Manifestation of intensive geomagnetic storms in the ionosphere of East Asia

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This paper describes the intensive geomagnetic storms with the index $D_{st} < (-200 - -300$ nT) observed during the period of two last cycles of solar activity. The analysis of variations of ionospheric parameters is based on the use of the measurement data from a network of ionospheric stations located at different latitudes in the longitudinal sector from 60 to 150°E. The results of numerical simulation of ionospheric parameters during the geomagnetic storm in April 2000 are also presented, which show a good agreement of calculations and measurements of critical frequencies in the $F2$ layer. Long-term negative ionospheric disturbances, observed during geomagnetic storms, may be produced by the change of thermosphere composition.

Introduction

The investigation of the influence of the solar and interplanetary phenomena on the circumterraneous space refers to the most important problem of the solar-terrestrial physics. Although a great amount of experimental and theoretical data is accumulated by now, the predicting of the solar activity effects in the ionosphere remains a complex task.

The ionosphere response to the geomagnetic disturbance represents a complicated set of phenomena specified both by parameters of the upper atmosphere and the ionosphere, as well as by characteristics of the magnetosphere and solar wind. The situation during intensive geomagnetic storms is particularly complicated.

Theoretical and experimental investigations of the ionosphere during magnetic storms have made it possible to recognize the most important physical processes, which determine the distribution of electron concentration in the ionosphere at different latitudes, and to present the general pattern of the manifestation of the ionospheric storm. One of the factors, which determine the ionosphere variations during the geomagnetic storm, is the change of neutral composition of the thermosphere and the system of circulation of neutral winds during this storm.[1–4]

The misalignment of geographic and magnetic coordinates complicates the pattern of ionospheric disturbances and results in the longitudinal dependence of ionospheric effects of geomagnetic storms.[5–8] The greatest difference between geographic and geomagnetic coordinates is observed in the East Asia. Formation of high-latitude large-scale structure of the ionosphere in this sector proceeds against the background of relatively low electron concentration. Therefore, this region is of increased interest.

Earlier, we presented the results of morphological analysis and numerical modeling of the ionosphere state during moderate storms observed in various seasons at the stations of a meridional chain.[9–10] We have also analyzed the ionospheric effects of extremal events in October–November 2003 and November 2004.[11–12] In this paper we try to systematize the manifestations of great storms in our region.

Analysis of ionospheric data

We have analyzed the intensive geomagnetic storms with $D_{st} < (-200 - -300$ nT) observed during last two cycles of solar activity (22nd and 23rd). The list of storms is given in Table 1. It is seen that 9 storms from 18 were observed in autumn (in November – 5, in October – 3 and one storm in September), 5 storms were observed in spring (the end of March – April) and 4 storms were observed in summer (July). It is of interest that three times great storms were observed in October and November of one year. All great storms were observed in the peak or in the decay and rise of solar activity. The seasonal dependence of the appearance of intensive storms is probably determined by the sector structure of the interplanetary magnetic field (IMF).

We have investigated the variations of critical frequencies of $F2$ layers during storms, including the preliminary and the reconstruction phases. As a smooth level, the hour values of f_0F2 were used, averaged over several calm days. Geographic and geomagnetic coordinates of the ionospheric stations used in this research, are given in Table 2.

The analysis of ionospheric data has shown that the reaction of the ionosphere to the storm depends on the time of its beginning and the shape of variations of D_{st} index. If the storm in D_{st} index has a pronounced beginning, one minimum, and short duration, then at night at high latitudes the absorption and screening of $F2$ layer by E_s layer are observed, and at mid-latitudes the negative perturbations are possible. In the daytime we can observe the high-power negative disturbances (> 50%) both at high latitudes and at mid-latitudes. Upon completion of the storm, the ionosphere is quickly reconstructed up to an unperturbed level already the next day. If the storm has more than one minimum and is of long duration, then the reconstruction of unperturbed level proceeds gradually and is completed in three or four days after the storm.

Table 1. The list of storms with indication of date, minimal D_{st} index, and the time of minimum

Date	$D_{st\,\min}$, nT	$T_{\min}$, UT
October 20–21, 1989	−203, −268	16, 12
November 17–18, 1989	−288	23
April 10–11, 1990	−278	19
March 5–6, 1991	−219	20
July 9, 1991	−190	15
November 8–9, 1991	−354	02
September 25, 1998	−230	10
October 22, 1999	−231	07
April 6–7, 2000	−321	01
July 15–16, 2000	−295	01
March 31–April 1, 2001	−285	22
April 12–13, 2001	−256	24
October 3, 2001	−182	15
November 1, 2001	−277	06
October 29–30, 2003	−263, −401	01, 23
November 19, 2003	−429	20
November 8–10, 2004	−373, −289	07, 11
August 25, 2005	−216	12

Table 2. The list of ionospheric stations and their geographical and geomagnetic coordinates

The name of the station	Geographical		Geomagnetic	
	latitude, deg.	longitude, deg.	latitude, deg.	longitude, deg.
Dikson	73.5	80.4	63.1	162.2
Norilsk	69.20	88.26	58.71	165.7
Salekhard	66.5	66.6	57.4	149.7
Yakutsk	62.0	129.6	50.99	194.1
Magadan	60.12	151.0	50.75	210.8
Tomsk	56.5	84.9	46.0	160.6
Sverdlovsk	56.4	58.6	48.5	139.6
Petropavlovsk	53.0	158.7	44.9	219.9
Irkutsk	52.5	104.0	41.1	174.8
Manzhouli	49.6	117.5	38.4	186.5
Khabarovsk	48.5	135.1	37.91	200.4
Tashkent	41.3	69.6	32.3	145.2
Ashkhabad	37.9	58.3	30.4	134.5
Beijing	40.0	116.3	28.7	174.1
Kokubunzhi	35.7	139.5	35.7	206.8
Manila	14.6	121.1	3.6	191.1
Vanimo	−2.75	141.3	12.3	212.6

The complex storms are observed rarely (three for the entire research period) – in October 1989, October 2003, and in November 2004. Unfortunately, during storms of such type the ionospheric data are often missing, especially at high latitudes. The storm with two basic phases in October 1989 is mostly supplied with data. Analysis of this storm is given in Ref. 13, but main attention has been given to the equatorial anomaly. We consider the mid-latitudes and high latitudes. Figure 1 (top) shows the variations of f_0F2 during this storm in two longitudinal sectors: 60–105°E and 120–160°E.

The onset of the storm takes place in the evening (local time) and results in violation of daily behavior and night reflections from $F2$ layer during the first basic phase at high latitudes with decrease of f_0F2 at mid-latitudes in both sectors. In the daytime, at the reconstruction phase the critical frequencies are less than the unperturbed level by 1.5–2.5 times depending on the latitude of the station.

The second basic phase also corresponds to night hours and results in the same effects that the first phase. The differences in variations of f_0F2 in various sectors were observed at the reconstruction phase. In the sector 60–105°E the diurnal critical frequencies of $F2$-layer in October 22 were reconstructed to the unperturbed level, but on October 23 the critical frequencies decrease again. The final reconstruction occurs only on 24 October.

In the sector 120–160°E, the daytime values of f_0F2 are lower and on October 22 and 23 the ionization reconstruction proceeds gradually in $F2$-layer and only on October 24, i.e., in the third day the critical frequencies are close to the calm level.

The night values of f_0F2 remain low during the whole period of phase reconstruction in both sectors. At low-latitude stations the disturbances are positive. The distinctions in manifestations of geomagnetic storm at the reconstruction phase at various longitudes were described in Refs. 7, 8.

The perturbation pattern is readily illustrated at the map of isolines f_0F2 in the coordinates of UT – geomagnetic latitude for the 120–160°E sector, shown at the bottom of Fig. 1.

The storm with one minimum of D_{st} is given in Fig. 2, where the variations and the map of isolines of f_0F2 in November 1989 are shown (D_{st} = −266 nT at 23 UT on November 17). The onset of the storm is also observed at the evening sector of local time. With increasing K_p up to 4–7 we observe a break of f_0F2 daily variation, more pronounced in the longitude sector 60–105°E, because the perturbation there begins after noon. During the major phase of the storm at night the absorption and anomalous ionization in E and $F2$ layers appear at high latitudes, and at mid-latitudes – the negative perturbations. The high-power negative perturbations were observed at the reconstruction phase in the daytime, while at latitudes higher 45° the value of f_0F2 was by two times lower than at the calm level. The perturbation amplitude decreased at the decrease of the station latitude. The next day the level of ionization was almost fully reconstructed. It should be noted that the comparison of variations of critical frequencies at stations in sectors of 60–105°E and 120–160°E has shown their similarity, more clearly defined in the second sector.

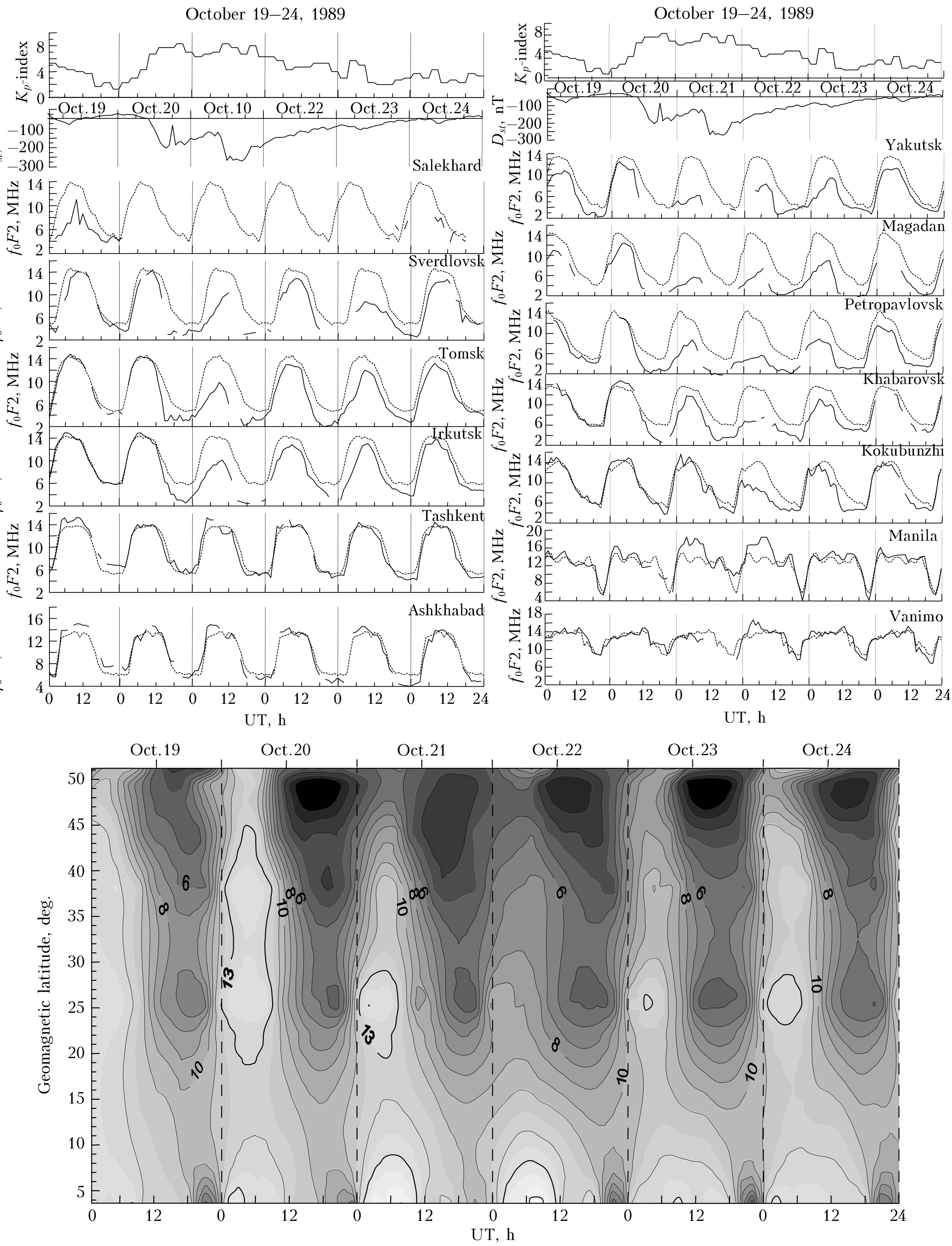

Fig. 1. Variations of D_{st} and f_0F2 during the storm with two basic phases in October 1989 in two adjacent longitudinal sectors 60–105°E and 120–160°E (upper panel). Dashed curves indicate the variations of f_0F2 during calm day, solid curves indicate the current values. Isolines of critical frequency of the layer $F2$ in the coordinate system UT – geomagnetic latitude for the sector 120–160°E (lower panel); LT = UT + Δt, where Δt = 6–8 h depending on the station longitude (see Table 2).

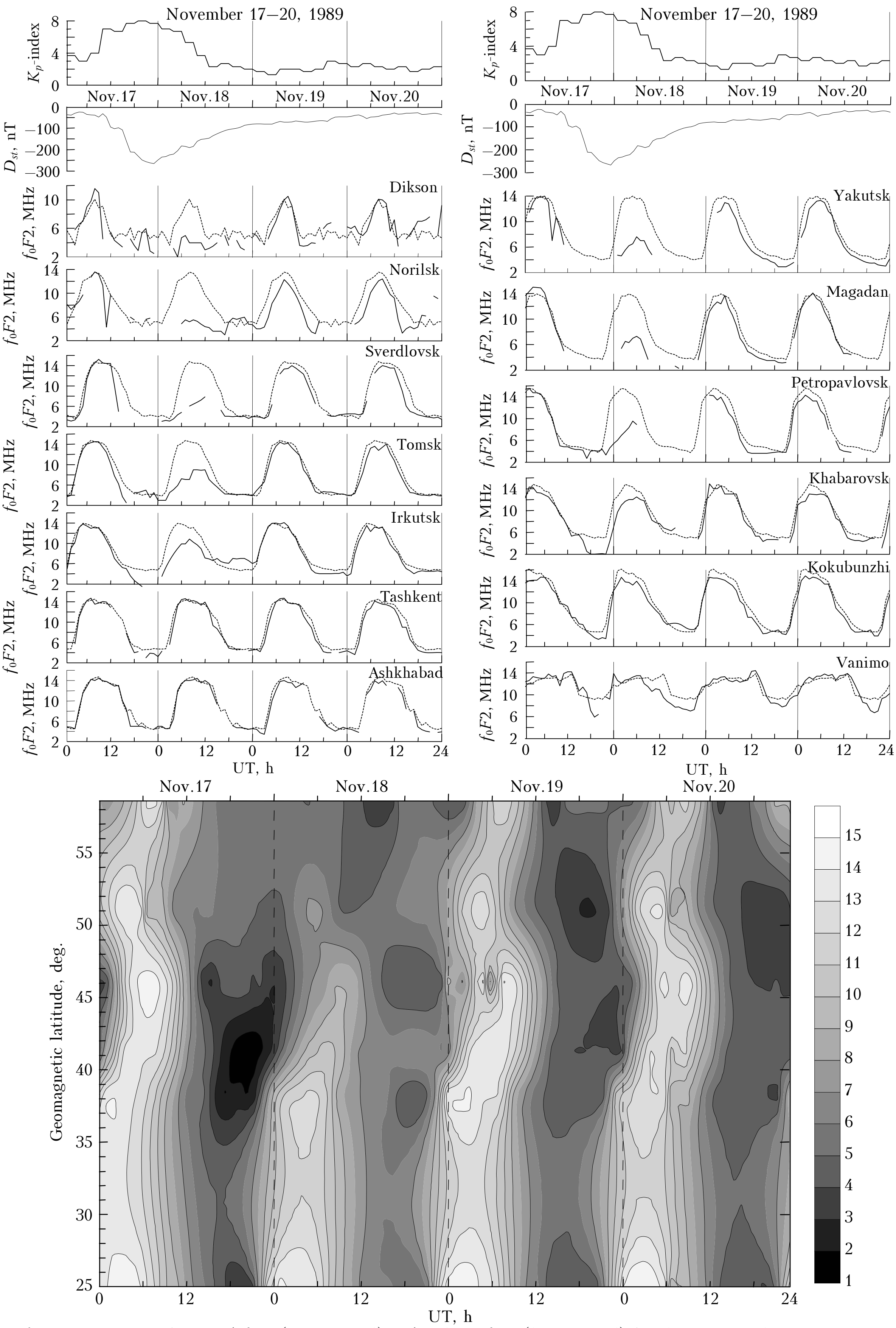

Fig. 2. Variations of D_{st} and f_0F2 (upper panel) and isolines f_0F2 (lower panel) for the storm with one minimum.

At the map of f_0F2 isolines it is clearly seen that the region of low ionization extends in time and is shifted to the equator during the major phase and in the beginning of the reconstruction phase and the ionosphere is reconstructed to the calm level already on 19 November.

Modeling

Some of electron concentration variations were made during the storm of April 6–7, 2000 were preliminarily calculated, and contributions of different processes were estimated. The magnetic storm of April 6–7, 2000 is one of the strongest geomagnetic disturbances for the last 20 years (D_{st} = –320 nT at 02 UT, 7 April). The maximum of K_p was 9^-. This storm by irradiance level was close to the equinox and was observed in the peak of solar activity. Selection of this storm is determined by the fact that in spite of its intensity, neither absorption nor sporadic layers in E region resulted in a long disappearance of reflections from $F2$ layer even at high-latitude stations that is rare for storms of such intensity.

In the modeling we used a theoretical model developed at the Institute of Solar-Terrestrial Physics.[10,14] This model is based on the numerical solution of the set of nonstationary equations of balance of particles and energy of thermal plasma in closed geomagnetic force tubes, which bases are located at a 100 km height.

To describe the spatiotemporal variations of temperature and concentrations of neutral components, a global empirical model of thermosphere MSIS-86 was used. The velocities of horizontal thermosphere wind were determined using the model HWM-90. The values of integrated light flux and mean energy of pouring out electrons, necessary for calculating the rates of auroral ionization, were taken from a global model of electron pouring out.[15] The electric field of magnetosphere convection was determined in accordance with an empirical model of potential distribution.[16]

The reaction of the ionosphere to the geomagnetic storm was reproduced by calculating the variations of plasma parameters throughout the geomagnetic tube, which base in the northern hemisphere was located at points with geographic coordinates of ionosphere stations from Table 2. The variations of electric fields with time were considered based on real variations of hour values of geomagnetic activity indices (K_p, A_p) and parameters of interplanetary magnetic field (B_z, B_y).

Figure 3 shows the variations of f_0F2 and indices K_p and D_{st} for this storm. The measured critical frequencies of $F2$ layer are denoted by thick solid curves, the f_0F2 values during a calm day are denoted by dashed curve and the f_0F2 values calculated by the model are denoted by thin curves.

The negative perturbation, observed in April 7, 2000 at all stations of Fig. 3, is of the perturbation form classified[17] as the "negative effect of the storm caused by the disturbance of the thermosphere composition." For this effect, the anomalously low electron concentration after the sun rise is typical, which can be observed from several hours to several days, as long as the magnetic activity continues. Warming up of thermosphere during disturbances results in the decrease of the relation [O]/[N_2] at a height of $F2$ layer maximum. This thermosphere disturbance extends from auroral latitudes up to low ones.

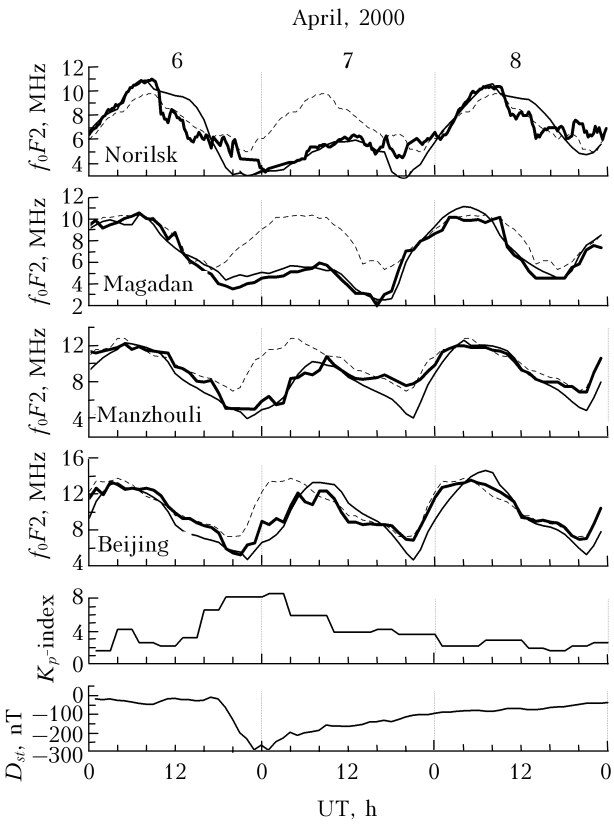

Fig. 3. Results of modeling of ionospheric parameters for the storm of 6–7 April 2000. The measured values of f_0F2 are shown by the thick line, the variations of f_0F2 during a calm day are shown by the dashed line, the model calculations are shown by the thin line.

In the theoretical model[10,14] the thermosphere parameters are given according to the empirical model MSIS-86. It is well known that the model MSIS-86 does not predict an exact relation [O]/[N_2] during disturbances. It gives an overestimated value for negative disturbances,[18] therefore the calculations were made with correction of this relation as we have shown.[10] Such calculations are in good agreement with the measured values of f_0F2.

Conclusions

The analysis of ionosphere data has shown that the ionosphere response to the intensive storm is determined by the time of a sudden onset of the storm and the time dependence of D_{st} variations. If the storm onset is clearly defined and the storm has one maximum and is short in time, at night we observe the total absorption and screening of $F2$ layer by a sporadic layer E_s at high latitudes and negative disturbances at mid-latitudes. In the day time the high-power negative disturbances (> 50%) are observed both at high-latitudes and at mid-latitudes. After the completion of the storm the ionosphere is reconstructed up to the unperturbed state the next day. If during the storm the D_{st}-variation character is complex with two or more minima, the ionosphere is reconstructed slowly and returns to the unperturbed state in three or four days after the completion of the storm.

The measured and calculated f_0F2 values are in good agreement both at high latitudes and at mid-latitudes. The long-term negative disturbances, observed during geomagnetic storms, can probably be caused by the variation of the thermosphere composition.

Acknowledgements

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References

1. A.D. Danilov and J. Lastovicka, Int. J. Geomagn. Aeron. **2**, No. 3, 1–24 (2001).
2. G.W. Prolss and M. Ocko, Adv. Space Res. **26**, No. 1, 131–135 (2000).
3. G.A. Reddy and H.G. Mayer, Geophys. Res. Lett. **25**, No. 6, 3075–3081 (1998).
4.H. Rishbeth, J. Atmos. Solar Terr. Phys. **60**, No. 14, 1385–1402 (1998).
5. E.L. Afraimovich, E.A. Kosogorov, L.A. Leonovich, and O.M. Pirog, Geomagn. Aeron. **42**, No. 4, 491–498 (2002).
6. D.V. Blagoveshchensky, O.M. Pirog, N.M. Polekh, and L.V. Chistyakova, J. Atmos. Solar Terr. Phys. **65**, No. 2, 203–210 (2003).
7. O.M. Pirog, N.M. Polekh, A.V. Tashchilin, and E.B. Romanova, Adv. Space Res. **37**, No. 2, 1081–1087 (2006).
8. G.A. Zherebtsov, O.M. Pirog, and N.M. Polekh, Chin. J. Space Res. **25**, No. 5, 468–473 (2005).
9. O.M. Pirog, N.M. Polekh, G.A. Zherebtsov, et al., Adv. Space Res. **37**, No. 5, 1075–1080 (2006).
10. E.B. Romanova, A.V. Tashchilin, G.A. Zherebtsov, O.M. Pirog, N.M. Polekh, et al., Int. J. Geomagn. Aeron. **6**, No. 3, GI 3003, doi:10.1029/2005GI000119 (2006).
11. G.A. Zherebtsov, O.M. Pirog, N.M. Polekh, K.G. Ratovskii, V.F. Smirnov, L.E. Stepanov, Dzankui Shi, and Khao Wang, Geomagn. Aeron. **45**, No. 1, 101–108 (2005).