experience impacts from above associated with solar and geomagnetic activity. We relate the observed variations to the disturbances from below, which are caused by the meteorological and wave processes occurring in the lower atmosphere.

Keywords: radio propagation, lower ionosphere, meteorology, Rossby waves.

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INTRODUCTION

The lower ionosphere of the Earth, which extends from ~60 to 90 km in altitude, is the least studied ionospheric region to-date, as there are almost no means for its continuous monitoring. The reliable in situ observations during the launches of geophysical rockets have laid the foundations for physicochemical modeling of the medium and for developing theoretical models of ionization–recombination cycles (Kozlov, Smirnova, and Vlaskov, 1982; 1988; Krinberg et al., 1986; Turunen et al., 1996) and dynamical processes (Ginzburg, Gulyaev, and Zhalkovskaya, 1987; *Printsipy...*, 1989). However, the lack of data on the rate constants of chemical processes, the sharp variability and ambiguity (even as to the order of magnitude) in concentrations of minor (neutral and excited) atmospheric components, unfortunately, prevent deterministic description of the response of the lower ionosphere to the perturbations of various physical origin, both coming from above (and associated with the solar and geomagnetic activity) and those acting from below (from the middle atmosphere and lithosphere).

At the same time, the analysis of the VLF–LF propagation (3–30 kHz and 30–300 kHz, respectively) provides a unique opportunity to monitor the processes occurring in the lower ionosphere. The waves of these frequency bands propagate in the Earth–ionosphere waveguide, being reflected from the D-layer ionosphere in the daytime and from the bottom E-layer (in the height interval from 60 to 90 km) in the nighttime. Variations in the ionospheric electron conductivity in this height interval manifest themselves as changes in the intensity of the received signal. Due to the waveguide character of signal propagation in this frequency band (Wait, 1996) (in the Earth–ionosphere waveguide), the intensity of the signal at the receiving point depends on the geometry of the waveguide and, in particular, on the variations in the vertical profile of the ionospheric electron density, as well as on the parameters of the neutral atmosphere which control the collision frequency of electrons with neutrals and the attenuation of the signal in the medium.

The data on variations in the intensity of radio signals are used for identifying the processes in the lower ionosphere and middle atmosphere which are associated with various external impacts. In particular, these observations are one of the key issues in the research discussed in the present paper; namely, in the study of the variability of the lower ionosphere, which manifests itself in the variations in the intensity of LF–VLF signals during the deep solar minimum conditions. The knowledge of these background variations is necessary both for estimating the relative contributions of solar and geomagnetic activity and for interpreting the anomalous LF–VLF propagation in seismically active regions.

Presently, there are a series of VLF monitoring systems worldwide. Among the foreign systems, we mention the network operated by Stanford University, which is installed in Alaska, Antarctica, and mainland USA (Poulsen, 1991; Cohen, Inan, and Paschal, 2010) and the observation sites in India (Cumar, 2009; Singh et al., 2010). The SAVNET network is deployed in South America (Raulin, Bertoni, and Rivero, 2009; Raulin et al., 2010). The 77.5-kHz radio transmissions from the DCF77 LF radio station located in Germany are monitored by the Astronomy Observatory in Nikolaev (Ukraine, www.mao.nikolaev.ua/rus/ion_r.html). The high-latitude observatories of the Polar geophysical institute of the Kola Science Center of the Russian Academy of Sciences carry out VLF monitoring. At present, the VLF transmissions from the Alpha radio navigational system are monitored at a frequency of 11.9, 12.6, and 14.9 kHz at the Gor'kovskaya observatory at St. Petersburg University (http://rns-alpha.niirf.spbu.ru/index.html).

Measurements at the observation sites mentioned above are conducted at fixed frequencies, mainly in the VHF band. The key objectives of this work are to verify the models of VLF–LF propagation; to construct empirical models of the lower ionosphere; and to determine the intensity of natural radio-frequency noise for practical applications (Fergusson, 1991; 1992; 1995; Tomko and Hepner, 2001). Another research task is to study the sudden ionospheric disturbances (SIDs) caused by thunderstorm lightning activity, discrete precipitation of high-energy charged particles, development of sprites (large-scale electric discharges high above the thunderstorm clouds), solar X-ray flares, and even such exotic events as cosmic gamma-ray bursts (Raulin, Bertoni, and Rivero, 2009). Monitoring of SIDs is also conducted by a series of amateur radio stations worldwide.

Generally, a great number of continuously broadcasting high-power transmitters provides a unique possibility for global monitoring the lower ionosphere and the middle atmosphere, which is physically closely associated with it.

In some works, the observations of VLF transmissions are used for searching for the precursors of earthquakes (Gufeld et al., 1988; Buchachenko et al., 1996; Molchanov and Hayakawa, 1998; Hayakawa and Molchanov, 2000; Poddel'skii and Poddel'skii, 2004; Slivinskii et al., 2006). These authors consider anomalous VLF propagation in seismically active regions as a result of the preparation of an earthquake.

The Mikhnevo geophysical observatory (MGO) of the Institute of Geosphere Dynamics of the Russian Academy of Sciences (IGD RAS) carries out VLF–LF radio monitoring. To date, the database of continuous measurements covers the period from October 2007 to the present time. The observations were launched in the period of a deep solar minimum. As MGO is located far from the regions of intense thunderstorm activity and high seismicity, the variations in the radio signals recorded at MGO are likely associated with the diurnal rhythms in the ionization of the ionosphere by solar radiation, the seasonal changes in the neutral atmospheric composition, and, probably, SIDs. At the same time, variations in thunderstorm activity may induce changes in the noise level in the corresponding frequency bands. Therefore, the deviations in the intensity of the observed radio signals from the expected pattern of temporal behavior are associated with impacts acting from below; in particular, they are contributed by perturbations of meteorological origin, which develop in the middle atmosphere or come from below (from the troposphere of the Earth), due to the large-scale dynamical processes.

Recently, such disturbances have become the focus of considerable research. The signatures of the acoustic-gravity waves (AGWs) were detected in the scintillations of GPS radio signals (Alexander, De la Torre, and Llamedo, 2008; Nath et al., 2009). The experimental study that included reanalysis of the 45-year time series of observations by the Arecibo incoherent radar supported by the numerical simulations showed that the wave disturbances have been transferred from the lower atmosphere to the ionosphere, and the oceanic waves were the primary source of the AGWs (Djuth et al., 2010; Vadas and Crowley, 2010). During geomagnetically quiet conditions, the temperature oscillations in the stratosphere were demonstrated to have strongly affected the undisturbed ionosphere (Chau et al., 2010; Conde and Nicolis, 2010). Excitation of the wave motion in the middle and upper atmosphere by the nonlinear interaction of the tidal waves in the troposphere was demonstrated by Hagan, Maute, and Roble (2009). Goncharenko et al. (2010a; 2010b) revealed the relationship between the disturbances in the high-latitude winter stratosphere (at an altitude of ~30 km) and low-latitude ionosphere (in the height interval from 200 to 1000 km) during the solar minimum.

In this work, we present new experimental results and theoretical estimates of the influence of the meteorological parameters and wave processes occurring in the middle atmosphere on the lower ionosphere and VLF–LF radio propagation.

THE GEOPHYSICAL CONDITIONS AND THE TECHNIQUE OF MEASUREMENTS

Radio monitoring at the MGO IGD RAS was conducted using the ESMB Rohde & Schwarz ESH-3 monitoring receiver and a vertical antenna 20 m in height. The measurements were carried out in a frequency scan mode with a bandwidth of 200 Hz in the frequency range from 9 to 300 kHz. The dynamic range of the receiver is 30–137 dBμV. The scanning time of a 200-Hz band was 50 μs, and the total scanning time of the entire frequency range was 2 min 30 s. With allowance for the time necessary for recording the information, the average interval between the measurements at a given frequency during a day was about 4 min. At some observation intervals, the scan-

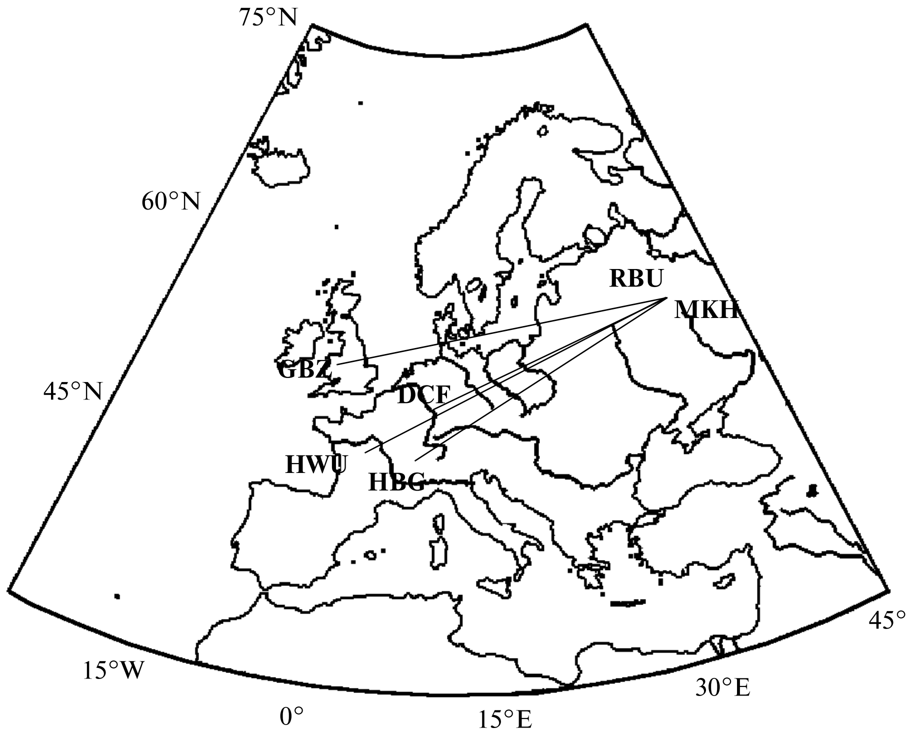

Fig. 1. The layout of the paths of VLF–LF monitoring.

ning frequency range was reduced, which halved the time interval between the successive measurements. Measurements were conducted in the round-the-clock mode except for the periods of switching the instruments in the mode of recording the amplitude at a fixed frequency and scanning within narrow frequency bands (beyond the frequency range of the transmitters) in order to measure the intensity of natural radio noise caused by thunderstorm activity. In July and August 2008, the measurements were suspended due to the failure of the instruments. The total data capacity of the database is ~100 000 measurements at each frequency. The ESMB receiver provided the root mean square (rms) amplitude of the carrier frequency.

The European radio stations that were used as the reference radio transmitters are listed in the table, and their locations are shown in Fig. 1. Among all the listed radio stations, only the LF-broadcasting HBG (75 kHz) and DCF77 (77.5 kHz) transceivers pertain to the civil network emitting the time code, for which the parameters of the transmission are known exactly. All the other European VLF–LF stations monitored at MGO are components of the NATO-operated network intended for communication with submarines. Their energy parameters are known only approximately (the values cited by various sources differ severalfold). Nevertheless, the range of variations in the amplitudes of radio signals transmitted by these stations almost did not change during the discussed period of observations. We note that, besides the transmitters listed in the table, there are dozens of stations broadcasting in the frequency range scanned with a step of ~0.5–1 kHz. However, most of these stations are switched on in a random mode; therefore, they cannot be used for studying geophysical effects in radio propagation.

As it can be seen, the propagation paths for all stations are located in the middle latitudes; the signal path from GBZ station partly passes oversea (Fig. 1). According to the commonly adopted theoretical models of VLF–LF propagation, the variations in the intensity of the signals transmitted by all stations except for RBU are probably associated with the variations in the ionospheric parameters, while the radio signal from the RBU station is unlikely to depend upon the state of the propagation medium.

In the interval from October 2007 to April 2009, according to the data of the World Data Center for Geomagnetism in Kyoto (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec1.html), the average Ap index was 6 ± 5 days. There were no days with Ap > 40 (which would mean geomagnetic storms). The solar activity was low. The average F10.7 was 69 ± 4 with a maximum value of 94. Overall, 14 X-ray C-class flares and 1 M-class flare occurred; there were no X-class events. In the optical range, there were 31 flares of optical importance 1; 4 flares of importance 2; 3 flares of importance 3; and no flares of importance 4. Thus, indeed, the observations over the period of study were free of any noticeable natural disturbances associated with solar activity. As it has been already mentioned, this indicates that the variations in the strength of the signals should have reflected only the diurnal and seasonal changes associated with the varying solar illumination of the radio paths.

The observations at MGO during quiet conditions (Egoshin et al., 2010) showed that the amplitudes of the signals rather widely varied both during a day and in the course of days. Three types of the anomalies were distinguished: (1) disruption of the typical (normal or regular) pattern of diurnal variations, (2) stepwise change in the maximal or minimal amplitudes with an undisturbed normal pattern of diurnal variations during a few (typically, 1–2) days, and (3) long-period oscillations of the envelope of amplitudes with an unchanged pattern of diurnal variations.

The day-to-day variations in the amplitudes of the signals coming to the receiver from all the monitored radio stations can attain and even exceed 10 dBμV. Qualitatively, the dynamics of the diurnal variations during the anomalous days resembles the changes caused by the passage of the solar terminator (Kumar, 2009). This fact probably points to the noticeable perturbations in the lower ionosphere and the changes in the geometrical parameters of the waveguide.

The statistical analysis of the variations of the signals for 2007–2009 (Egoshin et al., 2010) revealed a severe discrepancy between the seasonal variations of the signals transmitted by the VLF stations (GBZ and HWU) and those transmitted by the LF stations (RBU, HBG, and DCF). The minimal amplitudes on the LF paths were observed in May and June, while the amplitude of the signals on the VLF paths was minimal in August. The amplitudes of the signals transmitted from VLF stations have a local maximum in October; such maximum is absent in the LF signals transmitted by the RBU and DCF stations although it is observed in the LF transmissions by the HBG station.

The temporal dynamics of the LF signal of the RBU station, which is located close to the Mikhnevo receiver (at a distance of about 100 km), is of particular interest. Qualitatively, the dynamics of this signal follows the behavior of the amplitude of the LF signals transmitted by the HBG and DCF stations, which are located much farther from the receiver (at a distance of ~2000 km): during the studied time interval, the peak-to-peak amplitude of the variations was ~20 dBμV. The present-day theoretical models of the lower ionosphere prohibit any noticeable systematic variations over such short distances.

Variations in the amplitudes of the radio signals indicate that the radio physical parameters of the lower ionosphere vary. Since the external causes of these changes are excluded, as it has been mentioned above, the only source is the processes occurring in the middle atmosphere, which affect the radio propagation. The radio physical properties of the ionosphere can be affected by the varying composition or the structure of the middle atmosphere, as well as by some dynamical phenomena that develop there.

THE INFLUENCE OF METEOROLOGICAL PARAMETERS OF THE MIDDLE ATMOSPHERE ON RADIO PROPAGATION

In order to analyze the effects of the composition and the structure of the middle atmosphere, which manifest themselves in the variations of meteorological parameters, we compare the parameters of the middle atmosphere measured by the EOS-Aura satellite (Waters et al., 2006) (vertical profiles of temperature and water content) with the data of observations. The temperature governs the neutral collision frequency and the rate constants of the chemical processes, and the water content determines the production rate of cluster ions, which directly controls the electron concentration. From all the observations, we selected the measurements that were closest to the point where the signal path intersected the satellite orbit (to be more exact, to the point where the height profiles of the atmospheric parameters were measured). The individual measured profiles were accumulated and then compiled into a database, which contains a time series of such profiles for each propagation path. On average, on each path, from one to three measurements per day were conducted (with one or two measurements in the nighttime and one or two measurements in the daytime). The actual time of observation was specific to each case of measurement.

Since it is impossible to directly compare the temporal dynamics of the scalar amplitude of the radio signal with the vertical profile of atmospheric parameters, we selected the following procedure of the analysis. For a given propagation path, we represented the height distributions of temperature and water content as the functions of time. For a contrasting visualization, the data were converted into the rank values by a standard technique.

For the analyzed propagation path, the probability density of the amplitude of the signal was calculated for each day according to the method suggested in (Botev, Grotowski, and Kroese, 2010). The amplitudes were converted into the rank values, and the derived probability densities were represented as the functions of time in the same fashion, as was done for the height profiles of temperature and water content.

The variations in the height profile of temperature of the neutral atmosphere on the GBZ–Mikhnevo path and the temporal evolution of the probability density of the amplitude of radio signals for 2008–2009 are presented in the top and bottom panels of Fig. 2, respectively. The temperature profile experiences noticeable variations during the winter months. The graphs in the bottom panel show that during the same periods, the probability density of the amplitude bifurcates and becomes bimodal. The observed

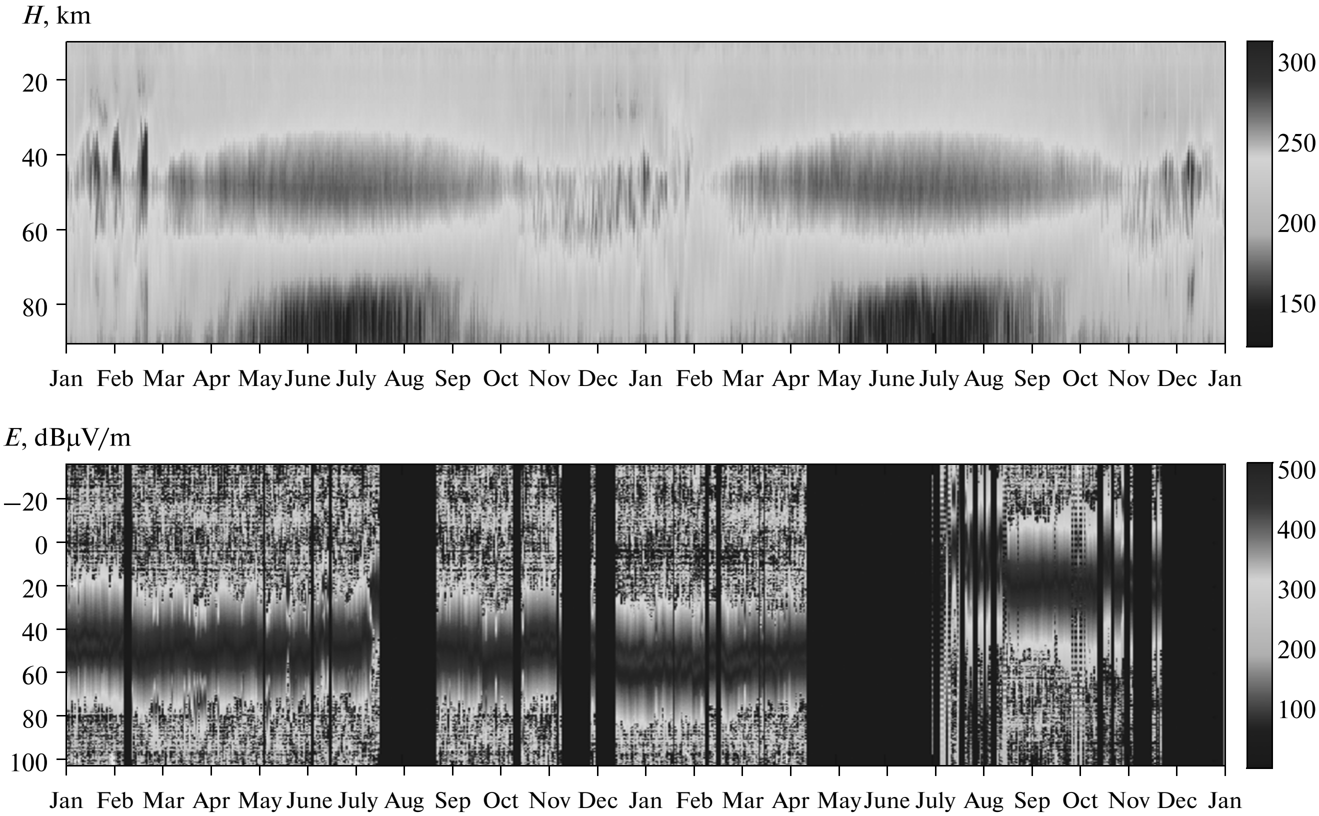

Fig. 2. (top) The variations in the height profile of air temperature on the GPZ–Mikhnevo path; (bottom) the probability density of the amplitude of the VLF signal transmitted from the GBZ station for 2008–2009.

dynamics of the radio signal amplitude is qualitatively consistent with the theoretical model of transient bimodality proposed by Nicolis and Prigogine (1989). In this regime, the behavior of amplitude is largely random: the discrepancy between the average and the most probable value sharply increases. Prigogine named the regime of transient bifurcation as the temporal development of bifurcation. In the context of the modal analysis (Wait, 1996), bifurcation can be considered as a continuous stepwise switching between the fundamental modes of the propagating radio wave, which is caused by the variations in the radio physical properties of the medium.

The evolution of the probability density of the LF signals from the DCF and HBG stations demonstrated the transition to bimodality; however, this transition is less pronounced during the periods when the secondary maximum appears at a height of 70–80 km in the vertical profile of the atmospheric water content (Fig. 3). The variations in the temperature profiles do not cause bimodality in the LF range. Previously, Raulin, Bertoni, and Rivero (2009) proposed to distinguish the C-layer in the ionosphere, which is characterized by strong pulsations in temperature at an altitude of 40–50 km, which are correlated with the anomalies in the VLF propagation in the equatorial region. The observations at the MGO support the results obtained at the SAVNET network and supplement them with a requirement to take into account the water content in the middle atmosphere.

In order to quantitatively estimate the probable implications of the day-to-day variability of the meteorological parameters of the middle atmosphere for VLF–LF radio propagation, we use the following simplified scheme of photochemical processes in the D-layer, similar to the one described in (Tomko et al., 1980). We consider the ionosphere composed of the ions NO^+, O_2^-, CB^+, and CB^- and electrons. Here, CB^+ and CB^- are positive and negative cluster ions, respectively.

$$\frac{d[NO^+]}{dt} = q - 4\times10^{-7}\left(\frac{300}{T}\right)^{1/5} \times [NO^+]N_e - B[NO^+] - 10^{-7}[NO^+]\left([O_2^-] + [CB^-]\right);$$

$$\frac{d[CB^+]}{dt} = B[NO^+] - 2\times10^{-5}[CB^+]N_e - 10^{-7}[CB^+]\left([O_2^-] + [CB^-]\right);$$

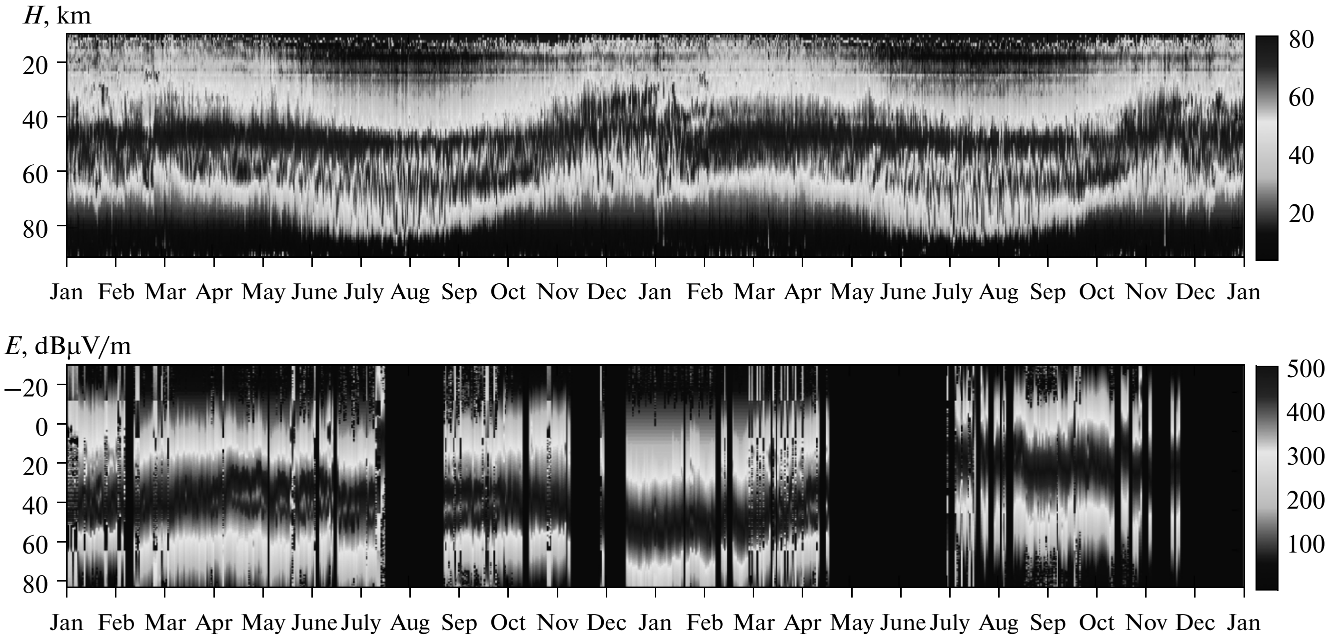

Fig. 3. (top) The variations in the height profile of water content on the GPZ–Mikhnevo path; (bottom) the probability density of the amplitude of LF signal transmitted from the HBG station for 2008–2009.

$$\frac{d[O_2^-]}{dt} = 1.4\times10^{-29}\left(\frac{300}{T}\right)\exp\left(-\frac{600}{T}\right)[O_2]^2 N_e - 0.33[O_2^-] - 6\times10^{-10}[O_3][O_2^-] - 10^{-7}[O_2^-]\left([NO^+]+[CB^+]\right) - 4\times10^{-31}[O_2]^2[O_2^-];$$

$$\frac{d[CB^-]}{dt} = 6\times10^{-10}[O_3][O_2^-] + 4\times10^{-31}[O_2]^2[O_2^-] - 10^{-7}[CB^-]\left([NO^+]+[CB^+]\right);$$

$$\frac{dN_e}{dt} = \frac{d[NO^+]}{dt} + \frac{d[CB^+]}{dt} - \frac{d[O_2^-]}{dt} - \frac{d[CB^-]}{dt};$$

$$B = 1.8\times10^{-28}(308/T)^{4.7}[H_2O][N_2] + \frac{2\times10^{-31}(300/T)^{4.4}[N_2]^2\times10^{-9}[H_2O]}{C} + \frac{10^{-9}[H_2O]}{3.1\times10^4 T^{-4}\exp(-4590/T)[N_2]+10^{-9}[H_2O]} \times\left(7\times10^{-30}(300/T)^3[CO_2][N_2] + \frac{2\times10^{-31}(300/T)^{4.4}[N_2]^2\times10^{-9}[CO_2]}{C}\right);$$

$$C = 1.5\times10^6 T^{-5.4} \times\exp(-2450/T)[N_2] + 10^{-9}\left([CO_2]+[H_2O]\right).$$

These equations allow for practically all aeronomic processes that are important in the D-region: ionization of the atmosphere by solar radiation and cosmic rays, photodetachment of electron from O_2^-, reactions of the transformation of NO^+ and O_2^- into complex positive and negative cluster ions, attachment of electrons to O_2, in triple collisions, and dissociation and ion–ion recombination. Only the photodetachment of electrons from CB^- is excluded due to ambiguity in the type of the end-ion species and in the corresponding rates of photodetachment. The rate constants of the reactions and their temperature dependences are included in the equations and are commonly accepted.

The initial data for the calculations are the parameters of the neutral atmosphere $[N_2]$, $[O_2]$, and $[CO_2] = 0.039\times10^{-2}([N_2]+[O_2])$. The vertical profiles of the water content, ozone, and neutral temperature are retrieved from the satellite observations. The ionization rate for the daytime midlatitude conditions ranges from 0.3 $cm^{-3}\,s^{-1}$ at an altitude of 50 km to 40 $cm^{-3}\,s^{-1}$ at an altitude of 85 km. The height interval of the calculation spans from 50 to 85 km. The calculations are carried out for two close days. On January 1, 2010, the profiles of the parameters were measured on the DCF77–Mikhnevo path at 11:00 UTC, and on January 3, measurements were carried out at 14:28 UTC. The height profiles of the temperature of neutral atmosphere and water content are shown in Fig. 4. The profiles of electron concentration and

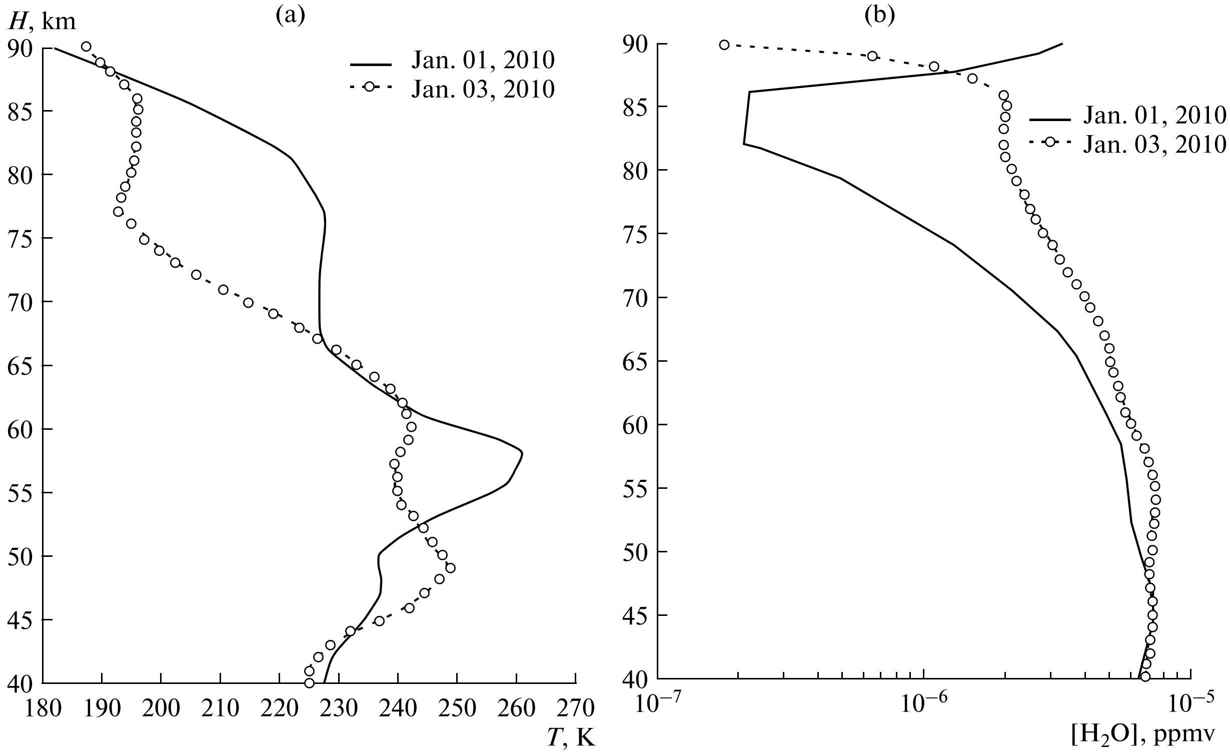

Fig. 4. The height profiles of (a) temperature of neutral atmosphere and (b) water content measured by the EOS-Aura satellite on the DCF77–Mikhnevo path.

electron-neutral collision frequency were used to calculate the spatial dependency of the amplitude of the signal from DCF-77 by the LWPM computer program (Fergusson, 1992).

The results of the calculations are presented in Fig. 5. The inset shows the profiles of electron density. The difference in the amplitude of the signal at the receiving site was ~5 dBμV/m. It is clearly seen how the observed day-to-day variations in the parameters of the middle atmosphere are reflected in the changes of the value of the signal. Besides, for the first day, we used 31 modes in order to calculate the field, whereas the number of the required modes for the second day was increased up to 38. The calculated coefficients of attenuation for various modes are shown in Fig. 6. We see that the transition from TM to TE modes occurs later and, more important, the seemingly small variation in the height profile of the electron concentration causes the attenuation of the lowest (i.e., the most important) modes to change severalfold! The physical peculiarities of the VLF–LF propagation and the close connection between the geometry of the Earth–ionosphere waveguide and its filling, on one hand, and the spatial structure of the field, on the other hand, make the recorded amplitude dependent on the meteorological parameters.

THE SPECTRAL PROPERTIES OF RADIO SIGNALS DURING DISTURBED PERIODS AND DYNAMICAL PROCESSES IN THE ATMOSPHERE

The intervals when the normal diurnal behavior is violated occur during any months. Let us thoroughly inspect one of such cases observed in August 2009. Figure 7 presents the recorded amplitudes of radio signals transmitted by the DCF (77.5 kHz, top panel, the thin line) and HBG (75 kHz, upper panel, the thick line) stations and by the stations not indicated in the table, namely TBB (26.7 kHz, 37.41°N, 27.32°E, middle panel, the thin line), NSY (45.9 kHz, 37.12°N, 14.43°E, middle panel, the thick line), GBZ (19.6 kHz, bottom panel, the thin line), and GQD (22.1 kHz, 54.73°N, 2.88°W, bottom panel, the thick line). The disturbances started in the evening of August 17. Before that time, the signals at all stations showed a normal (regular) diurnal behavior of the amplitudes. The earliest manifestations of the disturbances appeared in the LF band (on the signal paths to Germany and Switzerland); shortly after it, the disturbances developed in the VLF and lower LF bands (on the paths to Italy and Turkey). The VLF disturbances on the paths to Britain (GQD and GBZ) lagged several hours.

The recorded amplitudes were subjected to spectral analysis by Lomb's method (Press et al., 2001). The periodogram for the LF signal of the DCF transmitter

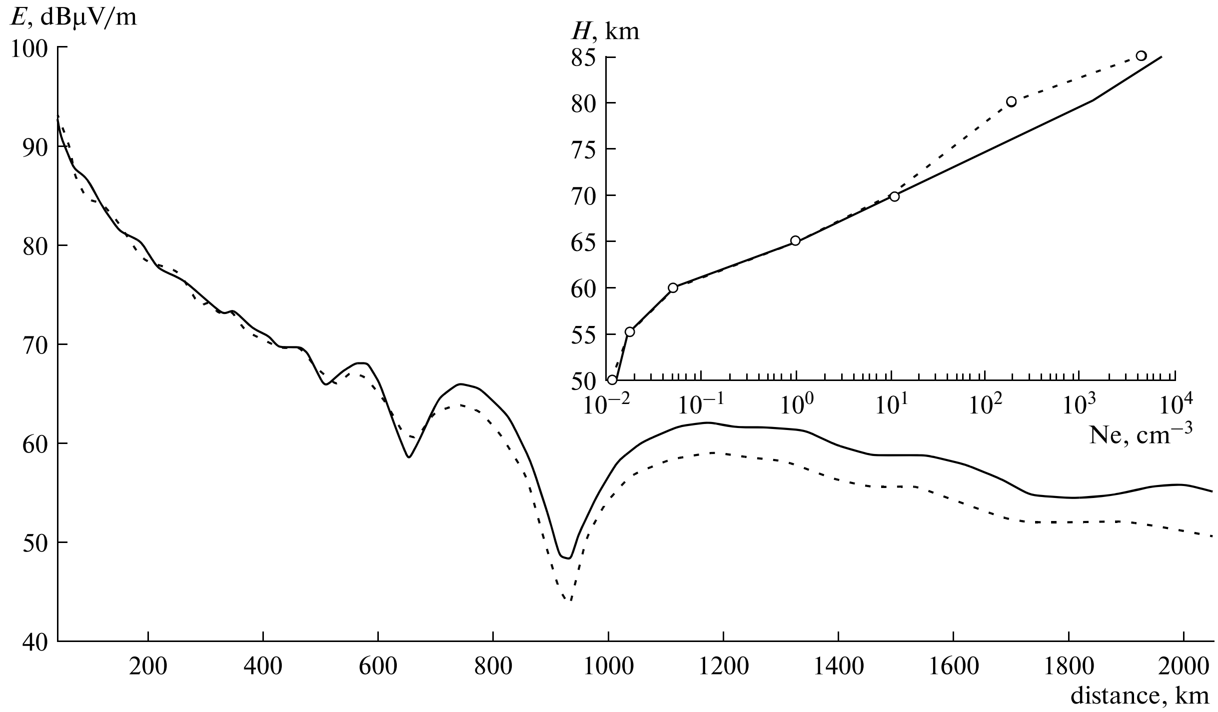

Fig. 5. The variations in the spatial amplitude of the field of DCF77 radio signal for different vertical profiles of electron density (shown in the inset).

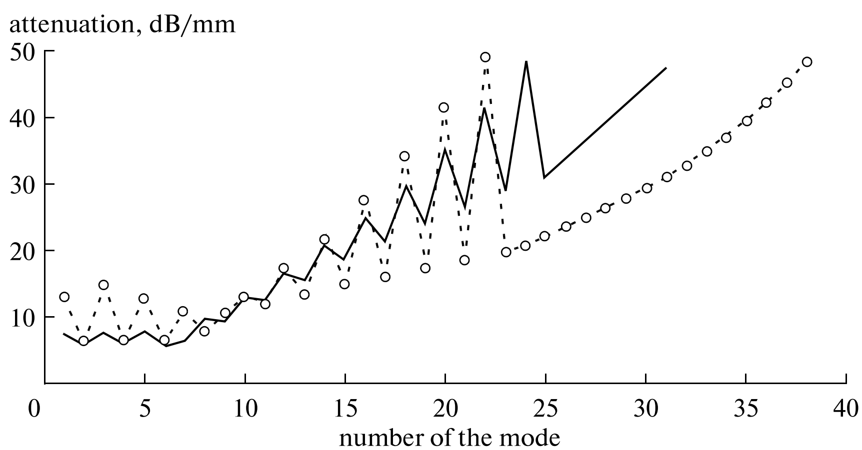

Fig. 6. The variations in the radio wave attenuation as a function of the number of the mode during rearrangement of meteorological parameters of the middle atmosphere.

is shown in Fig. 8 (the inset presents the periodogram for the preceding days). Before August 17, 2009, the spectra only contain a diurnal period and a weaker semidiurnal period. The spectra for the days with anomalous changes in the signal contain the periods at 1.5–3 days, 4–7 days, and ~20 days, which are statistically confident at a level of significance of $\alpha < 0.001$. The periodograms of the signals from other stations are similar to those shown in Fig. 8. The dependence of the identified periods (in days) on the transmitter frequency is displayed in Fig. 9. Here, we selected only the four strongest spectral peaks; generally, there were four to seven peaks altogether.

The identified periodicities are well known in meteorology; they are related to dynamical processes occurring in the atmosphere. The period of 1.5–3 days is associated with the passage of anemobaric formations; the period of 5–8 days is a natural synoptic period; and the period of 8–11 days is the period of oscillations of the baric centers of the Icelandic mini-

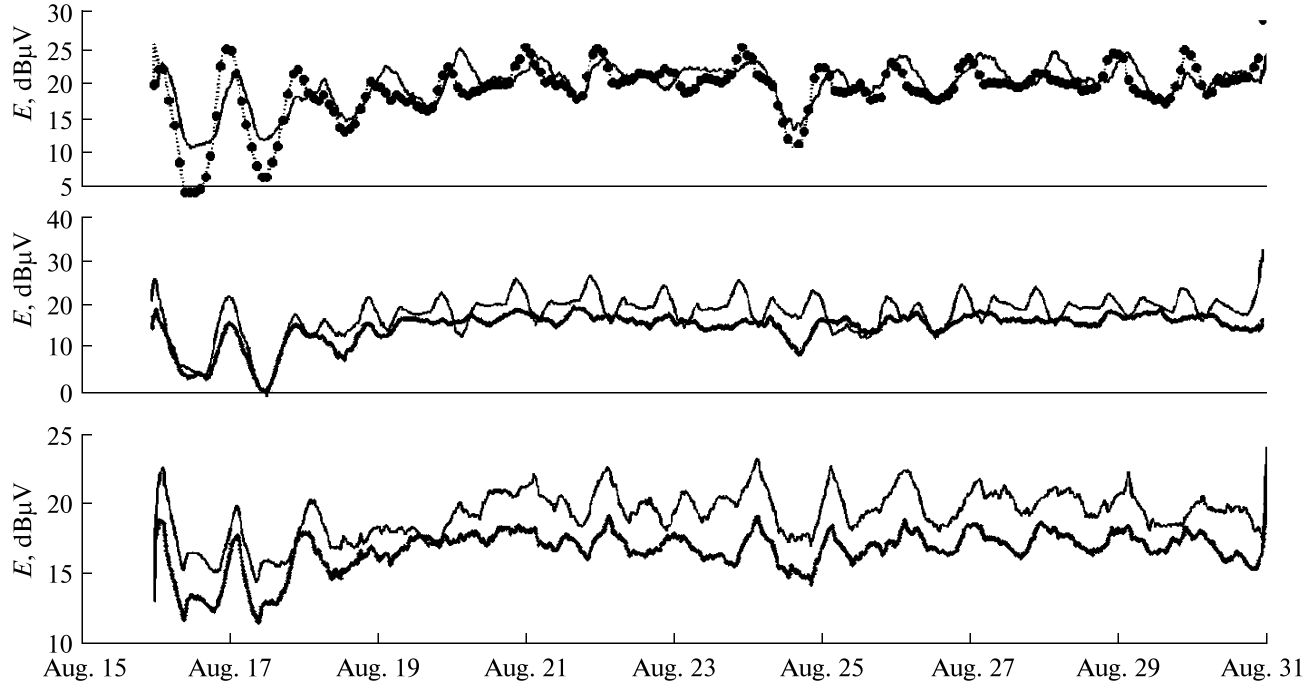

Fig. 7. Violation of the regular diurnal behavior of the signals transmitted by LF–VLF radio stations in August 2009.

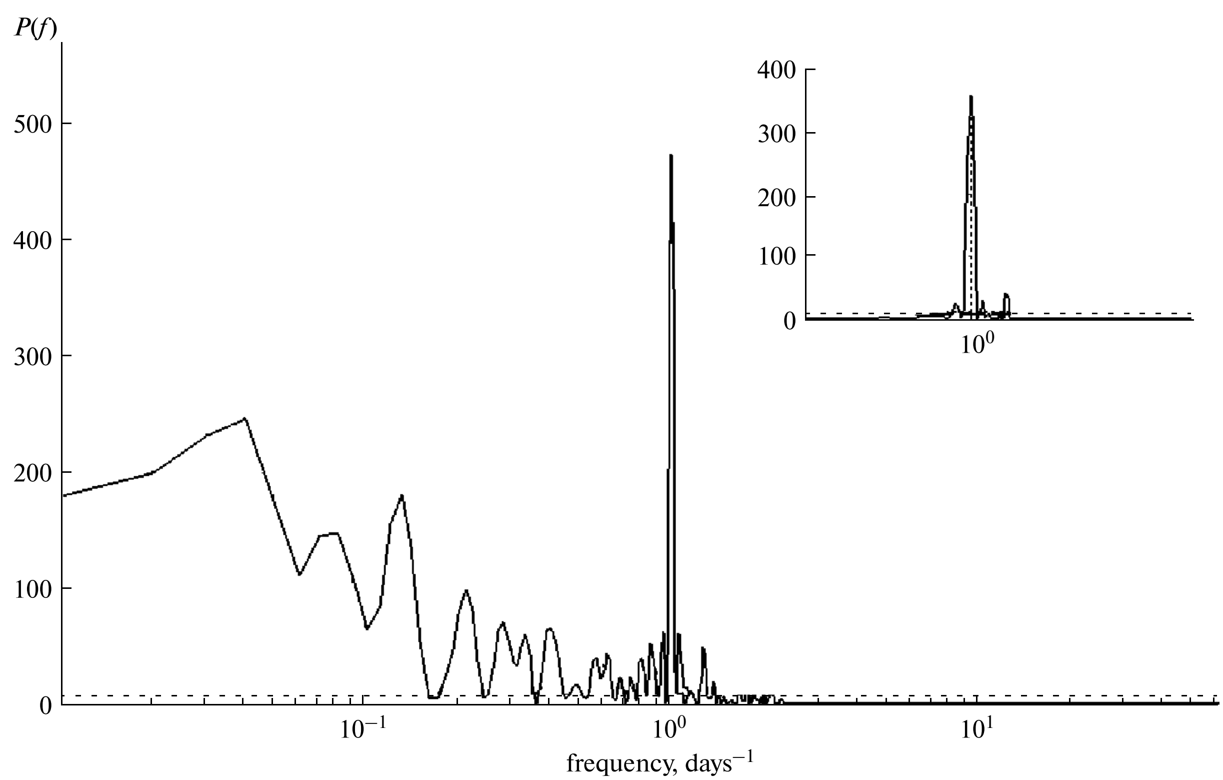

Fig. 8. The Lomb periodogram of the amplitude of the signal of DCF station in August 2009.

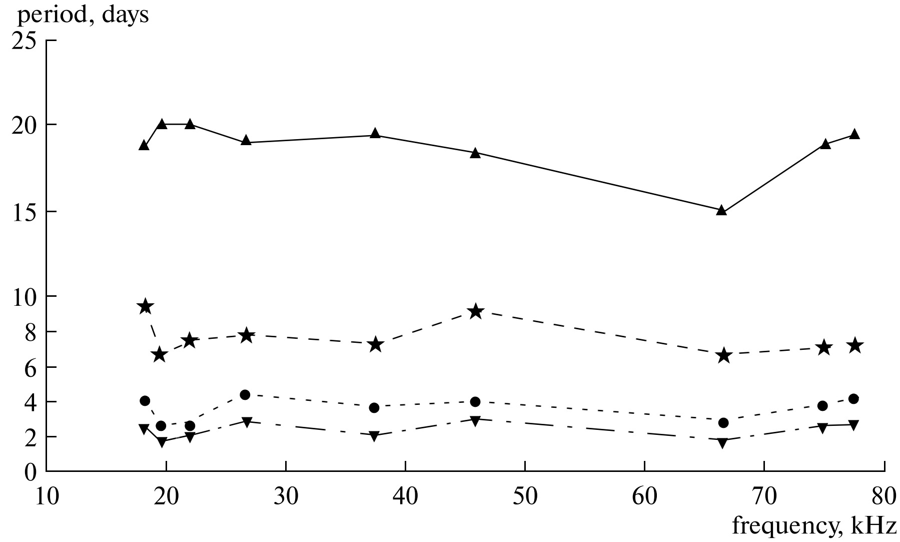

Fig. 9. The periods of oscillations identified in the signals of VLF–LF transmitters in August 2009.

mum and the Azores maximum, which cause changes in the trajectories of the cyclones and anticyclones.

The identified periods are close to the normal-mode Rossby waves (~2, 5, and 10 days). Previously, the periodicities of the Rossby waves were recognized in the variations of the midlatitude sporadic E-layer in the ionosphere (Haldoupis, Pancheva, and Mitchell, 2004). A period close to 20 days is revealed in the spectrum of the planetary waves (Fedulina, Pogoreltsev, and Vaughan, 2004). Based on the reanalysis data of the European Center for Medium-Range Weather Forecasts, the authors of the latter work showed that waves with a period of 4–6 days are observed in a time interval of ~10–15 days, which corresponds to the periods of anomalous diurnal behavior of the signals from LF–VLF radio stations identified in our work. The spectral analysis of the anomalous records during other months and years revealed harmonic components with similar periods. During quiet intervals, only the diurnal and semidiurnal harmonics are statistically confident at all frequencies and on all propagation paths.

According to the data of the European Center for Medium-Range Weather Forecasts (www.ecmwf.int), high-pressure air masses passed over the Western European region during the period from August 16 to 31, 2009. This high-pressure area was formed on August 16 above the western coast of France. This area strongly varied in shape and intensity; its passage and interaction with the cyclones over the northern Atlantic and Scandinavia, which were active at that time, might have generated the wave motion in the middle atmosphere, and this motion might have disturbed the radio physical properties of the medium and affected the propagation of radio waves.

The supplementary analysis of the VLF–LF transmissions from the French A118 station (http://sidstation.loudet.org) revealed similar effects: violation of the diurnal behavior, bimodal pattern of the probability density of the amplitudes of the signals, and the presence of the spectral components corresponding to planetary waves. In addition, it was established that the bimodality of the probability density of the amplitudes occurs on the west- and east-oriented propagation paths; however, it is almost absent on the strictly north-to-south paths, as well as on the paths of south-eastern orientation. The effects of bimodality develop during the periods of sharp variations in the height profiles of temperature and water content in a neutral atmosphere, which are identified from the EOS-Aura satellite observations.

CONCLUSIONS

Continuous three-year monitoring of the VLF–LF radio propagation at the Mikhnevo observatory on the paths from the European transmitting stations shows that during the conditions of minimum geomagnetic disturbances the amplitude of the radio signal experienced variations attaining 10–20 dBμV throughout the entire frequency band of the transceivers (from 18.3 to 77.5 kHz). According to the numerical calculations, these jumps in the amplitude are caused by the variations in temperature and water content in the middle atmosphere recorded by the EOS-Aura satellite.

During the intervals when the normal diurnal behavior of the amplitude of radio signals was violated, the time series of the signals contained harmonic components corresponding to the periods of planetary waves.

Our results together with the results obtained by the other authors indicate that the ionosphere not disturbed by solar activity responds in a regular fashion to the processes controlled by the meteorological and wave phenomena in the middle and lower atmosphere. This calls for the elaboration and improvement of the models of the lower ionosphere, which, as of now, do not allow for dynamical processes; moreover, this inference should be taken into account in seismoionospheric research.

The effects revealed in our work allow us to formulate the inverse problem of diagnosing the dynamical and wave disturbances in the middle atmosphere, which are caused by the meteorological processes, by means of distributed network monitoring of the VLF–LF transmitting stations. The abundance of such transmitters in Western Europe and in the European part of Russia, as well as the low cost and simplicity of the LF–VLF receivers, makes it possible to organize monitoring of the processes occurring in the middle atmosphere and lower ionosphere on a system of intersecting radio propagation paths.

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