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Modeling of ionospheric parameter variations in East Asia during the moderate geomagnetic disturbances

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Abstract

The results of modeling of ionospheric disturbances observed in the East Asian region during moderate storms are presented. The numerical model for ionosphere–plasmasphere coupling developed at the ISTP SB RAS is used to interpret the data of observations at ionospheric stations located in the longitudinal sector of 90–130°E at latitudes from auroral zone to equator. There is obtained a reasonable agreement between measurements and modeling results for winter and equinox. In the summer ionosphere, at the background of high ionization by the solar EUV radiation in the quiet geomagnetic period the meridional thermospheric wind strongly impacts the electron concentration in the middle and auroral ionosphere. The consistent calculations of the thermospheric wind permit to obtain the model results which are closer to summer observations. The actual information about the space-time variations of thermosphere and magnetosphere parameters should be taken into account during storms.

Keywords: Ionospheric storm; Geomagnetic disturbance; Critical frequencies; F2-layer; Plasmasphere; Photoionization; Recombination; Thermosphere; Magnetosphere; Convection; Neutral wind; Drift

1. Introduction

The ionospheric response to a geomagnetic disturbance is a complex set of events caused by both the upper atmosphere and ionosphere parameters and characteristics of the magnetosphere and solar wind. This response is a subject of many-year studies, the results being presented in numerous reviews (Buonsanto, 1999; Danilov and Lastovicka, 2001; Fuller-Rowell et al., 1996). The theoretical and experimental studies of the ionosphere during magnetic storms made it possible to find the main physical processes determining the electron concentration distribution in the ionosphere at various latitudes and to present the most general picture of an ionospheric storm manifestation. Changes in the neutral composition and system of neutral wind circulation are the most important factors determining ionospheric variations during a geomagnetic storm (Danilov and Belik, 1991; Prolss and Ocko, 2000; Reddy and Mayer, 1988; Rishbeth, 1998). At middle latitudes the negative and positive effects of storms are observed more often in summer and winter, respectively (Rodger et al., 1989; Field and Rishbeth, 1997). Fuller-Rowell et al. (1994) noted that the ionospheric response to a geomagnetic disturbance in a particular place depends on both, local and universal time. A typical storm consists of an initial positive phase later changed to a negative phase. The duration and intensity of these two phases depend on latitude and season.

Disagreement between the geographic and magnetic coordinates complicates the picture of ionospheric disturbances and leads to a longitudinal dependence of the ionospheric effects of geomagnetic storms (Afraimovich et al.,

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2002; Blagoveshchensky et al., 2003; Pirog et al., 2006b; Zherebtsov et al., 2005). In the Eastern Asia, the strongest deviation of geographic coordinates from geomagnetic coordinates is observed. In this sector the formation of the high-latitude large-scale structure of the ionosphere occurs on the background of relatively low electron concentration. The latter fact determines an increased interest to this region. Our investigations of ionosphere manifestations of magnetic storms in the Eastern Asia are continued in three directions: quiet ionosphere, weak and moderate storms, and great storms. In the previously works (Pirog et al., 2006a; Romanova et al., 2006) we presented the results of a morphological analysis and numerical modeling of the ionospheric state during storms observed in different seasons. The morphological analysis has produced the following conclusions. (1) For summer storms, negative disturbances prevail both at high and middle latitudes. At low latitudes, the disturbances mainly have a positive type. (2) In winter the daytime disturbances are positive in the beginning of the storm at all stations involved. During the early recovery phase they are negative at high and positive at middle latitudes. Night disturbances are positive at high latitudes, while being negative at middle latitudes. At low latitudes the disturbances are positive both in daytime and at night during all storms. (3) During an equinox storm positive disturbances are observed in the beginning of the storm, with negative disturbances observed during the main and recovery phases both at high and middle latitudes. At low latitudes they are both positive and negative with high amplitudes. (4) The disturbances change their sign near 30° geomagnetic latitude. Similar effect has been found in the study (Pirog et al., 2001a; Araujo-Pradere and Fuller-Rowell, 2002). It correlates with the change in global circulation (Araujo-Pradere et al., 2004). (5) The results of model simulations and the observed data were obtained by correcting the MSIS-86 thermospheric model which has a different character for summer and winter conditions. It was suggested that this reflects real variation of thermospheric composition during storm depending on the season. Such variations in the neutral composition of the thermosphere can result in the ionospheric storms being negative in summer while positive in winter. The disagreement of the modeled and measured values in the evening hours at high-latitude stations is determined by the variations in the auroral fluxes what are not described by the statistical model and also by the processes related to the motion of the main ionospheric trough.

This paper focuses on modeling the ionospheric effects and processes during moderate storms.

2. Modeling of the vertical sounding data

We have studied variations in the critical frequencies of the F2 and Es layers and also in the heights of the F2-layer maximum during a storm, including the initial and recovery phases. The hourly values of foF2, h′F, and hmaxF2 averaged over several quiet days of the month were used as the quiet level. Table 1 presents the geographic and geomagnetic coordinates of the ionospheric stations from whose data were used in this study.

As indicated earlier there exist differences in the manifestation of the ionospheric response in different seasons particularly during the recovery phase (Pirog et al., 2006b). The local-night storms with closely related intensities (Dst ≈ 80–100 nT) have been selected in this investigation.

2.1. Description of the model

A numerical model for ionosphere–plasmasphere coupling (Krinberg and Tashchilin, 1980; Tashchilin and Romanova, 1995, 2002) is used to interpret the observational data on the ionospheric response to the geomagnetic disturbances. The model is based on numerically solving a system of nonstationary balance equations of atomic (O^+, H^+, N^+, He^+) and molecular ($N_2{}^+$, $O_2{}^+$, NO^+) ions in conjunction with thermal plasma energy equations within closed geomagnetic flux tubes whose foots are at the height $h_0 = 100$ km. Concentrations of all ions, except $N_2{}^+$, are calculated taking into account the processes of photoionization, impact ionization by the magnetospheric electrons and recombination. Apart from ion transport along geomagnetic field lines due to ambipolar diffusion and the horizontal thermospheric wind, we also took into account the drift of plasma across magnetic field lines. The reference spectrum of the EUV radiation from Richards et al. (1994) is used for calculating the photoionization of thermospheric constituents and energetic spectra of the primary photoelectrons.

Electron and ion temperatures are calculated taking into account the heat conduction processes along geomagnetic field lines and of the thermal energy exchange between electrons, ions, and neutral species due to elastic and inelastic collisions. The rate of thermal electron heating is calculated self-consistently by solution of the kinetic equation of photoelectron transport in the conjugated ionospheres. The global empirical thermospheric model MSISE-90 (Hedin, 1991) is used to describe space-time variations of the temperature and concentration of the neutral constituents O, O_2, N_2, H, and N. The velocities of the horizontal thermospheric wind are determined from the HWM-90 model (Hedin et al., 1991).

Table 1
The list of ionospheric stations and their coordinates

Stations	Symbol	Geographic		Geomagnetic	
		Latitude	Longitude	Latitude	Longitude
Norilsk	NO	69.20	88.26	58.71	165.7
Zhigansk	ZH	66.3	123.4	55.2	190.0
Yakutsk	YA	62.0	129.6	50.99	194.1
Irkutsk	IR	52.5	104.0	41.1	174.8
Manzhouli	ML	44.0	117.0	32.0	189.0
Beijing	BP	40.0	116	28.7	188
Chongqing	CQ	29.0	106	18.1	177.8
Guanghou	GU	23	113	11.7	184
Hainan	HA	19.5	109.1	8.1	178.95

The values of the integral flux and mean energy of the precipitating electrons needed to calculate the auroral ionization rates are taken from the global model of electron precipitation by Hardy et al. (1987). The electric field of magnetospheric convection is determined according to the empirical model of the potential distribution (Sojka et al., 1986) for high-latitude ionosphere, and for the equatorial ionosphere according to the model of Richmond et al. (1980).

The reactions of the ionosphere to the selected geomagnetic storms are reproduced from modeling variations of the plasma parameters within the entire magnetic field tubes whose foots for the North hemisphere are located in the points with the geographical coordinates of ionospheric stations shown in Table 1. To obtain the spatial distributions of the charged particle density and temperatures and particle and heat fluxes at a certain time UT it is necessary to integrate the system of model equations simultaneously for a set of plasma tubes that move in different drift trajectories. In this manner the general solution algorithm is divided into two stages. The first stage includes calculating drift trajectories by integrating the equations of motion of the plasma tube under the action of convection and corotation electric fields backward in time from a given UT to a certain initial time UT_0. Time variations of the electric field are taken into account through the use of actual hourly values of variations of the geomagnetic activity indexes (Kp, Ap) and IMF-components (Bz, By) which are input parameters for empiric model of the electric field. The second stage involves calculating initial profiles of ion densities and temperatures along the field lines. Next the equations of ionospheric plasma balance are forward-integrated along drift trajectories from the initial time UT_0 to a given UT. The variations in parameters of precipitations, neutral atmosphere and thermospheric wind also are taken into account due to actual variations of the hourly geomagnetic activity indexes.

The model calculations were performed for three storms described below. In this study the initial distributions of the concentrations, temperatures, and fluxes of ions and heat along geomagnetic field lines were determined at time $UT_0 = (UT - 120)$ h for the storms under consideration. Such integration interval provides for an undisturbed level of the plasmasphere filling at the middle and low latitudes (Krinberg and Tashchilin, 1984).

At present the most difficulty in the study of the ionospheric response to a magnetic storm is a lack of available data of the thermospheric and magnetospheric parameters during actual geomagnetic storms. Because of this, to interpret the observed ionospheric data two versions of a model calculation were realized for the period spanning both undisturbed and disturbed days for the each storm under study. In the first version, the variations of magnetospheric inputs and thermospheric parameters were specified according to the previously reported empirical models. In the second version, those empirical models were adjusted to obtain the closest approach to the observed data.

2.2. Consideration of observed data and results of modeling

Figs. 1–3 represents variations of observed and calculated foF2 during three storms with relatively close intensities (Dst $\approx$ 80–100 nT) observed in different seasons.

A winter storm with main phase in the night LT hours (12–18 UT) and minimum value of the index Dst = −103 nT on February 11, 2004 is shown in Fig. 1. The value of Kp in this period does not exceed 6. Local time at stations is universal time plus Δt, where Δt is equal to 6–8 h depending on the longitude of station (see Table 1).

During the main and recovery phases (12–24 UT on February 11) at night at high latitudes, the disturbances are positive, whereas at middle latitudes they are negative. Anomaly reflections both in F and E-region typical for auroral zone are observed in Norilsk, Zhigansk and Yakutsk. At low latitudes the disturbances are positive both in the daytime and at night. In the recovery phase on February 12 the disturbances in the daytime hours are negative at high and positive at middle latitudes. At Hainan oscillations of foF2 were observed in both main and recovery phase of the storm.

The calculated values of foF2 also satisfactorily correspond to the daytime measurements. The simulation results at sub-auroral station Yakutsk agree with observations better then at other stations both in the daytime and at night. The strongest differences are found in the evening and night-time at equatorial station Hainan.

During the summer storms the disturbances are predominantly negative both at high and middle latitudes. Fig. 2 shows the variations in foF2 during the summer storm on July 15–18, 2004. Unfortunately we have got only Chinese station Hainan for this storm. The illumination conditions determined the weakly pronounced diurnal behavior at high latitudes with a slight decrease before the midnight. At stations Zhigansk and Yakutsk the quiet diurnal behavior of foF2 had a maximum around the midnight and a minimum in the morning hours of the local time. This effect was discussed previously (Pirog et al., 2001a,b). With a decrease of latitude, the difference between the minimum and maximum values of foF2 increased. In Hainan, a well pronounced diurnal behavior with a maximum and a minimum in the afternoon and morning hours, respectively, was observed. During the main and recovery phases of storm (23 UT on July 16 – 02 on July 17) the disturbances were negative at high latitudes. In Irkutsk the disturbances were less pronounced. In Hainan the disturbances were positive in the afternoon and negative in both evening and night hours. It is worth noting that the positive peak of foF2 was observed immediately after midnight on July 16 and 18.

A good agreement between the measured and calculated values of foF2 in the daytime both at high and mid latitudes is obtained. The model does not reproduce the evening peaks of foF2 at the stations Zhigansk and Yakutsk and sharp decrease of foF2 during storms at high latitudes.

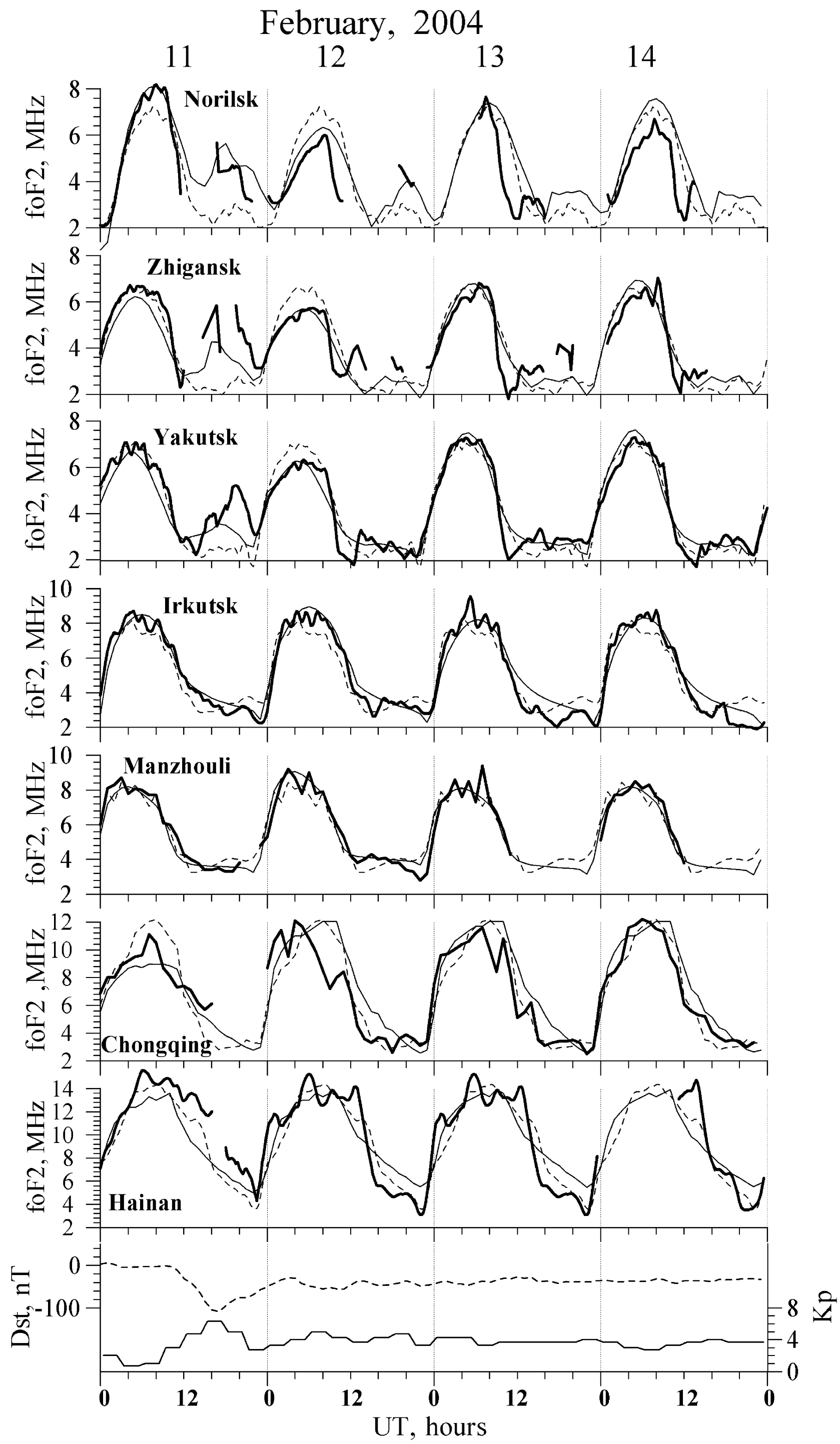

Fig. 1. Variations in critical frequencies of the F2 layer during the storm on February 11–14, 2004. Thick lines show current values of foF2; dashed lines show the diurnal behavior of foF2 in undisturbed time; solid lines are values calculated by the model. Values of the Kp and Dst indices are shown at the bottom. LT = UT + Δt, where Δt is equal to 6–8 h depending on the longitude of station (see Table).

At Hainan the main differences between measured and calculated values are found in the evening and night-time.

Fig. 3 shows the moderate storm with two minima of Dst on March 9–14. Negative disturbances during the main and recovery phases on March 9–10 were observed both at high and middle latitudes in the daytime and at night. The disturbances were positive at the low latitudes. The reversal of the sign occurred in the vicinity of a geomagnetic latitude of 30°N. During the second decrease of Dst on March 12 the amplitudes of negative disturbances at mid latitudes decreased in daytime and increased at night. Oblique reflections from the poleward wall of the trough were seen in the ionograms at Yakutsk. The auroral ionization zone was located northward from Yakutsk during the entire period.

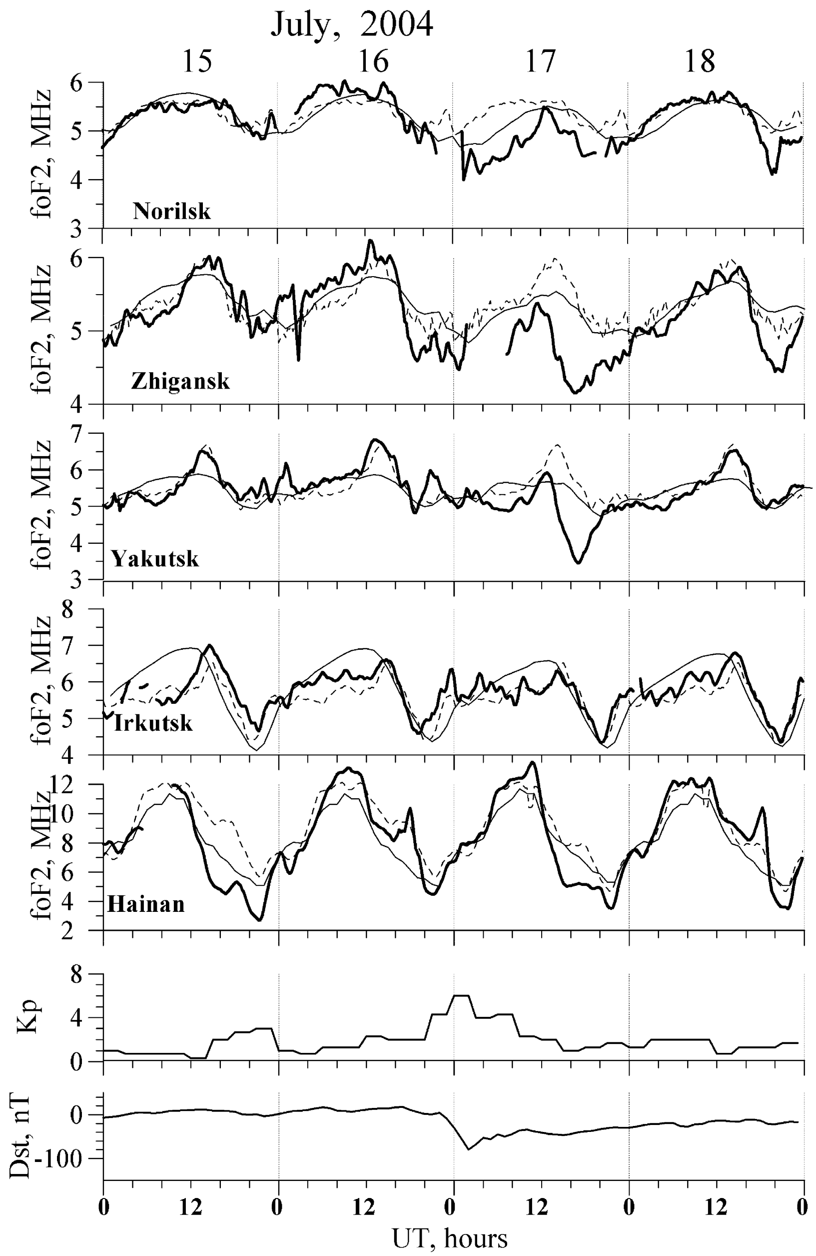

Fig. 2. The same as in Fig. 1, but for 15–18 July 2004.

In Hainan the disturbances were positive in day and negative in both evening and night hours as in summer. The absence of season dependence in Hainan reasonable for the station located close to the equator.

Calculated variations of the foF2 fitted well with those measured at mid latitude stations Irkutsk, Manzhouli and Beijing with the exception of the evening on March 12, when the very low values of foF2 were observed. Model values of the foF2 at two high latitude stations did not consist with those observed at the night, when the ionization was determined by precipitating electron fluxes. Calculated values of foF2 also satisfactorily corresponded to the daytime measurements at equatorial stations.

The differences between the measured and calculated value of foF2 in evening and night-time at equatorial latitudes can be the result of not correct values of the drift and thermospheric wind velocities. In spite of the fact that the model does not reproduce the storm variations of equatorial ionosphere in detail it describes its qualitative structure well enough. The latitude–altitude electron density distributions are presented in Fig. 4. From this figure we notice daytime ionization crests at 05 UT and the nighttime increasing of Ne above equator at 16 UT. These phenomena are typical for the equatorial ionosphere.

3. Discussion

Nowadays, the ionospheric storm is believed to be a superposition of two oppositely directed actions on the $[O]/[N_2]$ value in the F2 region maximum. Heating of the

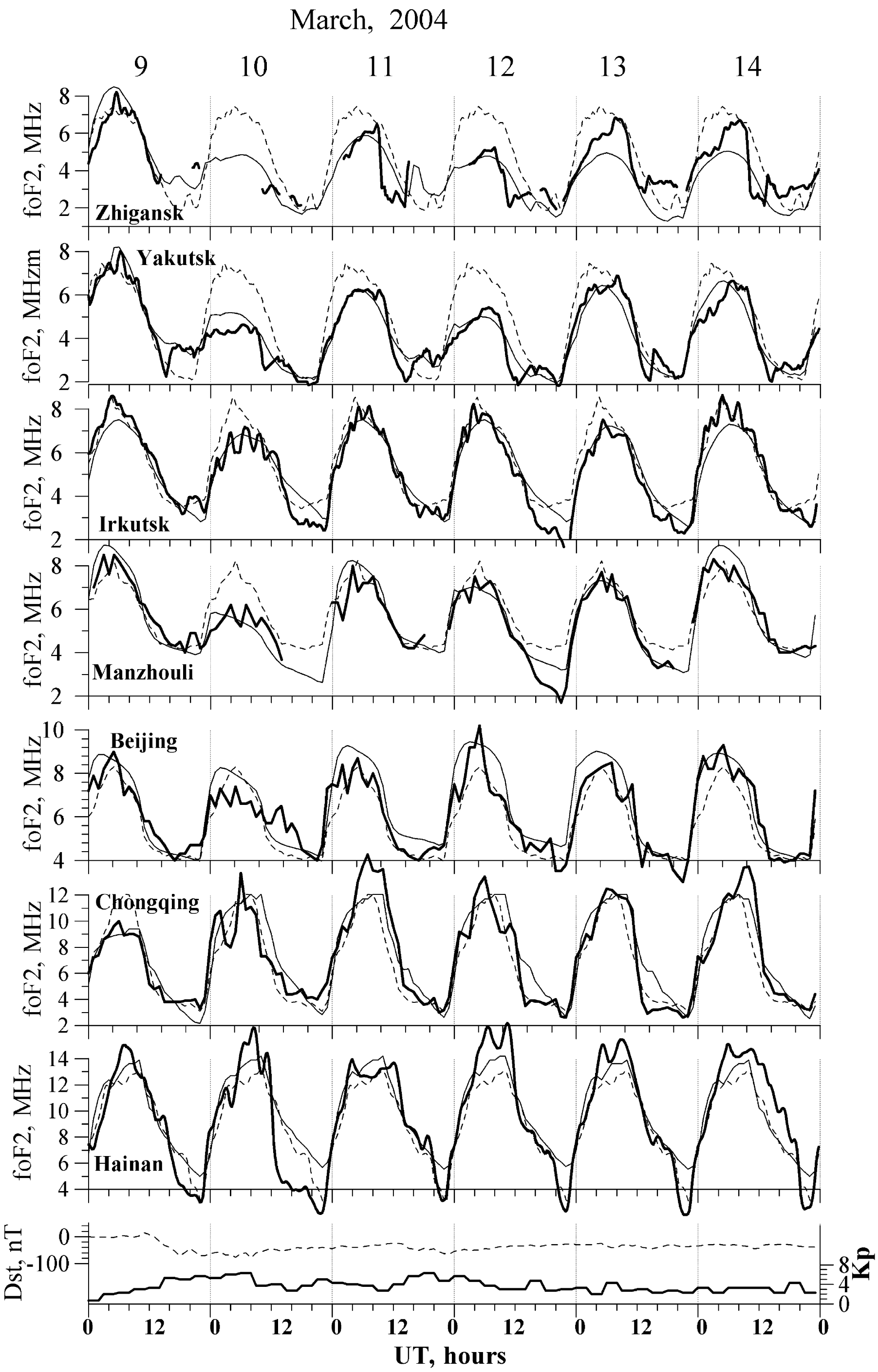

Fig. 3. The same as in Fig. 1, but for 9–14 March 2004.

atmosphere during disturbances is the main process which decreases the [O]/[N_2] ratio near the peak of F2-layer and it forms the storm negative phase. The positive phase of the ionospheric storm is associated with increasing of the ionization density can be caused by two processes: either the horizontal transport of thermospheric gas with an elevated [O]/[N_2] ratio or lifting of the F2 layer maximum under the action of the vertical drift that is initiated by electric fields or by the meridional wind (Danilov and Belik, 1991). Besides, at auroral and high latitudes, the influence of fluxes of precipitating energetic electrons should be taken into account.

In model calculations we present here the effect of these processes is taken into account through using empirical models of magnetospheric sources and thermospheric parameters which can not reproduce their actual variations for real storms. As shown previously (Romanova et al., 2006) this is the reason of the discrepancy between the modeling results and measurements at evening and night hours at high-latitude stations. On the whole, the using

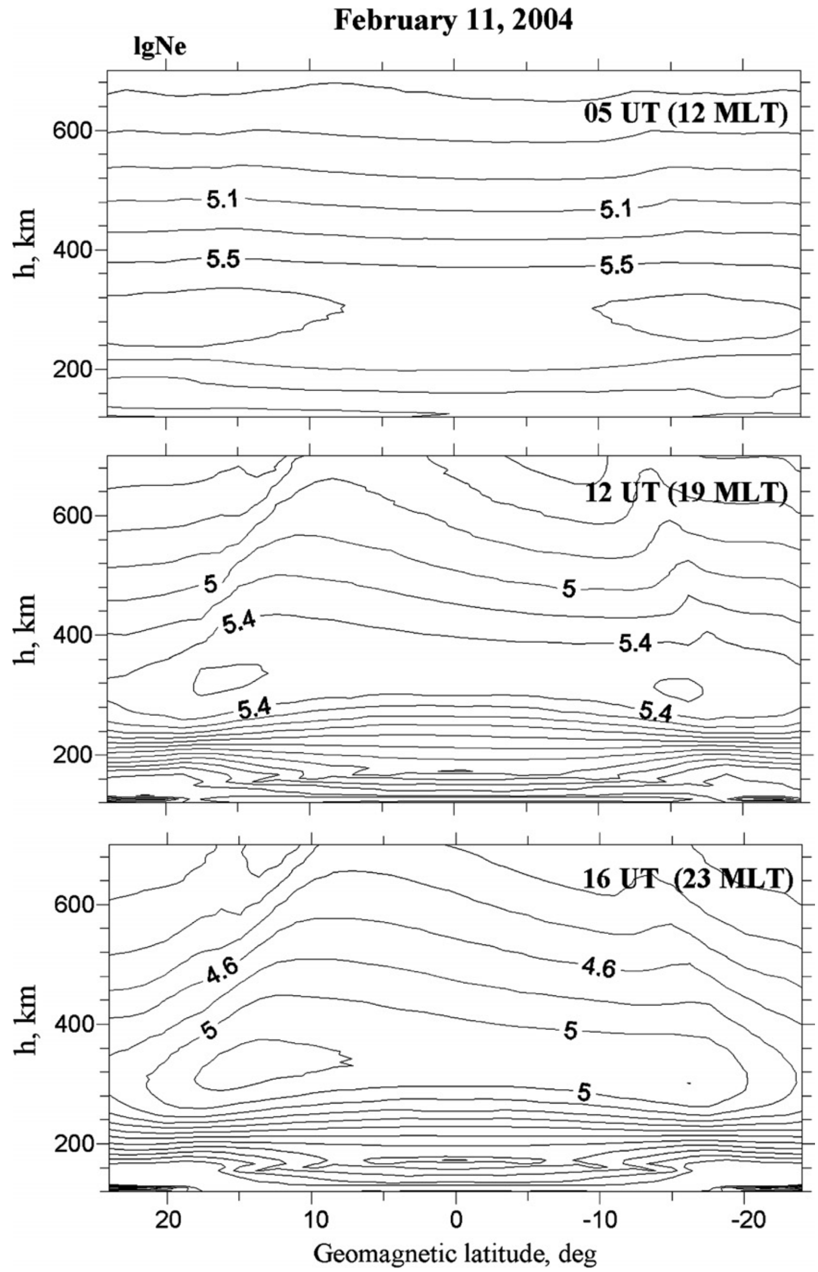

Fig. 4. Distributions of lgNe in the plane of magnetic meridian 179°E in a system of coordinates altitude–geomagnetic latitude.

of empirical models of magnetospheric inputs, and the correction of the [O]/[N_2] ratio for the disturbed conditions can give a reasonable agreement between modeling results of the ionospheric response to moderate storms and observed data. Similar method for correcting the MSIS model for the negative phase was used by Buonsanto et al. (1999), Mikhailov and Forster (1999), Emery et al. (1999).

Of particular interest is the summer period of research, for which the discrepancy was greatest between the modeling results and the foF2 measurements. In summer, the whole ionosphere at geomagnetic latitudes more than 62° is constantly illuminated. The high ionization is provided by the solar EUV radiation. At the background of this ionization, the role of magnetospheric sources in the formation of electron density profile reduces for low and moderate geomagnetic activities, whereas the effect of the thermospheric wind on the formation of the electron density profile both at the mid and high latitudes is still essential (Hagan, 1988; Buonsanto et al., 1999; Emery et al., 1999; Prolss and Ocko, 2000). As mentioned above, in this study the influence of magnetospheric inputs was solely by empirical models. In accordance with the specification the equatorial boundary of precipitations and magnetospheric convection during moderate geomagnetic disturbances is about the geomagnetic latitude 60° (Sojka et al., 1986) and it lies between auroral and polar regions. To estimate the effect of these magnetospheric inputs on the electron density variations in the high-latitude ionosphere for summer conditions the calculations did not take into account the convection and electron precipitations for two ionospheric stations Norilsk and Zhigansk. The results did not essentially differ from those presented in Fig. 2. Only values of critical frequencies foF2 calculated without taking into account precipitations and convection were 0.4 MHz less than measured data during the period 04:00–12:00 LT on July 17, 2004. This demonstrates that the employed empirical models of the magnetospheric convection and precipitations provide an insignificant contribution to the calculated variation of the electron density for storm in question.

To estimate the contribution of the horizontal thermospheric wind to the deviation of the modeling results from the observations at the middle and subauroral latitudes we have made three calculation variants for ionospheric stations Irkutsk and Yakutsk: (1) without thermospheric wind; (2) taking the wind into account according to the HWM-90 model; (3) wind velocities were calculated by the method of Kohl and King (1967) mutually consistently with the ionospheric equations. The calculation results are presented in Fig. 5. Time variations of the electron density above Irkutsk and Yakutsk are plotted in Fig. 5a (top panel) for three variants. At the bottom panel (Fig. 5b) appropriated variation of the wind projection along a geomagnetic field line $U_{\|}$ are shown.

At the ionospheric station Yakutsk the behavior of the critical frequency, obtained by variant 1, is closed to the quiet conditions in the daytime, while the night values foF2 were

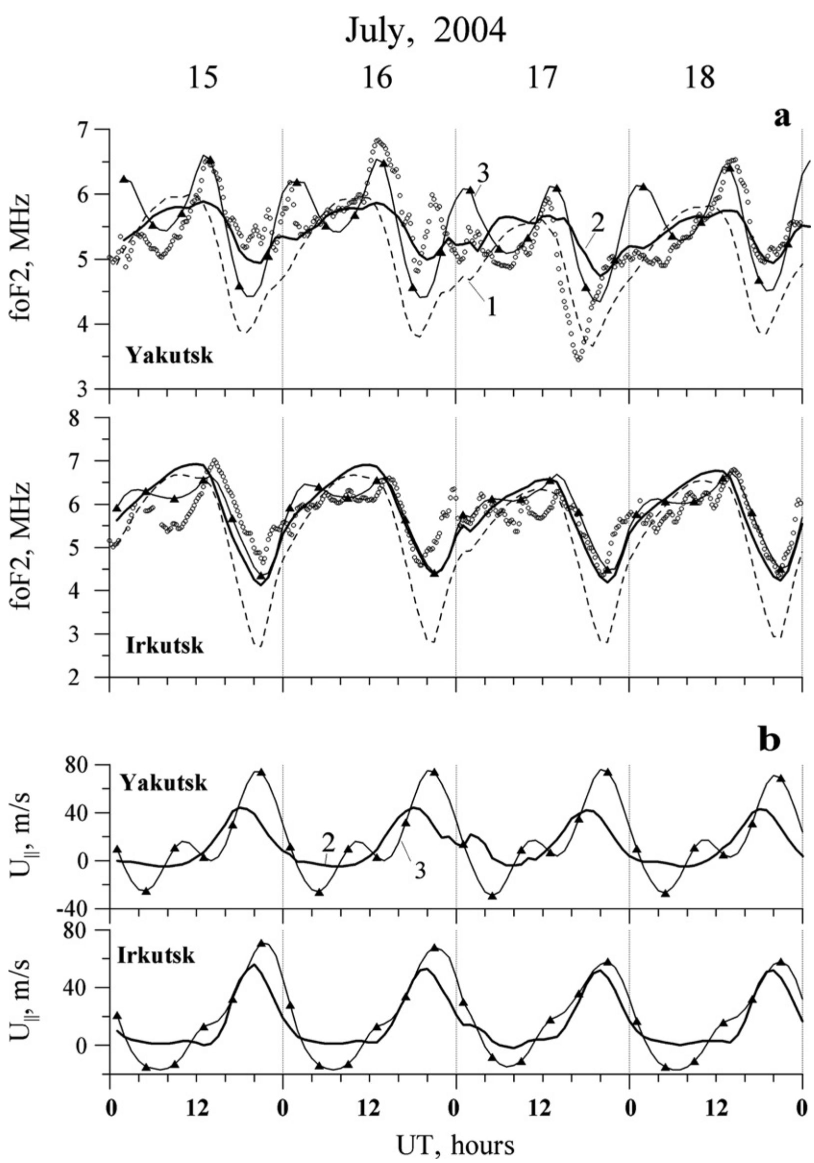

Fig. 5. Variations in foF2 for 15–18 July 2004 at two stations (a). Open circles show measured values of foF2. Solid lines show values calculated by the model without considering the neutral wind – variant 1; dashed lines are values calculated by the model with consideration the neutral wind obtained from HWM90 – variant 2; lines with triangles are values calculated by the model with velocities of the neutral wind obtained by approximate method of Kohl and King (1967) – variant 3. Projections of velocities of the neutral wind on the field lines for variants 2 and 3 are shown at the bottom (b).

1–1.5 MHz less than the measurements, except those obtained on July 17, 2004, when the calculations essentially coincided with the measurements. Variant 2 does not reproduce the daytime foF2 variation and its results have overrated night values. Simulation by variant 3 gives a good agreement with the observations for the quiet period but during the main and recovery phases of the storm the calculated values foF2 exceed of the measurements.

At the ionospheric station Irkutsk the calculations by variant 2 have produced too high values of the critical frequencies foF2 in the noon sector, but at night hours values of foF2 were found to be close with observations. The calculation results of variant 3 are in the best agreement with the observations. Only this variant is capable of giving two maxima in the daily variation of foF2 about 09 and 21 LT which are typical features of the summer midlatitude ionosphere (Kohl and King, 1967).

Table 2 presents the maximum and minimum departures of foF2 calculated for three variants according to the model from measurements and the relative errors. From Table 2 we notice that the error of calculation according to variant 3 is the least.

It is of interest to compare the calculation results of the foF2 by these variants and the time variations of the wind velocity projection along geomagnetic field line ($U_{\|}$) near F2-layer peak presented in Fig. 5b. It is well known that at middle latitudes in the night time the meridional equatorial wind supports the night ionization (particular in the winter), and in the daytime the meridional polarward suppresses the increase of ionization at about noon (particular in the summer). It follows from Fig. 5b that the summer F2 layer in both Irkutsk and Yakutsk is supported by the upward drift ($U_{\|} = 40$ m/s for variant 2, $U_{\|} = 80$ m/s for variant 3) at after-midnight LT hours. The daytime minimum, observed about 15 LT, coincides with downward drift that is clearly represented in variant 3. Two ionization peaks at 09 and 21 LT also are consistent with upward drift of variant 3. The fact that at the station Yakutsk the abrupt foF2 decrease agrees with the variant 1 calculations (without the wind) at the recovery phase at 16 UT on July 17, 2004, means that the meridional wind has not a pronounced effect on the support of ionization. The equatorward displacement of the main ionospheric trough due to the convection zone expansion during the storm can cause the abrupt decrease of electron concentration. Such situation was analyzed in detail in the paper by Romanova et al. (2006).

Thus, in the summer ionosphere, the electron concentration profile in quiet geomagnetic conditions is mainly controlled by the thermospheric wind both at the middle and auroral latitudes. The consistent calculation of the thermospheric wind permits to obtain the model results, which are closer to the observations both for quiet and disturbed summer periods. The real distributions of the magnetospheric convection and precipitations should be taken into account during magnetospheric storms.

Table 2
Maximum and minimum departures of foF2 calculated for three variants according to the model from measurements and the relative errors

	min δfo	max δfo	Error (%)
Variant 1	−1.30	2.55	15.59
Variant 2	−1.44	1.29	9.65
Variant 3	−1.10	0.92	6.84

4. Conclusion

Modeling results of the ionospheric response to moderate storms for winter and equinox conditions show that the using of empirical models of magnetospheric sources and thermospheric parameters, as well as the correction of the $[O]/[N_2]$ ratio, results in the good agreement with the foF2 observations. So this modeling can be used for the prediction of electron density during the moderate disturbances.

The analysis of the modeling results for summer conditions shows that at the background of high ionization by the solar EUV radiation in the quiet geomagnetic period the meridional thermospheric wind strongly impacts the electron concentration in the middle and auroral ionosphere, while during geomagnetic storms it is essential to take into account the real information about the space-time variations of both thermospheric and magnetospheric parameters.

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References

Afraimovich, E.L., Kosogorov, E.A., Leonovich, L.A., et al. Global pattern of large-scale ionospheric disturbances during the magnetic storm of september 25, 1998, as inferred from GPS network data. Geomagn. Aeron. 42, 467–473, 2002.

Araujo-Pradere, E.A., Fuller-Rowell, T.J. STORM: an empirical storm-time ionospheric correction model 2. Validation. Radio Sci. 37 (5), 1071, doi:10.1029/2002RS002620, 2002.

Araujo-Pradere, E.A., Fuller-Rowell, T.J., Bilitza, D. Time Empirical Ionospheric Correction Model (STORM) response in IRI2000 and challenges for empirical modeling in the future. Radio Sci. 39, RS1S24, doi:10.1029/2002RS002805, 2004.

Blagoveshchensky, D.V., Pirog, O.M., Polekh, N.M., et al. Mid-latitude effects of the May, 15, 1997 magnetic storm. J. Atm. Solar-Terr. Phys. 65, 203–210, 2003.

Buonsanto, M.J. Ionospheric storms – a review. Space Sci. Rev. 88, 563–601, 1999.

Buonsanto, M.J., Gonzalez, S.A., Lu, G., Reinisch, B.W., et al. Coordinated incoherent scatter radar study of the January, 1997 storm. J. Geophys. Res. 104, 24625–24637, 1999.

Danilov, A.D., Belik, L.D. Thermospheric interaction during ionospheric storms. Geomagn. Aeron. 31, 209–223, 1991.

Danilov, A.D., Lastovicka, J. Effects of geomagnetic storms on the ionosphere and atmosphere. Int. J. Geomagn. Aeron. 2, 1–24, 2001.

Emery, B.A., Lathuillere, C., Richards, P.G., et al. Time dependent thermospheric neutral response to the 2-11 November 1993 storm period. J. Atmos. Solar-Terr. Phys. 61, 329–350, 1999.

Field, P.R., Rishbeth, H. The response of ionospheric F2-layer to geomagnetic activity: an analysis of worldwide data. J. Atmos. Solar-Terr. Phys. 59, 163–180, 1997.

Fuller-Rowell, T.J., Codrescu, M.V., Moffett, R.J., et al. Response of the thermosphere and ionosphere to geomagnetic storms. J. Geophys. Res. 99, 3893–4011, 1994.

Fuller-Rowell, T.J., Codrescu, M.V., Rishbeth, H., et al. On the seasonal response of the thermosphere and ionosphere to geomagnetic storms. J. Geophys. Res. 101 (A2), 2343–2353, 1996.

Hagan, M.E. Effects of geomagnetic activity in the winter thermosphere 2.Magnetically disturbed conditions. J. Geophys. Res. 93, 9937–9944, 1988.

Hardy, D.A., Gussenhoven, M.S., Raistrick, R., et al. Statistical and functional representation of the pattern of auroral energy flux, number flux, and conductivity. J. Geophys. Res. 92, 12275–12294, 1987.

Hedin, A.E. Neutral Atmosphere Empirical Model from the surface to lower exosphere MSISE90. J. Geophys. Res. 96, 1159–1172, 1991.

Hedin, A.E., Biondi, M.A., Burnside, R.G., et al. Revised global model of thermosphere winds using satellite and ground-based observations. J. Geophys. Res. 96, 7657–7688, 1991.

Kohl, H., King, J.W. Atmospheric winds between 100 and 700 km and their effects on the ionosphere. J. Atmos. Terr. Phys. 29 (9), 1045–1063, 1967.

Krinberg, I.A., Tashchilin, A.V. The influence of the ionosphere–plasmasphere coupling upon the latitudinal variations of ionospheric parameters. Ann. Geophys. 36, 537–548, 1980.

Krinberg, I.A., Tashchilin, A.V. Ionosphere and Plasmasphere, Moscow, Nauka, 189, 1984.

Mikhailov, A.V., Forster, M. Some F_2-layer effects during the January 06-11, 1997 CEDAR storm period as observed with the Millstone Hill incoherent scatter facility. J. Atmos. Solar-Terr. Phys. 61, 226–249, 1999.

Pirog, O.M., Polekh, N.M., Chistyakova, L.V., et al. The study of ionospheric responses to magnetic storms in the asian–pacific region. Geomagn. Aeron. 41, 65–73, 2001a.

Pirog, O.M., Polekh, N.M., Chistyakova, L.V. Longitudinal variation of critical frequencies in polar F-region. Adv. Space Res. 27 (8), 1395–1398, 2001b.

Pirog, O.M., Polekh, N.M., Zherebtsov, G.A., et al. Seasonal variations of the ionospheric effects of geomagnetic storms at different latitudes of east asia. Adv. Space Res. 37 (5), 1075–1080, 2006a.

Pirog, O.M., Polekh, N.M., Tashchilin, A.V., et al. Response of ionosphere to strong geomagnetic storm: observation and modeling. Adv. Space Res. 37 (5), 1080–1087, 2006b.

Prolss, G.W., Ocko, M. Propagation of upper atmospheric storm effects towards lower latitudes. Adv. Space Res. 26, 131–137, 2000.

Reddy, G.A., Mayer, H.G. Storm-time penetration to low latitudes of magnetic-ionospheric convection and convections-driven thermospheric winds. Geophys. Res. Lett. 25, 3075–3078, 1988.

Richards, P.G., Fennelly, J.A., Torr, D.G. EUVAC: a solar EUV flux model for aeronomic calculations. J. Geophys. Res. 99, 8981–8992, 1994.

Richmond, A.D., Blanc, M., Emery, B.A., et al. An empirical model of quiet-day ionospheric electric fields at middle and low latitudes. J. Geophys. Res. 85, 4658–4667, 1980.

Rishbeth, H. How the thermospheric circulation affects the ionospheric F2-layer. J. Atmos. Solar-Terr. Phys. 60, 1385–1402, 1998.

Rodger, A.S., Wrenn, G.L., Rishbeth, H. Geomagnetic storms in the Antarctic F-region. 2. Physical interpretation. J. Atmos. Terrest. Phys. 51, 851–866, 1989.

Romanova, E.B., Tashchilin, A.V., Zherebtsov, G.A., et al. Modeling of the seasonal effects of geomagnetic storms in the Eastern Asia ionosphere. Int. J. Geomagn. Aeron. 6, GI3003, doi:10.1029/2005GI000119, 2006.

Sojka, J.J., Rasmussen, C.E., Schunk, R.W. An interplanetary magnetic field dependent model of the ionospheric convection electric field. J. Geophys. Res. 91, 11281–11290, 1986.

Tashchilin, A.V., Romanova, E.B. UT-control effects in the latitudinal structure of the ion composition of the topside ionosphere. J. Atmos. Terr. Phys. 57, 1497–1502, 1995.

Tashchilin, A.V., Romanova, E.B. Numerical modeling the high-latitude ionosphere, in: Proceeding of COSPAR Colloquia Series 14, pp. 315–325, 2002.

Zherebtsov, G.A., Pirog, O.M., Polekh, N.M. Ionospheric effects of geomagnetic storms in different longitude sectors. Chin. J. Space Res. 25 (5), 468–473, 2005.