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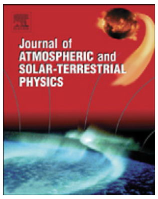

Ionospheric response to geomagnetic disturbances in the north-eastern region of Asia during the minimum of 23rd cycle of solar activity

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ABSTRACT

We present the results of studies of the subauroral and mid-latitude ionosphere variations in the north-eastern region of Asia. We used the data from network of vertical and oblique-incidence sounding ionosondes and optical measurements. Long-term experiments on the radio paths Magadan–Irkutsk and Norilsk–Irkutsk were carried out within the period 2005–2007. Vertical sounding stations operated in standard regime. Observation of airglow near Irkutsk was provided by the zenith photometer that measured intensities of 557.7 and 630.0 nm atomic oxygen emissions. The results may be summarized as follows. (1) Large daytime negative disturbances are observed during the main and recovery phases mainly at high latitudes, whereas the positive disturbances observed during the main phase at mid latitudes. The disturbances changed their sign between Yakutsk and Irkutsk. (2) During the main and recovery storm phases the fall of foF2 associated with the equatorward wall of the main ionospheric trough is observed in the afternoon and evening. (3) Fluctuations of the electron density more intensive at mid latitudes during the storm main phase are observed during all considered periods. They are classed as traveling ionospheric disturbances (TID). Such sharp gradients of electron density are responsible for the strong changes in the characteristics of the radio wave propagation, particularity MOF. (4) A large-scale ionospheric disturbance is noted at the meridional chain of ionosonds in December 2006 as the sharp increase of foF2. It appears in the evening in the minimum of D_{st} at high latitude and propagate to equator. (5) A maximum of 630 nm emission above Irkutsk corresponds to the foF2 increase. (6) The obtained experimental data on the net of vertical and oblique-incidence sounding with high time resolution show that such net is the effective facility to study the conditions of the radio wave propagation and can be used for the diagnostic of the ionosphere.

1. Introduction

Studying the influence of solar and interplanetary phenomena on the near Earth space has been the most important problem of the solar–terrestrial physics. In spite of the fact that a vast volume of experimental and theoretical data have been accumulated, some difficulties exist to forecast the effects of solar activity on the ionosphere. An ionospheric disturbance caused by a geomagnetic storm is a complex of events and depends on the sequence and intensity of various factors such as parameters of the interplanetary magnetic field, the

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intensity of the geomagnetic storm, the coordinates and local time of the observation point, etc. (Buonsanto, 1999; Danilov and Belik, 1991; Danilov and Lastovicka, 2001; Prölss et al., 1999; Prölss and Ocko, 2000; Field and Rishbeth, 1997; Fuller-Rower et al., 1994, 1996). A difference between the geographic and magnetic coordinates complicates the picture of ionospheric disturbances and leads to a longitudinal dependence of ionospheric responses to geomagnetic storms (Afraimovich et al., 2002; Blagoveshchensky et al., 2003; Pirog et al., 2006; Zherebtsov et al., 2005a).

We published the results of variations in the ionospheric parameters in October–November 2003 using the data of the network of ionospheric stations located in the longitudinal sector 90–130°E from the auroral zone to the equator (Zherebtsov et al., 2005b). They show that during superstorms the phenomena typical for the main ionospheric trough were observed equatorward, down to the geomagnetic latitude of 40°. Zolotukhina et al. (2000) analyzed manifestations of geomagnetic storm on October 1995 (minimum of the solar activity) and discovered intense high-frequency geomagnetic pulsations and ionospheric disturbances similar to those observed over auroral region at middle latitudes. Authors have got the conclusion that the dominant mechanism responsible for the development of these storm-induced disturbances is the quasi-stationary transport of plasma sheet particles as deep as $L \approx 2$ due to the enhanced magnetospheric convection. This process has become possible by the gradual and slow increase of the IMF B_z component after the abrupt B_z reversal, in the magnetic cloud surrounding the Earth.

We continued to analyze ionospheric disturbances within the same region during the geomagnetic storm on 7–11 November 2004 (Pirog et al., 2007; Afraimovich et al., 2006). The main feature of the ionospheric behavior during this storm was the appearance of large-scale ionospheric disturbances, which were registered on 8 and 10 November in the data of both vertical sounding and global GPS network as a considerable increase in foF2 and TEC in the evening hours of local time. The large-scale ionospheric disturbances propagated predominantly southwestward at mean velocities of 200 and 400 m/s on 8 and 10 October, respectively.

During geomagnetic and ionospheric disturbances the disruption in the regular variations of the airglow were noted in the middle latitudes (Degtyarev et al., 2004). The atmospheric emission of atomic oxygen 630 nm is the more responsive to the geomagnetic activity due to its location in the F region, the mechanism of formation associated with the recombination, and the dependence on the ionized component of the upper atmosphere. In the middle latitudes the moderate geomagnetic disturbances in the 630 nm emission manifests as the increase of

Table 1
The list of ionospheric stations

Stations	Geographic		Geomagnetic	
	Latitude	Longitude	Latitude	Longitude
Norilsk	69.20	88.26	58.71	165.7
Zhigansk	66.3	123.4	55.2	190.0
Yakutsk	62.0	129.6	50.99	194.1
Magadan	60.12	151.0	50.75	210.8
Irkutsk	52.5	104.0	41.1	174.8
Khabarovsk	48.5	135.1	37.91	200.4

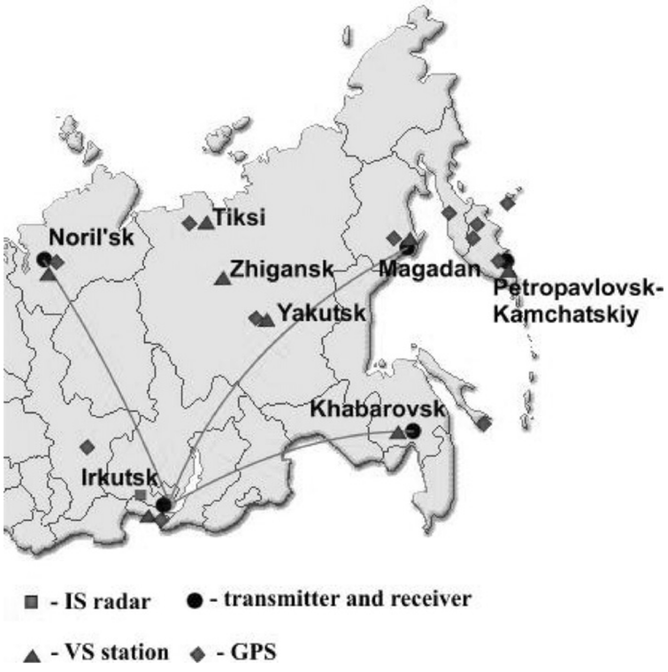

Fig. 1. The location of ionosondes, the oblique-incidence sonding paths and the types of experimental equipment.

average night intensity and the appearance of short-period oscillations of the intensity disrupted the regular night trend. Variations of 630 nm emission correlate with the variations of F2 layer parameters (Barbier, 1959). Specifically, during the geomagnetic disturbances the increase of the emission 630 nm in the short-period oscillations is consistent with going below the peak of F2 layer.

In this paper, we present the results of the regular prolonged coordinated observations on the radio physical complex of the Institute of Solar-Terrestrial Physics under the conditions of the low solar activity. We study the ionospheric and atmospheric disturbances observed during the extreme solar events on September 2005 and December 2006 and also during minor and moderate geomagnetic storms in the equinox of 2006–2007.

2. Experimental data

We used the data of oblique-incidence sounding obtained on the paths Magadan–Irkutsk and Norilsk–Irkutsk

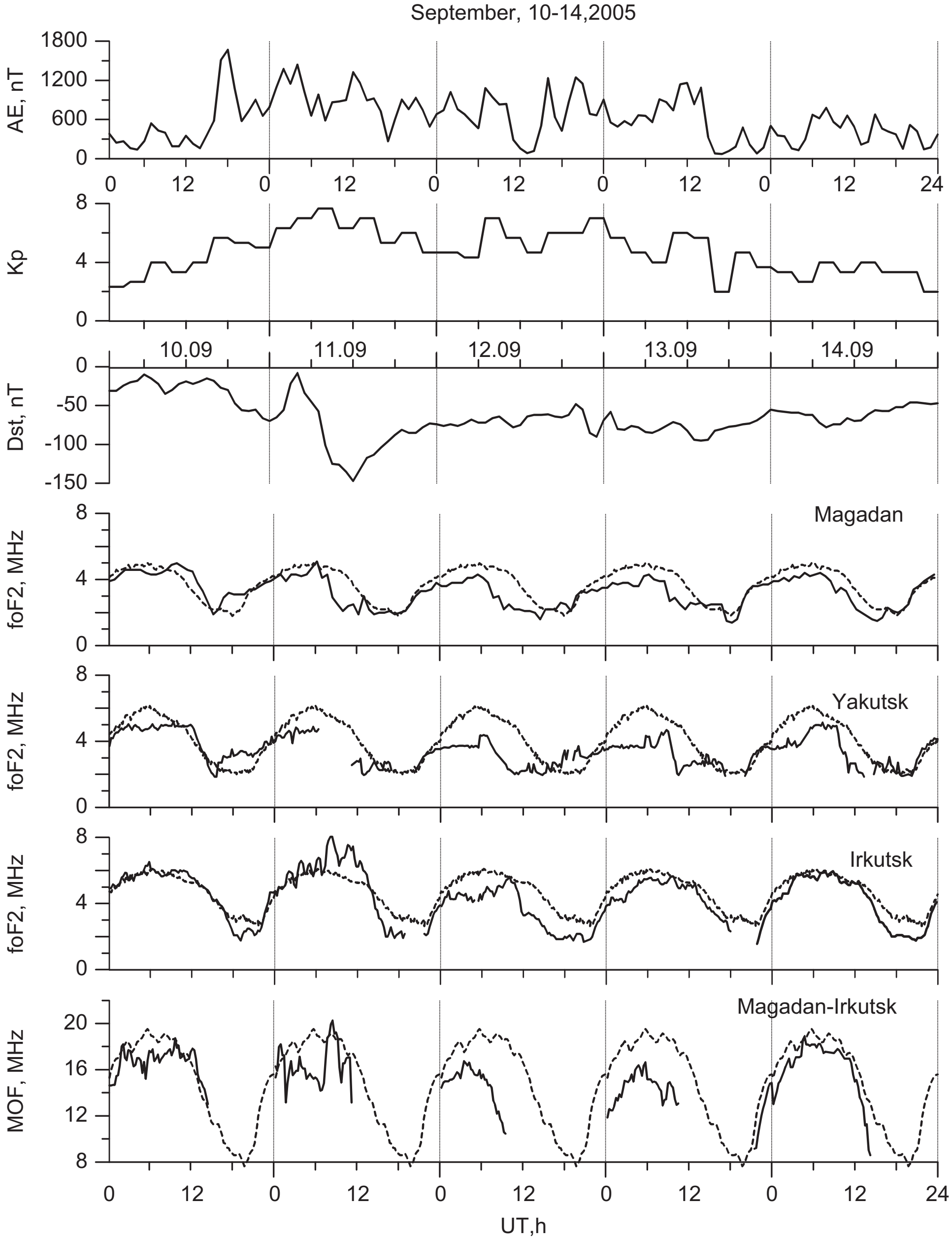

Fig. 2. Variations in the AE, K_p, D_{st} and foF2 on three stations and MOF on the path Magadan–Irkutsk on 10–14 September 2005. Dotted lines show foF2 in the quiet day and the median of MOF, thick lines are their current values. LT = UT+Δt, where Δt equals to 6–8 h depending on the longitude of station (see Table 1). The data of the MOF on the path Norilsk–Irkutsk are lacking. The large fluctuation in foF2 in Irkutsk on 11 September correlate with the MOF on the path Magadan–Irkutsk.

by the chirpsounder (frequency-modulated continuous wave ionosonde) of own construction (Ivanov et al., 2003) and vertical sounding of the ionosphere in Irkutsk, Yakutsk, Norilsk and Magadan with the temporal resolution of 15 and 5 min. The oblique-incidence sounding was performed every 5 min on a 24-h basis for 30 days for each experiment. The frequency range was from 4 to 30 MHz, the sweep rate used 500 kHz/s. The observational data of the atmospheric atomic oxygen emission 630 nm obtained in ISTP Geophysical Observatory near Irkutsk are also used. The observations were conducted over 1–2 weeks of the new moon.

The location of ionosondes and radio paths are shown in Fig. 1.

Coordinates of stations of vertical sounding, transmitters and receiver of chirpsounder are presented in the Table 1.

Solar and geomagnetic activity indices $F_{10.7}$, AE, K_p, D_{st} and values of the X-ray fluxes are obtained from the sites http://sec.noaa.gov/ and http://swdcdb.kugi.kyoto-u.ac.jp/dstdir. The main attention is focused on periods of equinox (September 2005, 2006, 2007) and December 2006.

2.1. *Extreme solar events on September 2005 and December 2006*

The geomagnetic situation on September 2005 varied within wide limits. The solar activity was not high ($F_{10.7}\approx(75\text{–}120)\,10^{-22}\,\text{W/Hz м}^2$). The first days on September were characterized by the slow recovery phase of the geomagnetic storm on 31 August. On its background the substorms were observed. The K_p index increased to 5–6 on 2 and 3 September.

During the first days in September the relatively low maximum observed frequencies (MOF) were recorded in the daytime and radio signals was lacking in the evening and night hours, particular on the path Norilsk–Irkutsk. The day MOF changed from 17 to 22 MHz on the path Magadan–Irkutsk and from 12 to 18 on the path Norilsk–Irkutsk. On 7 September the geomagnetic condition recovered to the undisturbed level and the radio signals were registered about the all day. The period on 7–15 September was the most interesting one. On 7 September the active groups of spots appeared at the solar disk that resulted in a massive solar flare and coronal mass ejection. Three new flares appeared after 24 h. The flares were routinely registered until 17 September.

The large X-ray fluxes with maxima at night and in the morning of local time (LT) were observed on 7 and 8 September. The influence of X-ray fluxes manifested as the rise of the lowest observed frequencies (LOF) in the morning hours of LT. During the appearance of a set of flares on 9 September the propagation of HF radio waves was recorded mainly in the day and the morning. The radio signals were lacking at night. The values of LOF increased of 1.5–3 MHz relatively to the previous days that testified about the rise of ionization in low layers of the ionosphere. It produced the reduction in the frequency range of reception radio signals. On 9 September the regular receive of radio signal on the path Norilsk–Irkutsk occurred only in the morning. The day reflections were observed seldom.

According to the data of digisondes located in Yakutsk and Irkutsk the minimum frequencies of reflections ($f_{\min}$) as the indicator of the absorption in the ionosphere particularly during the intensive flares did not essentially change on 7 and 8 September, whereas the sharp rise of the $f_{\min}$ on 9 September conformed to the peaks of X-ray intensity at both Yakutsk and Irkutsk. There were the intervals of time when the $f_{\min}$ initially increased up to 3–5 MHz then the short-time blackout was observed; after that the F2 layer reflections on the ionograms recovered with high $f_{\min}$. These intervals corresponded to the increased X-ray intensity. The estimation showed that the increase of $f_{\min}$ to 4–5 MHz indicated the increase of absorption level by factor 1.5–2.5. The similar short-time intervals of the sharp increase of $f_{\min}$ were obtained during the other stormy days.

The increase of K_p index was observed on 10 September after 06 UT. The geomagnetic storm started at 15 UT on 10 September. The minimum of $D_{st}=-147$ nT was reached at 11 UT on 11 September. This storm had the prolonged recovery phase. Fig. 2 presents the variations in the critical frequencies of the F2 layer at three ionospheric stations and MOF on the path Magadan–Irkutsk on 10–14 September. Variations in the AE, K_p and D_{st} are shown at top of the figure. The hourly foF2 values averaged over several quiet days of the month are used as the quiet level (dashed line). Notice that LT = UT+Δt, where Δt equals to 6–8 h depending on the longitude of

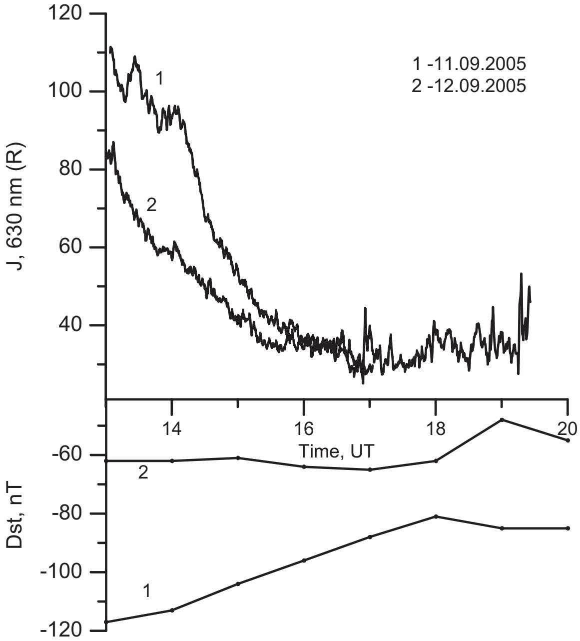

Fig. 3. Variations in the emission 630 nm during the recovery phase storm on 11 (line 1) and 12 September 2005 (line 2). In Asian region the disturbances in the variations of the 630 nm emission in the recovery phase of magnetic storms are most pronounced in the first half of night. A local midnight in Irkutsk corresponds to the 17 UT.

station (see Table 1). As can be seen in Fig. 2, in the storm main phase on 11 September the data of the vertical sounding showed the sharp fluctuations in foF2 above the quiet level with amplitude 1–3 MHz at Irkutsk. At Magadan and Yakutsk the foF2 were below the quiet level and the fluctuations were slight. At night the reflections absented or their frequencies were low (⩽2 MHz) at both Yakutsk and Irkutsk. The sharp fluctuations in the MOF with the amplitude 5–6 MHz were also observed during the storm main phase on 11 September in the evening

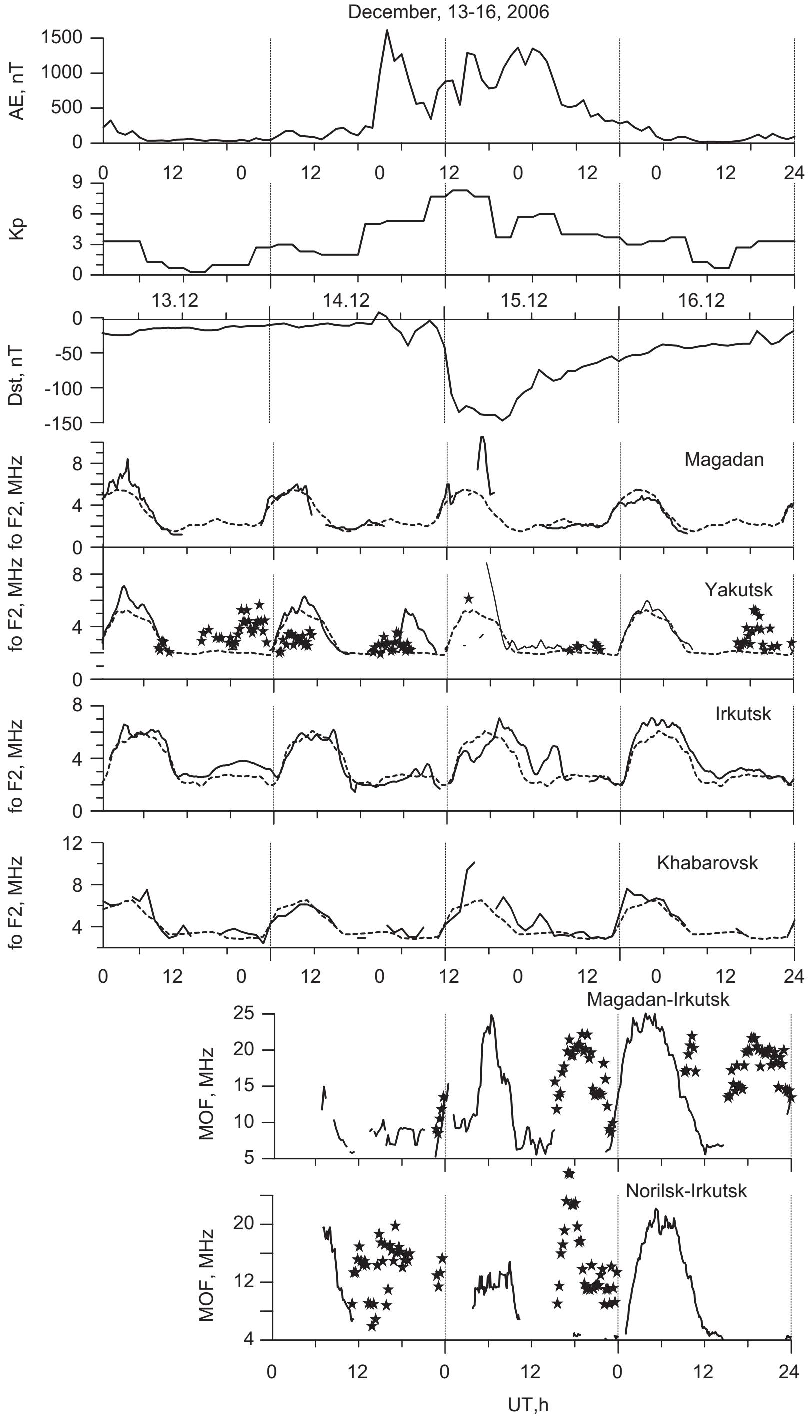

Fig. 4. Variations in the AE, K_p, D_{st} and foF2 on the meridional chain of station and MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk during the storm on December 2006. Dashed lines show the values of the foF2 in the quiet day, solid lines correspond to their current values of the foF2 and MOF; stars indicate the limited frequencies of sporadic E layer (foEs) and MOF from Es. The sharp peak in the fof2 firstly occurs in Zhigansk and moves to lower latitudes.

hours of LT. The reflections disappeared at night and they were observed only next days in the daytime. On the path Norilsk–Irkutsk the signals were lacking from 11 to 13 September because of the low foF2 and the increase of the absorption in the low layers of subauroral ionosphere. It resulted in the blackout on the path Magadan–Irkutsk for these hours. It should be noted that the wave-like changes of electron concentration during this storm were also recorded by Irkutsk incoherent scatter radar (Ratovsky et al., 2007).

The relationship between the mean intensity of 630 nm emission and the D_{st} index in the storm on 11–13 September is illustrated in Fig. 3. D_{st} index is best to correlate with the intensity of emission 630 nm during the geomagnetic disturbances. In Asian region the disturbances in the variations of the 630 nm emission in the recovery phase of magnetic storms are most pronounced in the first half of night (Mikhalev et al., 2005). A local midnight in Irkutsk occurs at 17 UT. As can be seen in Fig. 3 the intensity of the 630 nm emission on 11 September is higher than on 12 September in accord with the D_{st} magnitude.

The geomagnetic storm with minimum $D_{st} = -147$ nT at 07 UT on 15 December started at 20 UT on 14 December. Values of K_p increased up to 8 during the main phase of storm. Fig. 4 presents the variations of foF2 on the meridional chain of vertical sounding stations in the north-eastern region and the variations of MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk. The sporadic-E layers shielding of the F layer was observed in Yakusk and Zhigansk during the storm main phase. Only the reflections from Es with MOF close to the daytime MOF from F2 layer were recorded on the paths Magadan–Irkutsk and Norilsk–Irkutsk in the night. The main peculiarity of ionospheric response to this geomagnetic storm was an intensive large-scale positive disturbance that was detected by both vertical sounding stations and on the path Magadan–Irkutsk during the storm main phase in the afternoon on 15 December. As can be seen, the sharp increase of foF2 appears in the evening in the minimum of D_{st} against of the negative ionospheric disturbance at high latitude and propagate to equator. It was similar to the large-scale disturbances observed in this region on 8 and 10 November 2004 (Pirog et al., 2007). Analysis of the data from the stations located to the west of that longitudinal sector showed the absence of this disturbance.

The peculiarity of variation of the 630 nm emission during this storm was the intense oscillations. Fig. 5 presents the variation of emission 630 nm on 15 December. The oscillations with the period ~2.7 h stand out against the background of the night variation of this emission. The main maximum of emission intensity agrees with the foF2 maximum in Irkutsk.

2.2. Equinox 2006–2007

The geophysical conditions of experiment performed on September 2006 were quiet and corresponded to the solar activity minimum. The flux of solar radiation did not stand out above $F_{10.7} = 80 \times 10^{-22}$ W/Hz M^2. Sometimes the geomagnetic disturbances were registered and K_p increased to 4–5. The period 23–26 September was worthy of notice. The minor geomagnetic storm with two minimums of D_{st} index (−55 nT at 09 UT on 24 September and −35 nT at 10 UT on 25 September) was observed. The variations of foF2 on the meridional chain of ionosondes and the variations of MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk are presented in Fig. 6. In spite of the small intensity, this geomagnetic storm caused an important decrease of the day foF2 in the storm main phase and a fall of the foF2 in the evening in the storm recovery phase at high latitudes (Norilsk, Zhigansk, Yakutsk). The fall of the foF2 was more expressed on 25 September in the second recovery phase. It is similar to the sudden density drop on the equatorward wall of the subauroral trough (Prölss, 2007). At night the foF2 did not stand out above 2 MHz and sometimes the reflections in F2 layer absented because of the low level of ionization. In middle latitudes (Irkutsk and Khabarovsk) the most intensive fluctuations above the quiet level were observed on 24 September.

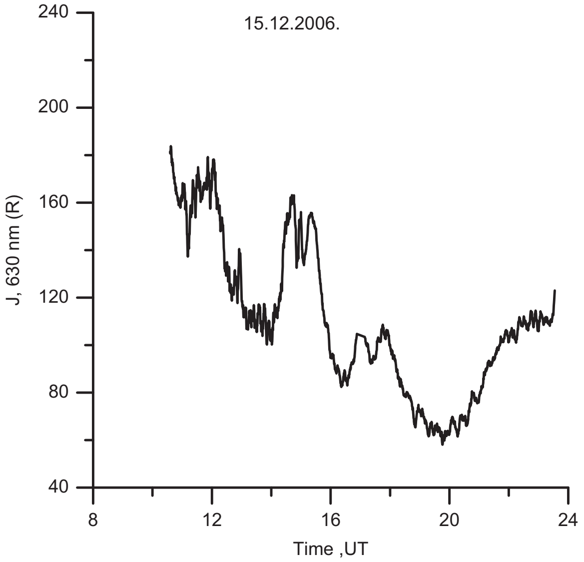

Fig. 5. Variations in the 630 nm emission on 15 December 2006.

The variations of foF2 produced the decrease of daytime MOF relative to the median on the path Norilsk–Irkutsk, their large fluctuations and the lack of reflections at night. The fluctuations of MOF with the amplitude 1.5–4.5 MHz were fixed in the daytime on 24 September on the path Magadan–Irkutsk.

Despite the small value of D_{st} index during this storm, the important disturbances of emission 630 nm with period about 2 h were observed, and the amplitude of the first wave was much higher than other. The disturbance of the 557.7 nm emission similar to the first wave in the emission 630 nm with the shift about an hour was indicated (Fig. 7). It should be noted that the maximum in the intensity of emission 630 nm at 15 UT

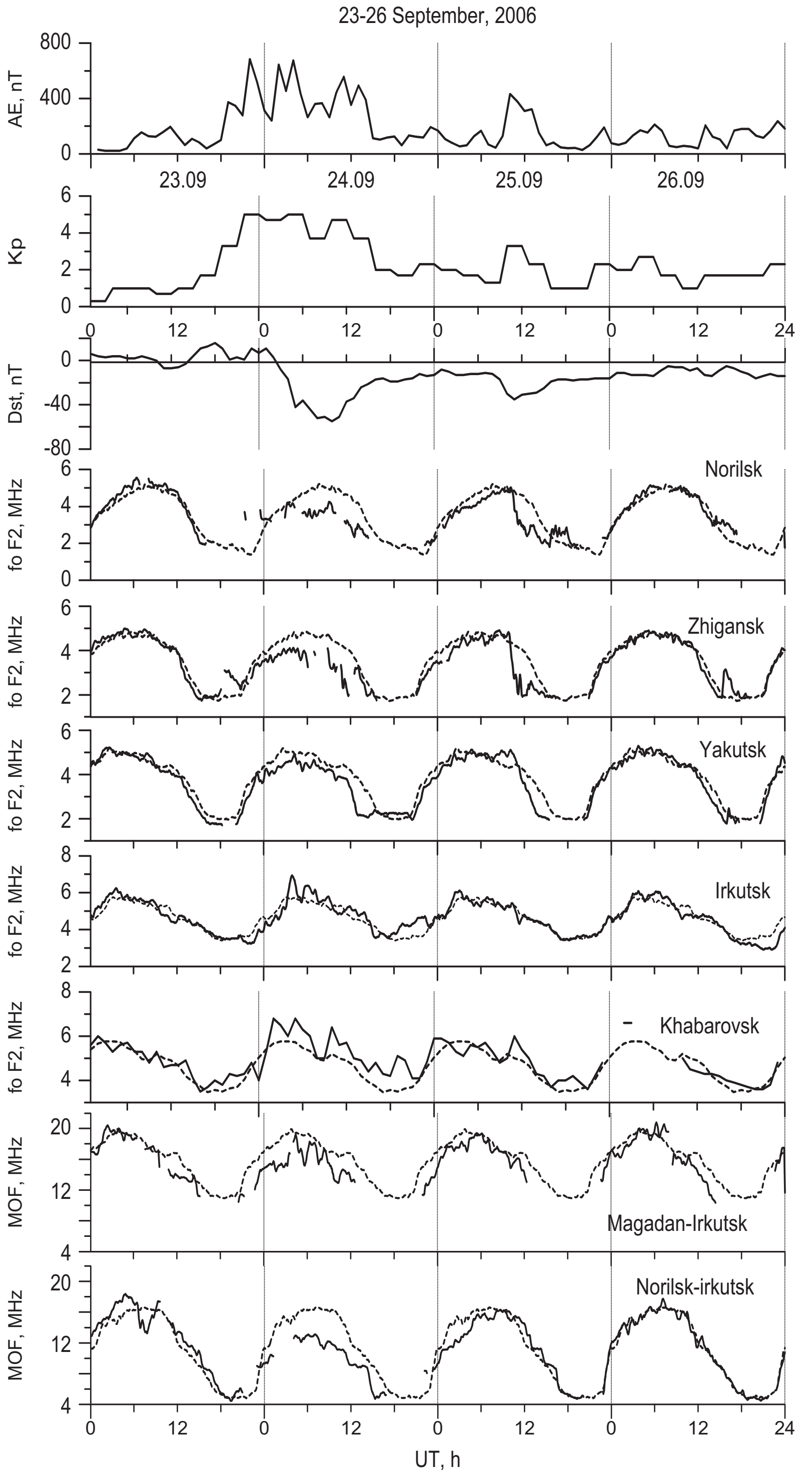

Fig. 6. Variations in the AE, K_p, D_{st} and foF2 on the meridional chain of station and MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk during the storm on 23–26 September 2006. Dashed lines show the values of foF2 in the quiet day and the median of MOF, solid lines correspond to their current values.

was coincident with the increase of MOF on the path Norilsk–Irkutsk. The increase of intensity after 21 UT was in agreement with the foF2 increase in Irkutsk.

On March 2007, D_{st} index changed in limits (5 to -20 nT) all month except on 13 March ($D_{st} = -34$ nT) and on 24 March when the moderate storm with minimum

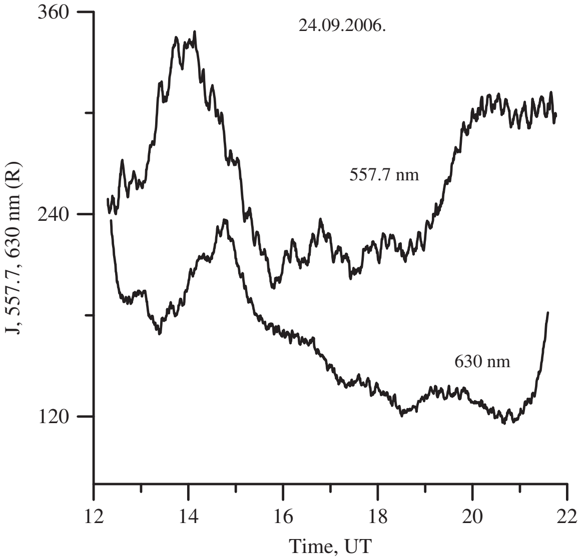

Fig. 7. Variations in the emission at 557.7 and 630 nm on 24 September 2006.

$D_{st} = -70$ nT at 08 UT was observed. Although the intensity of the first storm was low, it caused a significant change in the variation of foF2 (Fig. 8). Of particular interest is the decrease of ionization in the recovery phase at Yakutsk and Zhigansk on 15 March. The decrease of foF2 on 13 March was connected with the main phase. The foF2 recovered to the quite level next day. On 15 March the ionization decreased again at the station Zhigansk and Yakutsk. So there was observed a wave-like disturbance with period of 2 days on the meridian about 130°E. This disturbance absented at Irkutsk and Norilsk.

A similar effect we observed in the foF2 variations at different longitudes (Pirog et al., 2006). As to that study the negative daytime disturbances were observed at the stations of Yakutsk meridional chain in the main storm phase. The positive disturbances were observed in the storm recovery phase the next day. The disturbances were back to negative in a day. At the stations of Norilsk meridional chain the daytime values of foF2 after negative phase recovered slowly to the undisturbed level.

The strong decreases in the MOF (4–5 MHz relative to the median) were observed on the path Magadan–Irkutsk on 13 March. Next day the MOF recovered to the median, but on 15 March it decreased again. On the path Norilsk–Irkutsk the values of MOF recovered slowly to undisturbed level. The differences of the variation of MOF at different paths in the period 13–16 March might be caused by the location of the middle point of paths that was located close to Yakutsk for the path Magadan–Irkutsk and in the vicinity of Norilsk meridian for the path Norilsk–Irkutsk.

The second disturbance (Fig. 9) manifests the deep decrease of the foF2 in the evening at the subauroral stations connected with the formation of the equatorward wall of the MIT in the main phase and the positive disturbance at the middle latitudes (it is also dissimilar to the equinox storm). Disturbances are positive in the recovery phase at all stations. The storm effect on the variation of MOF was much weaker then in the first storm. The decrease of MOF was recorded in the daytime on the path Magadan–Irkutsk and in the morning and evening hours on the path Norilsk–Irkutsk. The positive disturbances in the MOF observed at both paths in the night hours on 23 March might be associated with the appearance of anomalous ionization in the point of reflection. The MOF increased in the daytime and evening hours next day after the storm. Moreover, the important fluctuations of MOF with the amplitude up to 4 MHz were observed on the path Magadan–Irkutsk. But their magnitude did not be over 2 MHz for MOF on the path Norilsk–Irkutsk. The most probable reason of these MOF fluctuations is the traveling ionospheric disturbances (TID) moving under the different angles to the studied paths.

The comparison of the ionospheric parameters variations during two March periods indicates that the variations of the foF2 and MOF at the subauroral and middle latitude during the minor and moderate geomagnetic disturbances depend slightly on the storm intensity.

As can be seen from figures, the AE index variations cannot explain these foF2 and MOF variations. The AE index value changed in the range from 0 to 500 nT during the first period. It increased up to 1000 nT only in the storm main phase on 13 March. So the decrease of the day foF2 and MOF on 15 March did not connect with the variation of AE index. During the second period AE index increased to 1000 nT on 24–26 March, but it did not correlate with the variations of the foF2 and MOF.

The geophysical conditions of experiment performed on September 2007 were quiet all month ($D_{st} > -30$ nT and $K_p < 4$). The geomagnetic activity increased only at the end of month beginning from 27 September. Fig. 10 presents the variations of AE, K_p, D_{st}, foF2 and MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk on 22–25 September. At high latitude (Norilsk) the fall of foF2 in the evening and the anomalous nighttime ionization were observed on 22–24 September caused by the minor increase of AE and K_p. The daytime disturbances were negative. In Magadan and Irkutsk the disturbances were mainly negative both in the daytime and at night. Only in the day on 23 September the positive disturbance were observed. The fluctuations of MOF above the median with amplitude to 6 MHz were observed on the path Magadan–Irkutsk on 23 September when both K_p and D_{st} increased their magnitude. Next day the MOF were lower than the median in the evening hours. The changes of MOF were little. The lack of the data on this path in the night is caused by the low level of ionization in the main ionospheric trough that moved to the region of signal reflection.

3. Summary

We performed the analysis on the data of vertical and oblique-incidence sounding and the observations of atmospheric emission obtained during the prolonged

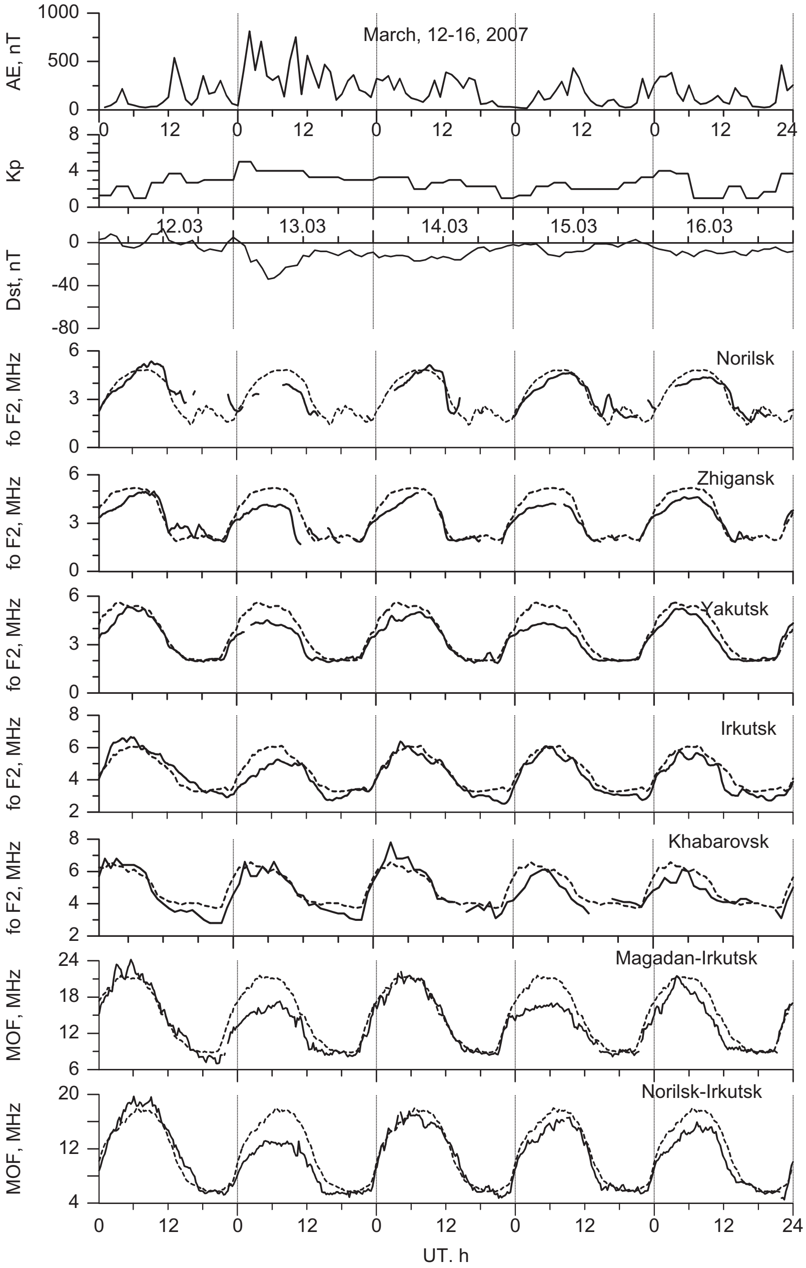

Fig. 8. Variations in the AE, K_p, D_{st} and foF2 on the meridional chain of station and MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk on 12–16 March 2007. Dashed lines show the values of foF2 in the quiet day and the median of MOF, thick lines correspond to their current values.

experiments in the period 2005–2007. The results may be summarized as follows.

- Large daytime negative disturbances are observed during the main and recovery phases of large storms (Figs. 2, 6 and 8) mainly at high latitudes. Positive disturbances observed during the daytime in the storm main phase are registered at middle latitudes (Figs. 2 and 6). Our result is consistent with previous studies (Buonsanto, 1999; Danilov and Lastovicka, 2001). The alteration of the disturbances sign in the region of East Asia came about between Yakutsk and Irkutsk.
- During the main and recovery storm phases in the afternoon and evening hours the sudden fall of the foF2 (sudden density drop associated with the equatorward wall of the main ionospheric trough) is observed (Figs. 2 and 6). It also distorts the characteristics of ionospheric radio channel.
- Fluctuations of the electron density more intensive at the middle latitudes during the storm main phase are observed in essentially all considered periods (Figs. 2,

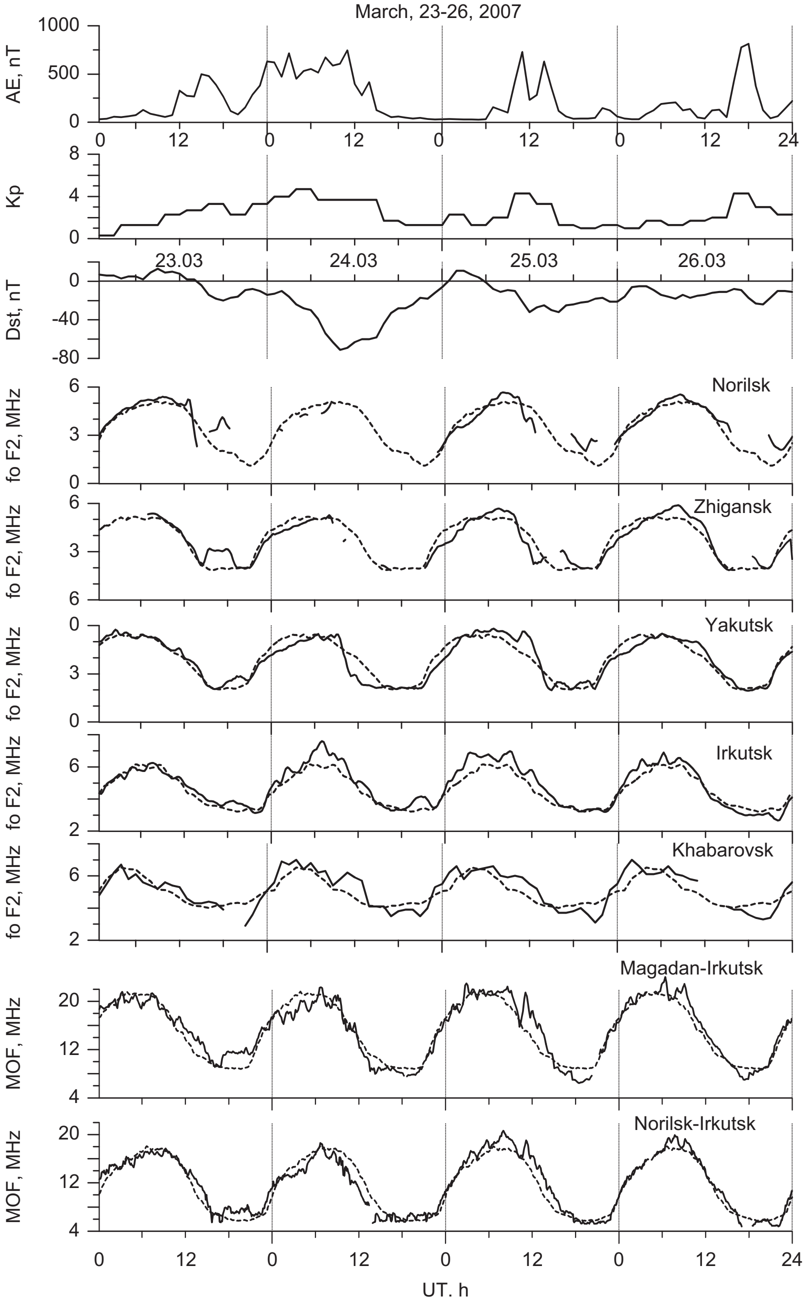

Fig. 9. Variations in the AE, K_p, D_{st} and foF2 on the meridional chain of station and MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk on 23–26 March 2007. Dashed lines show the values of foF2 in the quiet day and the median of MOF, thick lines correspond to their current values.

6, 9 and 10). They are noted on the ionograms of vertical sounding and registered by Irkutsk IS radar. Sharp gradients of electron density result in the strong changes in the characteristics of the radio wave propagation, particularity MOF; their magnitude depends on the variation of the foF2 and the height of the F2 layer maximum along the path of the radio signal propagation. Fluctuations of the density often in excess of the quiet level might be classified as the traveling ionospheric disturbances (TID). They might be caused by acoustic gravity waves (AGWs) of the auroral origin and propagate out of the auroral region (Hajkowicz and Hunsucker, 1987; Hocke and Schlegel, 1996). The significant part of them is caused by gravity waves from below with various propagation directions; there are also fluctuations of direct solar and geomagnetic origin (Prölss and Ocko, 2000; Bauske and Prolss, 1997; Lastovicka, 2006; Karpachev and Deminova, 2004). Nevertheless, it is essential in addition to investigate this phenomenon, its origin and parameters in future work.

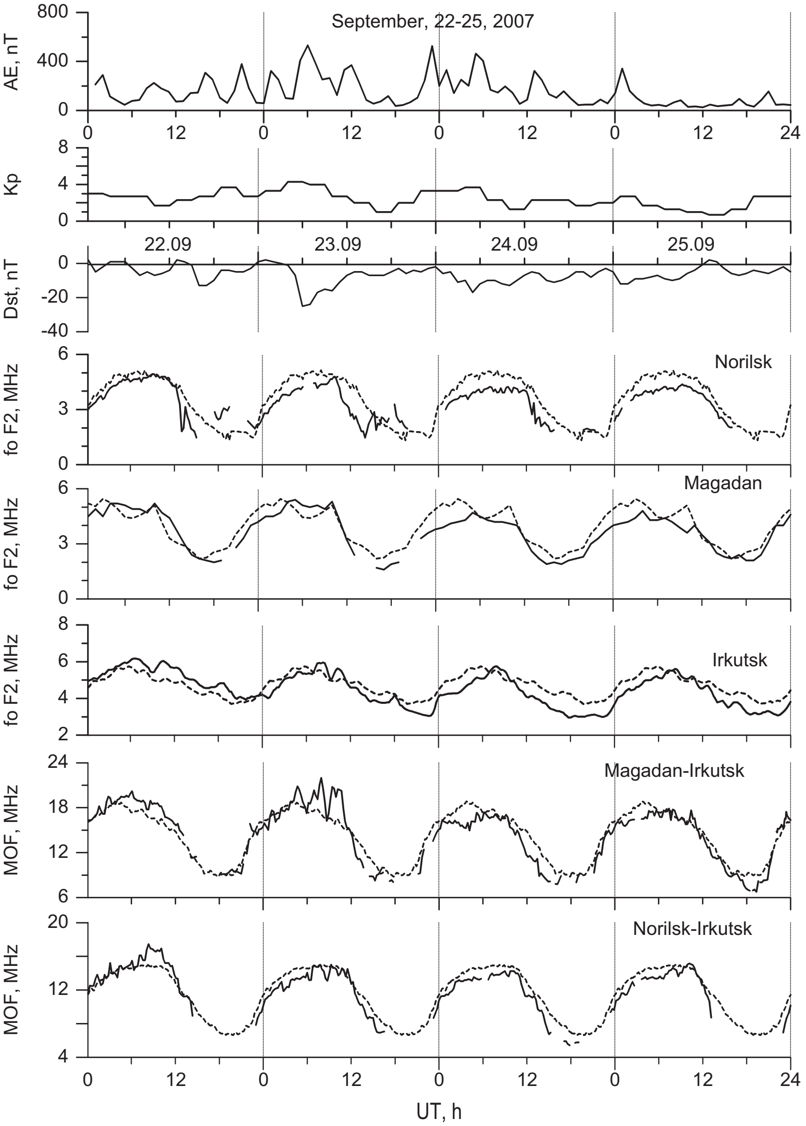

Fig. 10. Variations in the AE, K_p, D_{st} and foF2 on three stations and MOF on the paths Magadan–Irkutsk and Norilsk–Irkutsk on 22–25 September 2007. Dashed lines show the values of foF2 in the quiet day and the median of MOF, thick lines correspond to their current values.

- A large-scale ionospheric disturbance noted on the meridional chain of ionosonds in December is similar to the disturbance observed on October 2003 in Europe and on November 2004 in East Asia (Kunitsyn et al., 2004; Pirog et al., 2007). It causes the strong variation of the critical frequency and the peak height in the F2 layer. Their characteristics do not exactly correspond to the TID. Mendillo and Klobuchar (2006) suggested that such large positive disturbance associated with a "dusk" effect" followed by a "trough effect". However, the night maximum which appears after that in the middle latitudes (Irkutsk and Khabarovsk) does not fit in the above classification. It indicates that the interaction between atmospheric, ionospheric and magnetospheric processes is more complicated. The mechanism of generation and propagation of such disturbance has not been clarified to the end. There is a considerable need for additional model and morphology studies of the storm.
- Disturbances in the variations of the 630 nm emission in Asian region during the recovery phase of magnetic storm have a specific peculiarity: they are most pronounced in the first half of night (Figs. 3, 5 and 7). Disturbances of the 630 nm emission, which occurred during the recovery phase of magnetic storms, are often interpreted as SAR arcs (Mikhalev et al., 2005). The main 630 nm emission maxima above Irkutsk agree with the MOF rise on the path Norilsk–Irkutsk and correspond to the foF2 increase.
- The obtained experimental data on the net of vertical and oblique-incidence sounding ionosondes with high time resolution show that such net is the effective

facility to study the conditions of the radio wave propagation and can be used for the diagnostic of the ionosphere.

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References

Afraimovich, E.L., Kosogorov, E.A., Leonovich, L.A., Pirog, O.M., 2002. Global pattern of large-scale ionospheric disturbances during the magnetic storm of September 25, 1998, as inferred from GPS network data. Geomagnetizm and Aeronomy 42, 467–473.

Afraimovich, E.L., Voeykov, S.V., Perevalova, N.P., Ratovskii, K.G., 2006. Large-scale disturbances of auroral origin during geomagnetic storms on October 29–31, 2003 and November 7–11, 2004 according to the data of GPS and ionozondes. Geomagnetizm and Aeronomy 46, 637–642.

Barbier, D., 1959. Recherches sur la raie 6300 de la uluminescence atmospherique nocturne. Annals of Geophysics 15, 179–217.

Bauske, R., Prolss, G.W., 1997. Modelling the ionospheric response to traveling atmospheric disturbances. Journal of Geophysical Research 102, 14555–14562.

Blagoveshchensky, D.V., Pirog, O.M., Polekh, N.M., Chistyakova, L.V., 2003. Mid-latitude effects of the May, 15, 1997 magnetic storm. Journal of Atmospheric and Solar-Terrestrial Physics 65, 203–210.

Buonsanto, M.J., 1999. Ionospheric storms—a review. Space Science Review 88, 563–601.

Danilov, A.D., Belik, L.D., 1991. Thermospheric interaction during ionospheric storms. Geomagnetism and Aeronomy 31, 209–223.

Danilov, A.D., Lastovicka, J., 2001. Effects of geomagnetic storms on the ionosphere and atmosphere. International Journal of Geomagnetism and Aeronomy 2, 1–24.

Degtyarev, V.I., Kostyleva, N.V., Mikhalev, A.V., 2004. Correlation of midlatitude airglow characteristics with the state and dynamics of magnetospheric–ionospheric structures during geomagnetic disturbances. In: Tenth Joint International Symposium on Atmospheric and Ocean Optics/Atmospheric Physics II. Proceedings of the SPIE 5397, 340–347.

Field, P.R., Rishbeth, H., 1997. The response of ionospheric F2-layer to geomagnetic activity: an analysis of worldwide data. Journal of Atmospheric and Solar-Terrestrial Physics 59, 163–180.

Fuller-Rower, T.J., Codrescu, M.V., Moffett, R.J., Quegan, S., 1994. Response of the thermosphere and ionosphere to geomagnetic storms. Journal of Geophysical Research 99, 3893–4011.

Fuller-Rower, T.J., Codrescu, M.V., Rishbeth, H., Quegan, S., 1996. On the seasonal response of the thermosphere and ionosphere to geomagnetic storms. Journal of Geophysical Research 101, 2343–2353.

Hajkowicz, L.A., Hunsucker, R.D., 1987. A simultaneous observation of large-scale periodic TIDs in both hemispheres following on onset of auroral disturbances. Planetary and Space Science 35, 785–791.

Hocke, K., Schlegel, K.A., 1996. A review of atmospheric gravity waves and traveling ionospheric disturbances: 1982–1995. Annals of Geophysics 14, 917–940.

Ivanov, V.A., Kurkin, V.I., Nosov, V.E., Uryadov, V.P., Shumaev, V.V., 2003. Chirp ionosonde and its application in ionospheric research. Radiophysics and Quantum Electronics 46, 821–851.

Karpachev, A.T., Deminova, G.F., 2004. Planetary pattern of large-scale IGW effects in the ionosphere during the March 22, 1979, Storm. Geomagnetizm and Aeronomy 44, 737–750.

Kunitsyn, V.E., Khudukon, B.Z., Kozharin, M.A., Nesterov, I.A., Kozlova, M.O., 2004. Gelio-geophysical disturbances of the European ionosphere on October 2003 using GPS-tomography and ionosondes data. Moscow University Physics Bulletin 6, 12–16.

Lastovicka, J., 2006. Forcing of the ionosphere by waves from below. Journal of Atmospheric and Solar-Terrestrial Physics 68, 479–497.

Mendillo, M., Klobuchar, J., 2006. Total electron content: synthesis of past storm studies and needed future work. Radio Science 41, RS5SO2.

Mikhalev, A.V., Beletskii, A.B., Kostyleva, N.V., Chernigovskaya, M.A., 2005. Characteristics of midlatitude auroral during large geomagnetic storms within the current solar cycle. Atmospheric and Oceanic Optics 18, 144–148.

Pirog, O.M., Polekh, N.M., Tashchilin, A.V., Romanova, E.B., Zherebtsov, G.A., 2006. Response of ionosphere to the great geomagnetic storm of September 1998: observation and modeling. Advances in Space Research 37, 1081–1087.

Pirog, O.M., Polekh, N.M., Voeykov, S.V., Zherebtsov, G.A., Tatarinov, P.V., 2007. Ionospheric disturbances during geomagnetic storm in the East-Asian region in November, 2004. Advances in Space Research 39, 1335–1341.

Prölss, G.W., 2007. The equatorward wall of the subauroral trough in the afternoon/evening sector. Annals of Geophysics 25, 645–659.

Prölss, G.W., Ocko, M., 2000. Propagation of upper atmospheric storm effects towards lower latitudes. Advances in Space Research 26, 131–137.

Prölss, G.W., Brace, L.H., Mayer, H.G., et al., 1999. Ionospheric storm effects at subauroral latitudes: a case study. Journal of Geophysical Research 96, 1275–1288.

Ratovsky, K.G., Medvedev, A.V., Tolstikov, M.V., Kushnarev, D.S., 2007. Case studies of height structure of TID propagation characteristics using cross-correlation analysis of incoherent scatter radar and DPS-4 ionosonde data. Advances in Space Research 41, 1453–1467.

Zherebtsov, G.A., Pirog, O.M., Polekh, N.M., 2005a. Ionospheric effects of geomagnetic storms in different longitude sectors. Chinese Journal of Space Science 25, 468–473.

Zherebtsov, G.A., Pirog, O.M., Polekh, N.M., Ratovskii, K.G., Smirnov, V.F., Stepanov, A.E., Shi, J.K., Wang, X., 2005b. The ionospheric situation in the Eastern Asian longitudinal sector during the geoactive period October–November 2003. Geomagnetizm and Aeronomy 45, 101–108.

Zolotukhina, N.A., Polekh, N.M., Rakhmatulin, R.A., Kharchenko, I.P., 2000. Geophysical effects of the interplanetary magnetic cloud on October 18–19, 1995, as deduced from observations at Irkutsk. Journal of Atmospheric and Solar-Terrestrial Physics 62, 737–749.