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Ionospheric Disturbances in the North–East Region of Russia according to Ionosonde Data in the Periods of Equinoxes

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Abstract—Ionospheric disturbances in the equinox periods of 2005–2006 are considered on the basis of the ionosondes of vertical and oblique sounding located in the north–east region of Russia. It is found that the X-ray flares observed in the first half of September 2005 caused an additional increase in the ionization of the lower ionosphere in the daytime, this fact leading to a development of absorption and an increase in the lowest observable frequencies at the Magadan–Irkutsk and Noril'sk–Irkutsk radio paths. Wave-like changes in the maximum observable frequencies and critical frequencies with periods of about 2–2.5 h were detected during the magnetic disturbances. Oscillations of the planetary wave type with periods of 4–5 days were also revealed.

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1. INTRODUCTION

Ionospheric disturbances caused by the extreme solar events in July 2000 and October–November 2003 were observed in various regions of the globe using ground-based and space-borne diagnostic tools (see, for example, [1–4] and others). In the north–east region of Russia such studies were carried out using the spatially separated radio-physical complex of the Institute of Solar–Terrestrial Physics (ISTP) containing the Irkutsk incoherent scatter radar and the network of digital ionosondes of vertical and oblique sounding of the ionosphere [5–7]. In the years of low solar activity (beginning with 2005) ISTP conducted regular durable coordinated observations using the entire complex of equipment. This made it possible to study the variations of ionospheric parameters at middle and subauroral latitudes within the longitude range 90–150°E under both quiet and disturbed geomagnetic conditions. In this paper, the preliminary results of experiments with the network of ionosondes of vertical and oblique sounding of the ionosphere in the equinox periods (September 2005, and March and September 2006) are presented. It is worth noting that September 2005 was characterized by unique solar and geophysical events. From September 7, 2005 to September 21, 2005, 11 X-ray flares of the X class and 28 flares of the M class were detected (http://www.bu.edu/cawses/documents/cawses-news-v3-n1.pdf). These flares caused blackouts and distortions of radio signals in navigation systems and shortwave radio lines.

2. ANALYSIS OF THE EXPERIMENTAL DATA

In this paper we used the data of oblique sounding obtained at the Magadan–Irkutsk and Noril'sk–Irkutsk paths using LFM (linear frequency modulation) ionosondes of our own construction [8] and also the data of vertical sounding at points Irkutsk, Yakutsk, Noril'sk, and Magadan with the time resolution of 15 and 5 min. The information on the current index of solar radio emission $F_{10.7}$, K_p and D_{st} indices, and values of the X-ray flux of solar radiation were taken from the sites: http://sec.noaa.gov/ and http://swdcdb.kugi.kyotou.ac.jp/dstdir.

2.1. September 2005

Geophysical conditions in this month were very diverse. The solar background activity was not high: $F_{10.7} \approx (75–120) \cdot 10^{-22}$ WHz^{-1} m^{-2} s^{-1}. On August 31, 2005 a magnetic storm began during which the maximum K_p index reached 7 and the value of the D_{st} index decreased to –131 nT at 20:00 UT. The first days of September 2005 are characterized by a slow recovery phase on the background of which substorms with K_p index reaching 5–6 (September 2–3, 2005) were observed. As a rule, in the region under study during the equinox period the main phase of a magnetic storm and the beginning of the recovery phase are accompanied by development of a negative ionospheric disturbance [9]. Therefore, on the first days of September 2005 relatively low maximum observable frequencies (MOF) in the conditions of complete illumination of the paths and the absence of signal propagation in the evening and nighttime hours (especially at the Noril'sk–Irkutsk path) were observed. The daytime values of MOF varied from 17 to 22 MHz at the Magadan–Irkutsk path and from 12 to 18 MHz at the Noril'sk–Irkutsk path. To September 7, 2005, the geomagnetic conditions recovered to the undisturbed level and the signal propagation was registered during almost the entire day.

The interval from September 7, 2005 to September 15, 2005 is of particular interest. On September 7, 2005, an active group of sunspots (808 according to the NOAA classification) was formed on the visible part of the solar disk. As a result of the activity of this group, on September 7, 2005, a powerful flare X1.7 was observed which was accompanied by a coronal mass ejection. 24 hours later, this region became a source of new three flares of the X class. In the following days until September 17, 2005, flares of the M class were registered every day. On September 15, 2005, a flare of X class was registered. We first consider the changes in parameters of SW signals during the observations of strong X-ray flares under quiet geomagnetic conditions. As an illustration, Fig. 1a shows the variations in the intensity of X-ray fluxes within two ranges 1.0–8.0 Å (curve *1*) and 0.5–4.0 Å (curve *2*) from September 7, 2005 to September 9, 2005. The variations of the planetary K_p index are shown in Fig. 1b. One can see that in almost quiet geomagnetic conditions, during the first two days large fluxes of the X-ray radiation were observed, their maximum values being registered on September 7, 2005 at 17:30–17:50 UT and on September 8, 2005 at 21:05–21:30 UT, which corresponds approximately to nighttime and early morning hours at the observation points. On September 9, 2005, several flares of smaller intensity were observed during almost the entire day. Figure 1c shows the variations of the maximum observable frequencies and the lowest observable frequencies (LOF) for the one-hop mode on the Magadan–Irkutsk path (curves *1* and *2*, respectively). Dashed curve shows the values of the maximum usable frequencies calculated using the International Reference Ionosphere (IRI) model [10], which almost coincide with the median values of MOF calculated over all days of the experiment. One can see that on September 7, 2005 and September 8, 2005, the reflections were present almost during the entire day, except for very narrow time intervals. On September 7, 2005 the observed values of MOF were slightly lower than on the following days due to more disturbed geomagnetic conditions. The impact of the X-ray flares of September 7, 2005 and September 8, 2005 on the parameters of the propagating SW radio signals manifested itself in the substantial increase of LOF in the morning hours of local time on September 8, 2005 and September 9, 2005. These intervals are marked by arrows in the plot. On September 9, 2005, when a series of flares was observed, the propagation of short radio waves in the daytime and morning hours was mainly registered, while in the nighttime the signals were absent. The values of LOF in this case increased overall by 1.5–3.0 MHz relative to the previous days, this fact indicating to the increase in the ionization in the lower ionospheric layers. This led to a decrease in the frequency range of the received signals. At the Noril'sk–Irkutsk path, on September 9, 2005 a regular reception of signals was performed only in the morning hours, while in the daytime reflections were seldom observed.

In the bottom part of the figure, the diurnal variations of the critical frequencies (curve *1*) and the minimum reflection frequency (curve *2*) are shown according to the data of the DPS-4 digisondes located at Yakutsk (*d*) and Irkutsk (*e*). The minimum reflection frequency $f_{\min}$ (though depending on many factors, such as the sensitivity level of the recording system and noise level) could serve as an indicator of absorption in the ionosphere, especially during intense flares [11]. The absorption is connected with $f_{\min}$ by the relation:

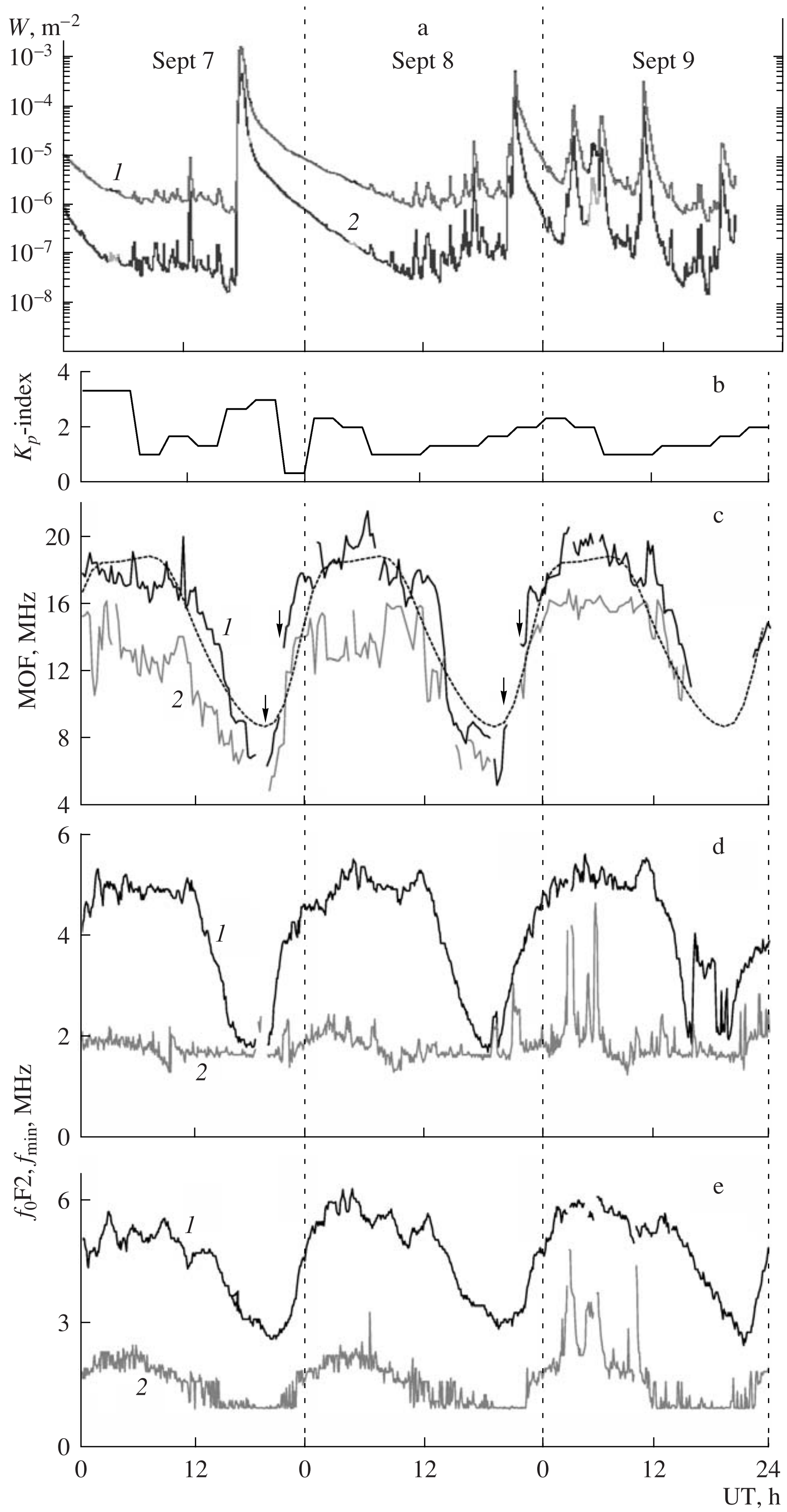
$$A = K(f_{\min} + fl)^2,$$

where K is the proportionality coefficient, $f_{\min}$ is the minimum reflection frequency, and fl is the field-aligned component of the gyrofrequency. If $(f_{\min})_q$ and $(f_{\min})_f$ are the minimum frequencies of reflection in quiet conditions and during the flare, respectively, then the extra absorption ΔA during the flare can be estimated as a difference between the calculated values of absorption during the flare and under quiet conditions

$$\Delta A = K[\{(f_{\min}\}_f + fl\}^2 - \{(f_{\min})_q + fl\}^2].$$

One can see in Figs. 1d and 1e that $f_{\min}$ increases with the sharp increase in the X-ray flux on September 9, 2005. One can select the time intervals during which the minimum frequency level first increased up to 3–5 MHz, then a short-time absorption was observed, and after that the traces of reflections in the ionograms were recovered with higher minimum frequencies. This intervals, for example, the ones observed on September 9, 2005 at 02:50–03:30 and 05:45–06:15 UT at Yakutsk and Irkutsk correspond to enhanced values of the X-ray flux. The estimates show that at the increase in $f_{\min}$ up to 4–5 MHz the absorption level increases by a factor of 1.5–2.5. Such short-time intervals of sharp increase in $f_{\min}$ were also observed in other days.

On September 9, 2005 and September 10, 2005 after 14:00 UT, an intensification of the auroral activity and increase in the K_p index were observed. This substantially influenced the behavior of the critical frequencies at Yakutsk: the nighttime values of the critical frequencies caused by diffuse precipitation of auroral particles increased. At the same time, the interval of radio signal absorption on the Magadan–Irkutsk path at the nighttime hours of the local time increased. As a result, on September 10, 2005, a new magnetic storm began, whose maximum was registered on September 11, 2005 at 11:00 UT with the value of D_{st} equal to –147 nT. This storm also had a long recovery phase during which on September 15–16, 2005 weaker magnetic disturbances



W, m−2
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Fig. 1.

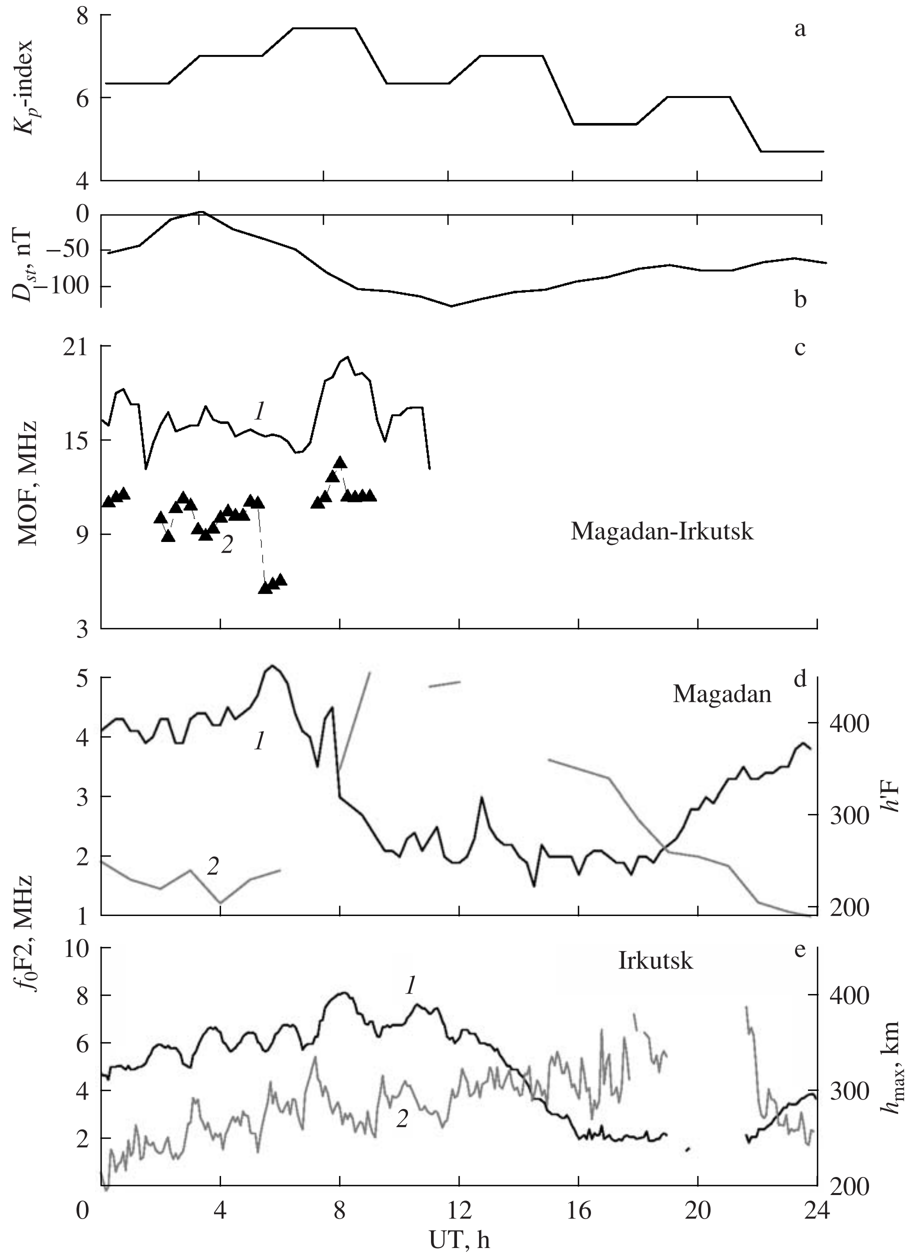

Fig. 2.

were registered. Figure 2 shows the changes in the characteristics of the oblique sounding on the Magadan–Irkutsk path and critical frequencies and layer heights registered at Magadan and Irkutsk stations on September 11, 2005. Due to the fact that during the magnetic storm the critical frequencies of the h'F and F1 layers at Magadan were close to each other, it was difficult to determine the F2-layer height from ionograms. So the minimum height of the layer h'F was used for the analysis. In the top part of the figure, the values of the K_p index and variations of the D_{st} index are presented. One can see that during the main phase of the magnetic storm on September 11, 2005 in the evening hours of local time, wave-like variations of both one-hop (Fig. 1c, curve *1*) and two-hop (curve *2*) modes with amplitudes of 5–6 and 2–4 MHz, respectively, were observed. The oscillation periods were about 2–2.5 h. The reflections disappeared at night because of strong absorption, and in the following days the reflections were registered only in the daytime. The data of the vertical sounding (15-min intervals) show that at Magadan in the daytime during the main phase of the storm, the variations of the critical frequencies (curve *1*) demonstrate an additional increase in the critical frequencies at about 07:30–08:15 UT. Unfortunately, we had only hourly values of the minimum reflection frequencies, so they do not show any peculiarities (curve *2*). The Irkutsk data were obtained with a 5-min interval of sounding (Fig. 2e). One can see that oscillations of critical frequencies and heights of the maximum are observed in anti-phase. One should note that wave-like changes in the electron density during this storm were also detected at Irkutsk according to the data of the incoherent scatter radar and ionosonde [12].

The last weeks of observations in September 2005 had quiet geomagnetic conditions. In the morning and daytime hours from September 22, 2005 to September 26, 2005 at both paths relatively high maximum observable frequencies (approximately by 25–35% above the median values [13]) were registered. After September 28, 2005 the deviations of the observed values of MOF from the median values in the daytime were less than 15%. Similar increases of the critical frequencies were observed on these days at ionospheric stations Irkutsk, Magadan, and Yakutsk. Moreover, according to the satellite data *GUVI TIMED* (http://guvi.jhuapl.edu/guvi_accessdata.html) over the vast region of the East Siberia together with the general tendency of a small increase caused by the seasonal reconfiguration of the neutral atmosphere, from September 24, 2005 to September 28, 2005 at altitudes of the lower thermosphere enhanced values of the $[0]/[N_2]$ ratio were detected with a sharp decrease to September 29, 2005. According to the data of the *MLS Aura* satellite (http://mls.jpl.nasa.gov) on the same days substantial variations of the temperature at heights of the stratopause and mesopause were detected. All these experimental data testify that there existed a large-scale disturbance of the planetary-waves type.

2.2. March 2006

The studies of ionospheric disturbances during equinoxes were continued in March and September 2006. The March observations began on March 6, 2006 and continued until April 6, 2006. The level of the solar radio emission flux varied insignificantly during the month within the limits (70–80) $\cdot$ 10^{-22} $\mathrm{WHz^{-1}\ m^{-2}s^{-1}}$, and only on the last days an increase up to 100 units was detected. The level of magnetic activity was changing from quiet to moderately disturbed conditions which were registered in the beginning of the observations on March 6–7, 2006, March 10–11, 2006, and March 18–20, 2006. On these days, the values of the K_p index increased to 5–6, however, no substantial decrease in the D_{st} index was observed. At the end of the observational cycle, a magnetic storm with the minimum value of D_{st} equal to –87 nT was registered. In this and the next experiment in September 2006, the sounding interval of the LFM ionosonde was 5 min, therefore, various short-period variations in MOF with periods from a few hours to fractions of an hour were detected. On the background of relatively quiet geomagnetic conditions, one can distinctly see changes in the ionization at the transition from the winter to summer conditions. This becomes apparent in the increase in MOF in the morning and evening hours at the end of March 2006 on both paths. In addition, in the diurnal behavior of MOF in the evening hours, an appearance of an extra maximum in the evening hours is detected, the maximum being related to the peculiar electron concentration density in this region [14]. The moderate growth in magnetic disturbance caused, in the same way as in September 2005, a decrease in MOF, especially in the morning and daytime hours (Fig. 3a). During the main phase of the storm on April 4, 2006 at the evening hours of the local time on the Magadan–Irkutsk path, an increase in MOF was observed. Then in the daytime, the values reduced by 2–4 MHz were registered on both paths. In the evening of the next day on the Magadan–Irkutsk path on the background of low values of MOF a sharp increase in MOF by 3–5 MHz during 1–1.5 h was again registered, after which a similar rapid decrease in MOF by 8 MHz occurred during the next hour and a half.

2.3. September 2006

The geophysical conditions of the experiment carried out in September 2006 corresponded to a minimum of solar activity, the solar radio emission flux not exceeding $80 \cdot 10^{-22}$ $\mathrm{WHz^{-1}\ m^{-2}\ s^{-1}}$. Overall, the geomagnetic conditions were quiet. On some days (September 4, 2006, September 18, 2006, September 23, 2006, and September 24, 2006) geomagnetic disturbances were registered at which the K_p index reached 4–5. This determined a decrease of the electron dencity at heights of the *F* region and, therefore, a decrease in the maximum observable frequencies relative their median values on both paths in the daytime and their strong variability. At the nighttime hours the reflections often were absent. In the same way as in March 2006, substantial oscillations of the MOF values were observed in the illuminated part of the day. Figure 3b shows the variations of maximum observable frequencies for the days in succession: September 23–25, 2006. The dotted curve shows the median values determined over all days of the experiment. A decrease in the MOF values with the beginning of the magnetic storm development is seen. In addition, on September 24, 2006 in the interval 05:00–14:00 UT, oscillations in MUF with an amplitude of 1.5–5 MHz were registered, the oscillation period increasing with time.

3. DISCUSSION OF RESULTS

On the basis of the performed analysis of the experimental data of oblique and vertical sounding obtained during the durable experiments in the periods of equinoxes of 2005–2006 one can isolate four types of ionospheric disturbances. The first type of ionospheric disturbances is related to X-ray flares and manifested itself in a sharp short-time increase of minimum reflection frequencies in vertical sounding ionograms and an

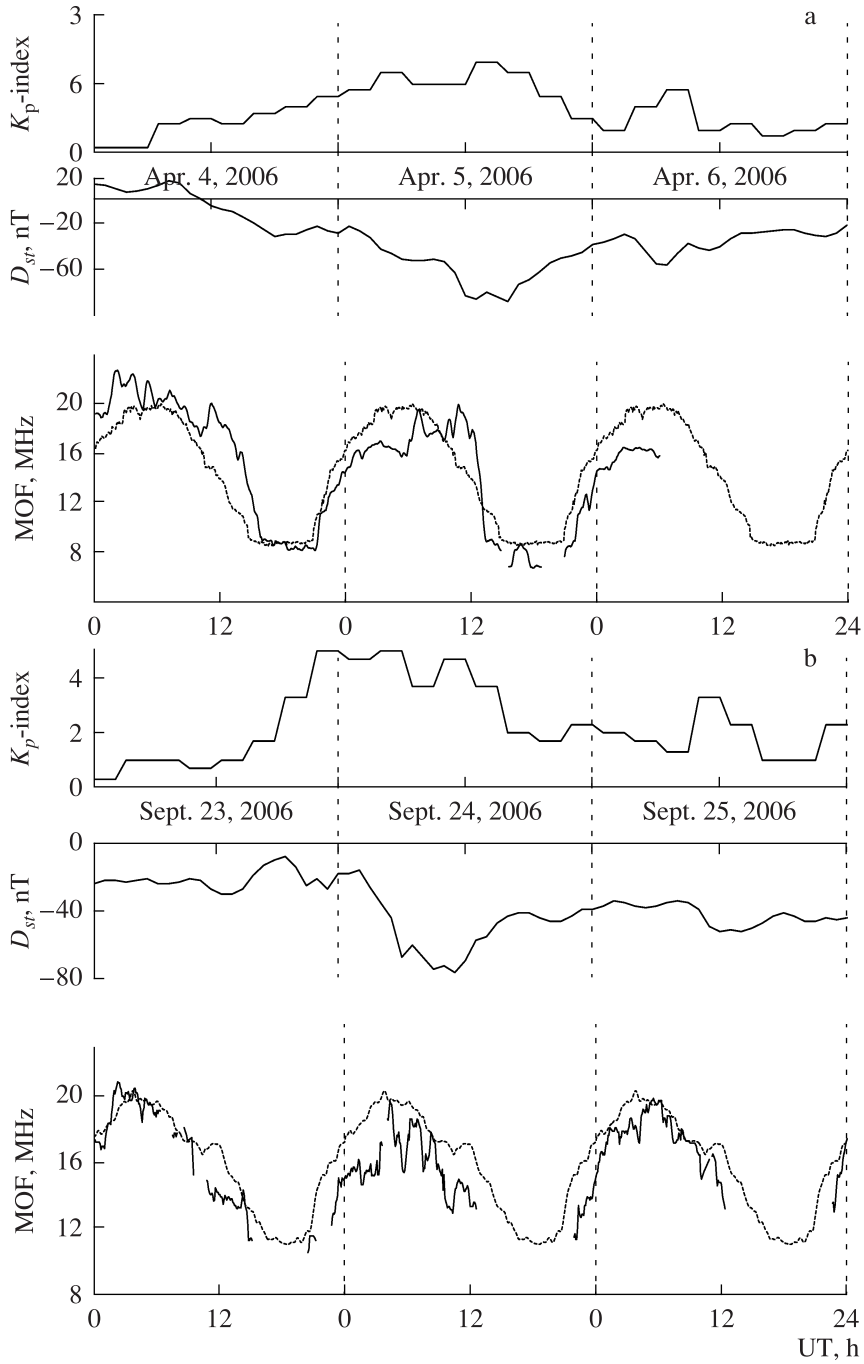

Fig. 3.

increase of the lowest observed frequencies in oblique sounding ionograms. This type of disturbances represents the type of sudden ionospheric disturbances (SID). Such disturbances cause substantial interferences in the radio transmitting and navigation systems. The second type of ionospheric disturbances is related to the ionospheric response to a magnetic storm and manifested itself in a sharp short-time increase of the electron density in the *F*-region maximum followed by a similar sharp decrease in ionization. This type of disturbances is observed, as a rule, in the evening and afternoon hours during the main phase of a storm. Such sharp gradients of the electron density in a substantial degree distort the properties of ionospheric radio channel. The theoretical calculations presented in [15] showed that the joint action of the meridional winds and zonal electric field is able to cause such variations in the electron density in the evening sector of the ionosphere. The analysis of such disturbances performed using direct measurements of the ionospheric plasma at the incoherent scatter radar at Millstone Hill during a strong "twilight" effect on May 26–27, 1990 and the results of modeling of the distribution of the electron density, temperature, and ion drift velocity revealed no dominant mechanism of formation of disturbances of such kind. The analysis showed that for explanation of the observed variations in the electron density a combination of all the mechanisms considered is possible, including the traveling atmospheric disturbances, plasma motion, and changes in the composition of neutrals due to changes in the rates of photochemical reactions [16]. The third type of disturbances is related to a formation of wave-like changes in the electron density and is registered also during magnetic disturbances. Such variations of maximum observable frequencies on the Magadan–Irkutsk path have been detected earlier at the afternoon hours during the main phase of the magnetic storm on May 15, 1997 [17]. The most probable cause of these variations is the motion of large-scale ionospheric disturbances which are formed in the auroral zone and can travel to equatorial latitudes to large distances [18–20] causing substantial variations of the critical frequencies and heights in the *F*-region maximum. Such sharp gradients of electron density lead to large changes in the characteristics of radio wave propagation especially in the values of the maximum observable frequencies, the values of which depend on the gradients of the critical frequencies and heights of the F2-layer maximum along the radio signal propagation path. The forth type of disturbances concerns long-lasting disturbances in the ionosphere and atmosphere of the planetary waves type having periods of a few days. It was demonstrated in [21–23] and other review papers that planetary waves propagate from the lower layers of the ionosphere upward and can influence substantially the parameters of not only the lower ionosphere (100–150 km), but have an effect also on the characteristics of the *F* region. Probably, the day-to-day variations of ionospheric parameters can be related to meteorological processes, but so far no mechanism of energy transfer from tropospheric heights to the ionosphere is revealed.

4. CONCLUSIONS

On the basis of presented experimental data of oblique and vertical sounding obtained during long-term experiments at equinoxes of 2005–2006 one can draw the following conclusions.

1. The series of X-ray flares observed in the first half of September 2005 caused an increase of ionization in the lower ionosphere in the daytime hours, which led to the development of absorption and to an increase in the lowest observable frequencies on the Magadan–Irkutsk and Noril'sk–Irkutsk paths and to a decrease of the frequency range of the received SW radio signals.

2. During magnetic disturbances an increase in the ionization in the evening hours on the Magadan–Irkutsk path and wave-like changes in MOF with an oscillation period of about 2–2.5 h are observed. Manifestations of such wave disturbance are seen in vertical sounding ionograms at Irkutsk and were also registered by the incoherent scatter radar. Apparently, their appearance is caused by formation of large-scale disturbances in the auroral zone and by their propagation equatorward to large distances.

3. Under quiet geomagnetic conditions, oscillations of ionospheric and atmospheric parameters of the planetary waves type with a period of 4–5 days were registered. Such oscillations caused variations in the maximum observable frequencies reaching 25–35%.

Thus, the experimental data obtained at the network of vertical and oblique sounding ionosondes with a high time resolution showed that the network of ionosondes is a modern tool of studying radiowave propagation conditions and can be used for the diagnostics of the state of the ionosphere.

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