Density gradients at afternoon ionospheric troughs in the Eastern sector

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Ionospheric storms of different intensities are examined based on the data of the meridional chain of ionospheric stations located in Eastern Siberia and China. It has been determined that afternoon troughs can be observed either during the main phases of strong and moderate storms if their starts fall on evening hours or during the recovery phase if they start at some other time. They are mainly observed in the equinox. Model calculations of variations of the electron density during the storm on April 3–6, 2004, are carried out. It is shown that the positions of the minimum and the polar wall of the afternoon trough coincide with the belt of the westward drift in the time sector 13–17 MLT at geomagnetic latitudes between 55 and 65°.

Introduction

Sharp decreases of ionization at the $F2$ layer maximum in the daytime F region, known as a main ionospheric trough, mid-latitudinal trough, and drastic decrease in diurnal variations of f_0F2 were observed for a long time. Although all three terms possibly describe the same phenomenon, their properties have little in common. It was generally believed that the daytime trough appears sporadically, is connected with a high magnetic activity and is typical of subauroral latitudes.[1,2]

Drastic decreases of diurnal variations of f_0F2 in the afternoon were associated with the motion of the main ionospheric trough to equator during geomagnetic storms. This type of the negative effect of storms is characterized by a deep drop of ionization, which looks especially impressive, if follows the positive phase.[3–5] The increase of ionization in the evening sector before the drastic decrease in diurnal variations was called the "twilight effect."[6] In addition, a wide difference was observed in the local time (LT) of trough appearance at the stations lying at the same magnetic latitude, but different magnetic longitudes. Thus, the trough appeared in the afternoon in Greenland and in the morning in Alaska.

Accumulated experimental data have allowed the main dependences of the trough position and structure on local time, season, and levels of magnetic and solar activity to be revealed. Troughs observed near the noon are usually narrow with a width of ~4–6° regardless of the season, but they may have a long length along the longitude.[7] As geomagnetic activity changes, the position of the trough minimum shifts in the equatorial direction roughly by 2° per unit K_p. However, the ionospheric trough is a more complex formation than a simple decrease of the electron concentration in a certain latitudinal interval. In the trough area, latitudinal and altitudinal anomalies are observed in the temperature distribution of charged particles, variation of the ionic composition, plasma drift, and so on. Formation of a trough is one of manifestations of the ionospheric–magnetospheric interaction, which generally determines the regime of the high-latitudinal ionosphere. It is believed that a significant role in formation of a trough is played by the magnetospheric convection and by precipitation of high-energy electrons.[6,8,9] Thus, in night and evening hours, a complex system of convection is observed in a trough region with a slow eastward drift on its equatorial wall and a fast westward drift at its minimum and polar wall.

This paper considers peculiarities of appearance of an afternoon trough in East Asia. For analysis, we used the data of the meridional chain of ionospheric stations in Eastern Siberia and China and the data of geomagnetic indices D_{st}, K_p, and AE, as well as the theoretical model of the ionospheric–plasmospheric interaction.[10]

Analysis of data

We have considered ionospheric storms of different intensity for the period of 2000–2005 at different stations (Table 1).

Table 1. Stations, whose data were used in analysis, and their coordinates

Station	Geographic		Geomagnetic	
	latitude, deg	longitude, deg	latitude, deg	longitude, deg
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
Manjouli	44.0	117.0	32.0	189.0
Beijing	40.0	116	28.7	188

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Table 2. Date, number of events, and phase of storms, during which a drastic decrease was observed in diurnal variations of f_0F2

Date	N	Storm phase
Apr 06–08, 2000	1	recovery
Sep 17–20, 2000	1	recovery
Apr 17–21, 2002	4	main, recovery (3)
Oct 01–06, 2002	3	initial, recovery (3)
Aug 17–19, 2003	1	main
Oct 13–16, 2003	1	recovery
Oct 22–22, 2003	2	recovery (2)
Mar 9–14, 2004	1	recovery
Apr 03–07, 2004	3	recovery (3)
Oct 12–16, 2004	1	main
May 07–10, 2005	2	initial, main
May 15–19, 2005	3	recovery (3)
May 28–31, 2005	3	initial, recovery, main
Aug 23–26, 2005	2	initial, main
Aug 31–Sep 04,2005	4	initial, recovery (3)
Sep 22–28, 2005	2	recovery (2)

N o t e s . The number of events of afternoon troughs in the given phase of a storm is given in parenthesis.

It follows from Table 2 that geomagnetic storms are mostly observed in the equinox periods and in early and later summer at the recovery phase. Analysis of the data together with geomagnetic indices has shown that afternoon troughs at the recovery phase are observed at high and auroral latitudes with $L > 3$ during substorms, when $500 < AE < 1000$ nT and $K_p > 3$. They are similar to negative distortions at subauroral latitudes, which are described in Ref. 3, and connected with the motion of the main ionospheric trough (MIT). During the growth phase or at the storm maximum, the data of high-latitude stations are often absent owing to absorption or screening by the E-layer, and the main ionospheric trough shifts to midlatitudes.

Figure 1*a* shows variations of D_{st} and f_0F2 at the meridional chain of stations during the moderate storm at equinox on October 13–16, 2003. Dashed curves show variations of f_0F2 in an undisturbed day, while solid curves correspond to current values. At the phase of development of the geomagnetic storm at D_{st} equal to –60 nT, the drastic decrease in diurnal variations of f_0F2 was observed at high latitudes (Norilsk and Yakutsk) in the evening hours. It should be noted that $\text{LT} = \text{UT} + \Delta t$, where $\Delta t = 6$–8 h depending on the longitude of a station (see Table 1).

Figure 1*b* shows variations of isolines of the $F2$ layer critical frequency in the coordinate system "local time – geomagnetic latitude" for two subsequent days: October 13 (undisturbed day) and October 14, when the drastic decrease was observed. In the map of f_0F2 isolines, it is clearly seen that on October 13 the area of the main ionospheric trough ($f_0F2 < 3$ MHz) lies at geomagnetic latitudes of 47–55° in the period 01–05 LT. On October 14 at $K_p > 4$ the isolines are distorted in daytime, and after the drastic decrease in diurnal variations at 18 LT the area of low values extends toward the equator to 35° from 20 to 06 LT. The polar boundary remains roughly at the same level. The values of the AE index increase up to 1000 nT at the time of the drastic decrease in diurnal variations of f_0F2.

The drastic decrease in diurnal variations in evening hours of August 31 (Fig. 2*a*) coincides with the sharp increase of K_p and AE (up to 500 nT). During the main phase, which coincides with local midnight, reflections from the $F2$ layer are absent. Analysis of ionograms has shown that the E_s layers with limiting frequencies of 6–7 MHz screen the $F2$ layer at this time. Intense negative distortions (up to 50%) were observed in daytime during the recovery phase on September 1. The values of f_0F2 began to recover to the undisturbed level on September 2. However, the increase of the K_p and AE indices resulted in a new drop of f_0F2.

Isolines of f_0F2, shown in Fig. 2*b* for the disturbed day of September 2, illustrate how the steep equatorial wall of the deep and wide trough is formed in the evening sector and extends to Manjouli (geomagnetic latitude of 32°).

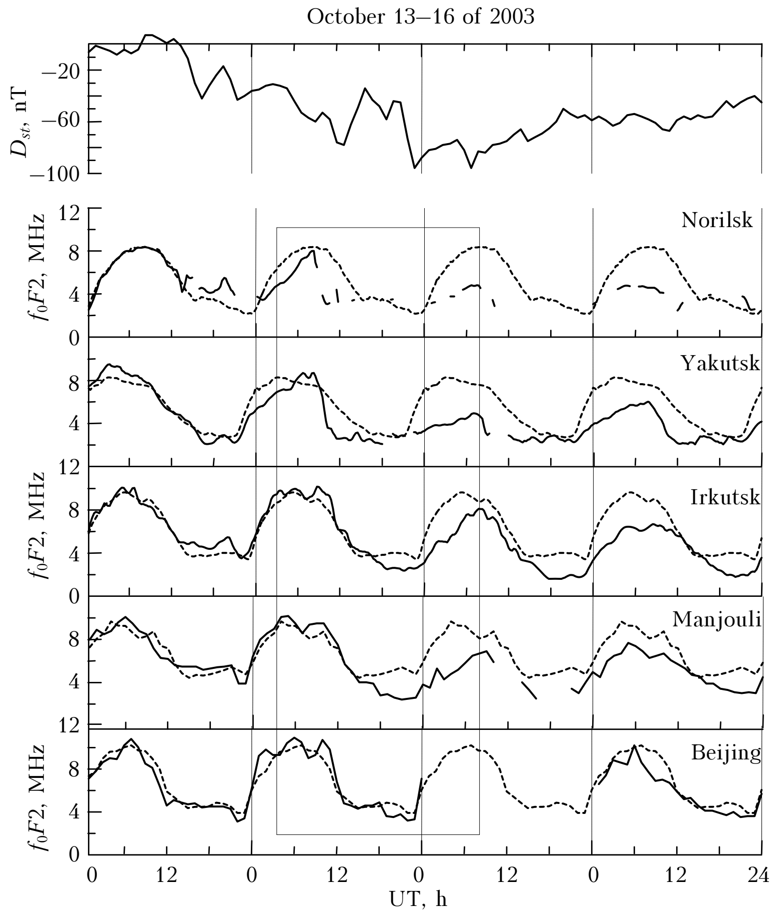
The presented examples of afternoon troughs illustrate the stability of this phenomenon relative to the Sun, dependence on geomagnetic activity, and extension of the region of abnormally low nighttime ionization to middle latitudes.

Simulation

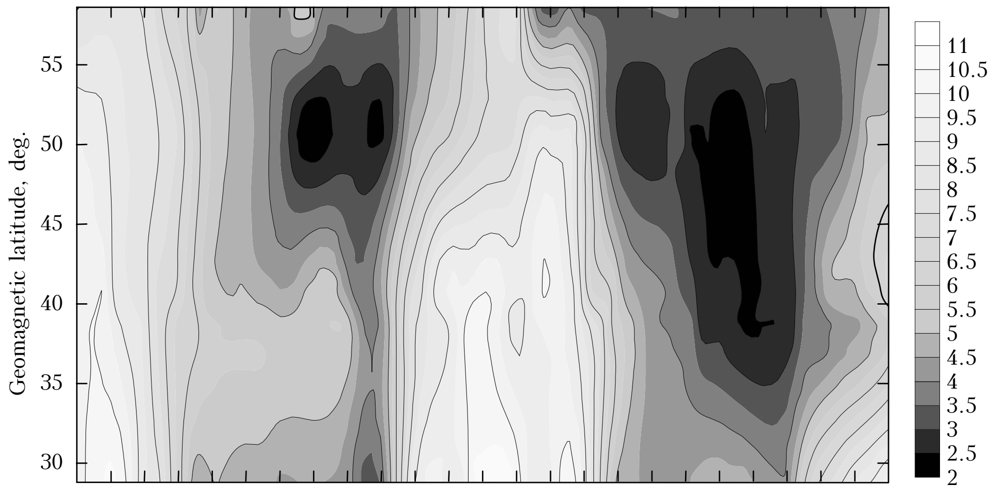
To examine the ionospheric response to the studied geomagnetic storm, we used the theoretical model of ionospheric–plasmospheric interaction developed at the Institute of Solar-Terrestrial Physics (ISTP) SB RAS.[10] This model is based on the numerical solution of a system of nonstationary equations of particle and energy balance of thermal plasma in closed geomagnetic field tubes, whose bases lie at a height of 100 km.

To describe spatiotemporal variations of temperature and concentrations of neutral components, we used the MSIS-86 global empirical model of the thermosphere. Velocities of the horizontal thermospheric wind were determined by the HWM-90 model. The values of the integral flow and the mean energy of precipitating electrons needed for calculation of the rates of auroral ionization were taken from the global electron precipitation model.[11] The electric field of magnetospheric convection was determined according to the empirical model of potential distribution.[12]

The reaction of the ionosphere to the considered magnetic storms was reconstructed by calculating variations of the plasma parameters in the entire geomagnetic tube, whose base in the Northern Hemisphere lied at the points with geographic coordinates of the ionospheric stations from Table 1. Variations of the electric fields in time were taken into account through actual variations of hour values of geomagnetic activity indices (K_p, A_p) and parameters of interplanetary magnetic field (B_z, B_y).



a



b

Fig. 1. Variations of D_{st} and f_0F2 at the meridional chain of stations on October 13–16, 2003 (*a*); isolines of f_0F2 in the coordinate system "local time–geomagnetic latitude" (*b*).

Variations of the thermospheric composition ($[O]/[N_2]$) obtained by the MSIS-86 model failed to reconstruct the observed behavior of the ionosphere during magnetic storms, and, therefore, they were corrected as shown in Ref. 13.

The results of simulation obtained after this correction (version 1) are shown in Fig. 3. The thin line (version 1) shows the calculated variations of f_0F2 for the stations Norilsk, Zhigansk, and Yakutsk; circles correspond to the measured values of f_0F2;

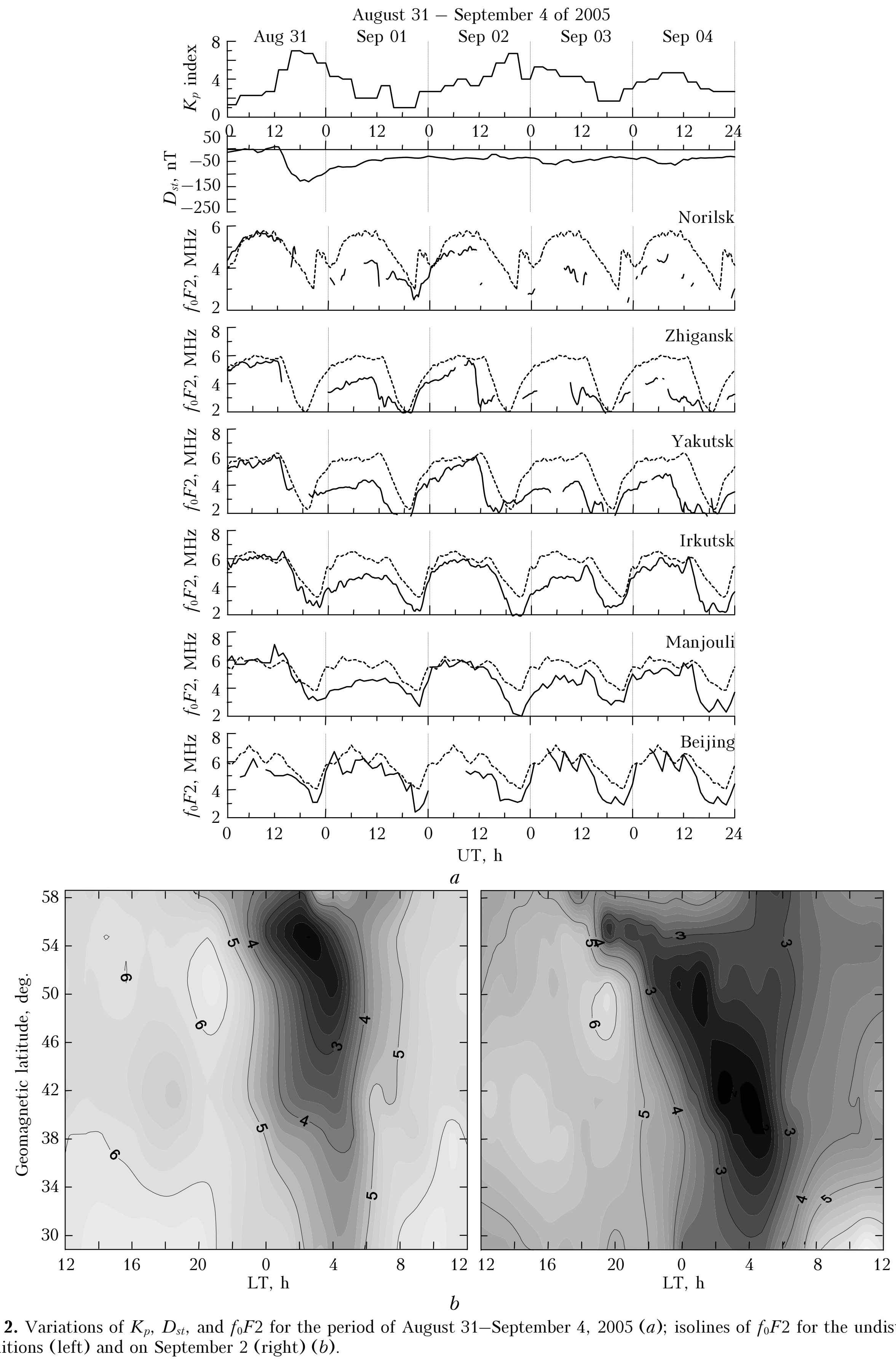


Fig. 2. Variations of K_p, D_{st}, and f_0F2 for the period of August 31–September 4, 2005 (*a*); isolines of f_0F2 for the undisturbed conditions (left) and on September 2 (right) (*b*).

dashed curves stand for the undisturbed level calculated from f_0F2 measurements in undisturbed days. To be noted is a good agreement between the calculated and measured variations of the critical frequency in undisturbed and moderately disturbed periods. The drastic decrease in diurnal variations of f_0F2 observed on April 6, 2004 near 12 UT is not reconstructed by the model calculations by version 1.

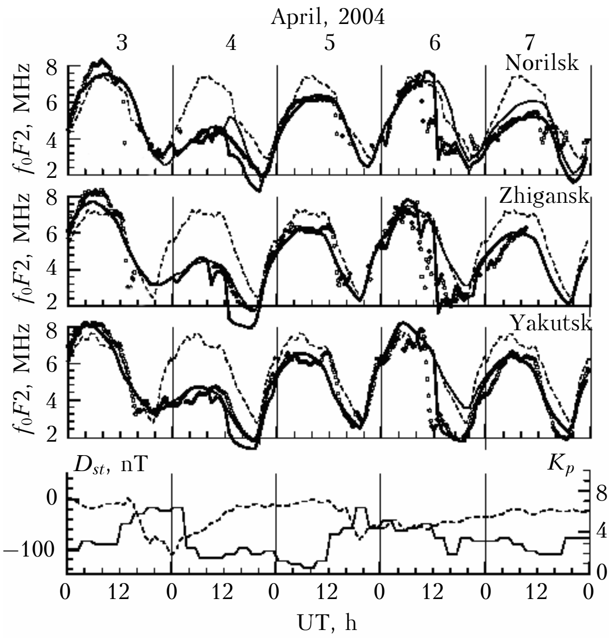


Fig. 3. Results of simulation of f_0F2 obtained for three high-latitude stations. Variations of D_{st} and K_p are shown in the bottom part.

To reconstruct the situation of trough passage over stations Norilsk, Zhigansk, and Yakutsk, it is necessary to correct the empirical models of magnetospheric sources for the conditions of the considered geomagnetic storm. To do this, we have calculated diurnal variations of f_0F2 by version 2 (bold line in Fig. 3) with the following corrections to the empirical model[12]: the magnetospheric convection zone is extended by 10° toward the equator, the drop of electric potential through the polar cap is defined according to Ref. 14. These corrections were discussed in Ref. 15. As can be seen from Fig. 3, the model calculations by version 2 (bold line) reconstruct the drastic decrease in diurnal variations of f_0F2 at all considered stations.

For analysis of the results obtained, we have calculated the global distributions of the electron concentration and the rates of electromagnetic drift taking into account corotation for the undisturbed day of April 2, 2004, by version 1 and for the disturbed day of April 6, 2004, by version 2 for 13 and 17 UT. Figure 4 shows the values of $\log N_e$ at a height of 300 km in the coordinate system "geomagnetic latitude–MLT" for versions 1 and 2, respectively. The calculated rates of electromagnetic drift W are shown by arrows.

The eastward electromagnetic drift with slight deflection in the polar cap predominates in the undisturbed day (corresponds to the counterclockwise direction in Fig. 4). Its rate is ~200 m/s. The main ionospheric trough is formed on the night side due to the slow plasma drift in the absence of sources of ion formation, which leads to recombination of plasma to very low values. Differences in the MIT position and shape at 13 and 17 UT likely follow from UT variations.[10]

During the storm on April 6, 2004 at 13 UT, MIT converges and extends along the longitude from 17 to ~07 MLT. Obviously, the trough on the evening side is formed due to the carry-over of the low-concentration plasma from the night side to the evening side by the westward drift. The drift rate achieves ~700 m/s in the sector from 17 to 20 MLT and at geomagnetic latitudes from 65 to 72°. In the sector from 00 to 07 MLT, the MIT position coincides with the eastward drift, whose rates are also high (~1000–1200 m/s). This drift carries over the low-concentration plasma from the night side to the morning sector, forming a trough on the morning side. At 17 UT, the eastward drift current (rate ~1000–1300 m/s) coinciding with the MIT position on the night side appears also on the night side. The MIT position in the afternoon sector coincides with the band of the westward drift (rate ~700 m/s), which is present in the sector from 13 to 17 MLT and from 55 to 65° of geomagnetic latitude.

Discussion

The most probable explanation for sharp decreases of critical frequencies of the $F2$ layer in the afternoon is the influence of the fast plasma convection in the westward direction under the effect of intense electric fields.[16,17] Satellite measurements have shown that during magnetic storms high-intensity (up to 250 mV/m) meridional electric fields directed to the pole are observed on the equatorial boundary of the auroral zone.[18] These fields give rise to the westward drift with high rates. According to incoherent scattering data, the westward drift with rates higher than 1000 m/s is observed in the main ionization trough. Simultaneous satellite and ground-based measurements of the effects of fast subauroral drifts show that development of a narrow band of westward drift with high rates (polarization jet according to the authors' terminology) for 15–20 minutes leads to intense depletion of ionization in the F region.[19] This corresponds to a fast formation or deepening of a trough in the existing background ionization.

Model calculations of electron density variations during observations of evening ionization gradients presented in this paper confirm the assumption that a narrow trough in the afternoon sector is formed by the band of westward drift with high rates.

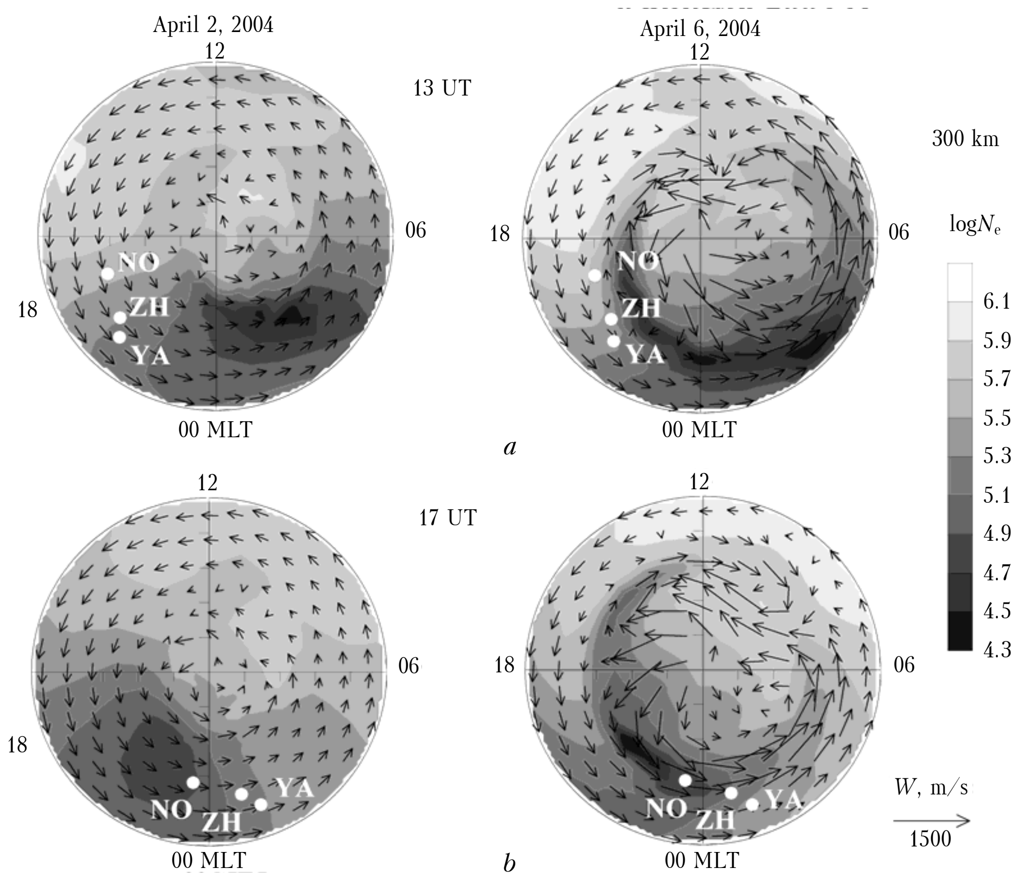


Fig. 4. Variations of logNe at a height of 300 km in the coordinate system "geomagnetic latitude–MLT" for versions 1 (*a*) and 2 (*b*). The outer circle corresponds to geomagnetic latitude of 40°.

Simultaneous measurements of the electron concentration, electron and ion temperature, and ion drift by the incoherent scattering method[8,20] have shown the high values of T_e and T_i, as well as drift rates, in the trough. This allowed us to suppose that, in addition to the influence of the fast drift, the increase of the coefficient of the reaction $O^+ + N_2 = NO^+ + N$ in the presence of strong electric fields can play a significant role. As this takes place, a trough with a sharp equatorial edge and its shift to the day side are observed.

Consequently, the sharp decrease of critical frequencies of the *F*2 layer in the afternoon and evening hours can be a consequence of fast plasma convection in the westward direction under the effect of high-intensity electric fields.

Conclusions

Our investigations in the East-Asian region have allowed the following conclusions.

Sharp gradients of ionization in the afternoon sector are determined by formation of a steep equatorial wall of the main ionospheric trough.

The afternoon trough is observed at subauroral latitudes of the East-Asian region mostly at equinox and in the transient period between equinox and summer at the recovery phase of a geomagnetic storm. If the K_p and *AE* indices increase, then the trough area extends to low latitudes in time and space.

The results of simulation demonstrate that MIT in the evening sector is formed by the band of the westward drift with rates ~700 m/s, which carries low-concentration plasma from the night side to the evening one. In the morning sector, the eastward drift with high rates ~1000–1200 m/s carries the low-concentration plasma from the night side to the morning sector, forming a trough on the morning side.

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