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Mid-latitude effects of the May 15, 1997 magnetic storm

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Abstract

We investigate the May 15, 1997 magnetic storm effects on the mid- and low-latitude ionosphere. The study is based on using the data from three chains of ionospheric stations located approximately along the meridians 20°, 140° and 280°E in the geomagnetic latitude range 13–65°N. Variations in f_0F2 are considered. Estimates of the zonal electric fields are made. Results of our analysis show that the main ionospheric effects of the storm under consideration are: (1) long-lasting intense negative disturbances during the storm main and recovery phases at subauroral and mid-latitudes; (2) positive disturbances at stations of the European and American chains observed prior to the storm, regardless of the local time; (3) a positive peak of Δf_0F2 at stations of the Asian chain during the storm main phase in the evening hours; (4) a similarity of the form of the Δf_0F2-variations at different latitudes and (5) the largest effect on the F region is observed at the Asian chain. The resulting differences of the Δf_0F2-variations can be driven both by the local time of the sudden storm commencement and by magnetic dip. It is not mere chance that the largest differences are observed along the meridian 140°E where the difference between the geographic and magnetic poles is the largest.

Keywords: Ionosphere; Ionospheric disturbances; Geomagnetic storm; Thermosphere; Magnetosphere

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1. Introduction

Notwithstanding the fact that the ionospheric storm has been the subject for scientific enquiry for several decades now, its effects have not yet been fully explained. The most significant problems and recent advances in the study of ionospheric storms have been emphasized in the review by Buonsanto (1999). Ionospheric storms represent an extreme form of space weather with important effects on ground- and space-based technological systems. A state of the ionosphere depends on a large number of variables, such as the local time, the geomagnetic latitude, the season, solar activity (SA), the storm onset time, the storm duration (the time that elapsed from the storm onset), the storm intensity and prestorm activity. During geomagnetic storms the disturbed solar wind compresses the Earth's magnetosphere, and intense electric fields are mapped along geomagnetic field lines to the high-latitude ionosphere. At times these penetrate to low latitudes, and at high latitudes they produce a rapid convection of plasma which also drives the neutral winds via collisions. At the same time, energetic particles precipitate to the lower thermosphere and below, expanding the auroral zone, and increasing ionospheric conductivity. Intense electric currents couple the high-latitude ionosphere with the magnetosphere, and the enhanced energy input causes considerable heating of the ionized and neutral gases. The resulting expansion of the thermosphere produces gradients of pressure which drive strong neutral winds. The disturbed thermospheric circulation alters the neutral composition, and moves the plasma up and down magnetic field lines, changing rates of production and recombination of the ionized species. At the same time the disturbed neutral winds produce polarization electric fields by a dynamo effect, as they collide with the plasma in the presence of the Earth's magnetic field. These electric fields in turn affect the neutrals and the plasma alike, illustrating that the ionized and neutral species in the upper atmosphere are closely coupled.

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Statistical patterns were described in earlier works. Long-lasting decreases in N_mF2 and TEC during the main phase of the storm at mid-latitudes may be thought of as representing the principal indicator of a storm in the F2 layer. According to observations, this negative phase is usually preceded by the positive one which can appear during the main phase and in winter at low and mid-latitudes, respectively. This classical picture of the ionospheric storm is based on a statistical study reported in reviews by Matsushita (1959) and Danilov (1985), and is supported by many observations (Rishbeth, 1998; Rodger et al., 1989; Szuszczewicz et al., 1998; Wrenn et al., 1987). Prolss et al. (1991) made an attempt to classify the effects of ionospheric storms in subauroral latitudes according to their anticipated sources, based on the data from ground-based ionosondes. They identified the following effects: (1) positive effects of storms caused by traveling atmospheric disturbances, (2) positive effects caused by changes in large-scale circulation of the thermospheric wind, (3) positive effects caused by the equatorward displacement of the ring of auroral ionization, (4) negative effects caused by the mixing of neutral gas composition and (5) negative effects caused by the equatorward displacement of the trough region. Cander and Mihajlovic (1998) analyzed the manifestations of geomagnetic storms in the ionosphere over the European region where the F2 layer critical frequency is much higher or lower than the median level, depending on the season and on the disturbance onset time, and produced a predictive model for the behavior of ionospheric parameters during the storm. A global response to the magnetic storm, using the data from a network of ionosondes, was investigated by Yeh et al. (1994). The study revealed low-latitude auroras over a large area in the Northern Hemisphere. Long-lasting global-scale decreases in ionization at mid-latitudes are the most conspicuous storm effect. The zone of negative disturbances extended equatorward to the geomagnetic latitude less than 10° at the time of the main phase, causing the equatorial anomaly to be temporarily suppressed. Short-duration positive effects were observed during the sudden storm commencement (SSC) and the main phase of the storm after sunset. Depending on the local time of the SSC, the ionospheric response was different in different longitudinal sectors. Sporadic layers and geomagnetic pulsations typical of the auroral zone were observed during the magnetic storm of October 18–19, 1995 at the Irkutsk latitude (Polekh et al., 1998; Zolotukhina et al., 2000). Based on the data from the DE-2 satellite, it was found that during disturbances high-speed ion fluxes penetrate as far as the latitudes of 30°, thus changing the thermosphere wind pattern (Reddy and Mayer, 1988).

Liu et al. (2000) studied high-latitude ionospheric response in polar cap and auroral oval to a major geomagnetic storm on May 15, 1997. This storm lasted about 40 h. The D_{st}-index rose slightly at 02 UT, indicating the storm sudden commencement. After being nearly constant for four hours, it decreased rapidly and reached a minimum of −115 nT at 12 UT. Afterwards it recovered gradually to normal level. The maximum K_p value was 7^+. According to the illumination level, this storm was near the solstice, and corresponded to minimum SA. The objective of this study is to ascertain the features of variations of the main ionospheric parameter f_0F2 at different middle latitudes and in different longitudinal sectors during all stages of this magnetic storm.

2. Data analysis

The data from three chains of ionospheric stations located in the European, Asian and American sectors of the Northern Hemisphere were used in the analysis. The stations and their locations are listed in Table 1. As the index of ionospheric disturbances, we used relative deviations of critical frequencies from the quiet level

$$\Delta f_0\mathrm{F2} = (f_0\mathrm{F2}_{\mathrm{dist}} - f_0\mathrm{F2}_{\mathrm{quiet}})/f_0\mathrm{F2}_{\mathrm{quiet}} \times 100\%.$$

2.1. The European chain of stations

The latitudinal chain of ionospheric stations located near the meridian 20°E is considered. The geomagnetic storm in this longitudinal sector began after midnight. Fig. 1 presents the variations of the index of ionospheric disturbance for the stations under consideration. The values of the D_{st}-variation and of the K_p-index are shown at the top of the figure. Open and solid circles on the time axis correspond to local noon and midnight.

Moderate changes of the D_{st}-index occur from 00 to 18 UT on May 14, whereupon D_{st}-variations remains virtually zero until the SSC around 03 UT. Small, uncorrelated variations of f_0F2 with respect to the monthly median are taking place during this relatively quiet period at all stations of the chain. Around local midnight, over Kiruna there appears a minor negative Δf_0F2 (less than 15%) which, with increasing latitude, changes its sign and increases its amplitude by as much as 30% over almost all stations of the chain. Following the beginning of the positive phase of the storm on May 15, the values of Δf_0F2 at all stations tend essentially to decrease (by changing from positive to negative values). Negative low amplitude deviations of Δf_0F2 are observed at all stations of the chain when the positive phase of D_{st}-variations changes to a negative phase and during the growth phase of the magnetic storm. Significant positive disturbances (up to 60% or higher) arise at the maximum of the storm at 13–14 UT after local noon over Sofia, which change to negative during the storm recovery phase around 18 UT. At higher latitudes negative Δf_0F2 were observed throughout the period till the end of the day. Their amplitude increased to local midnight. Negative disturbances were observed at high-latitude stations of the chain on May 16. With decreasing latitude, Δf_0F2 change their sign and remain positive till the end of the day. The wave-shaped form

Table 1
A list of ionospheric stations from which data were used in this study

Station name	Code	Geographic		Geomagnetic	
		Latitude	Longitude	Latitude	Longitude
European chain					
Kiruna	KI	67.8	20.4	65.17	115.9
Lycksele	LY	64.7	18.8	62.7	111.4
Uppsala	UP	59.8	17.6	58.4	106.3
Juliusruh/Rugen	JR	54.6	13.4	54.4	99.06
Dourbes	DB	50.1	4.6	51.89	88.15
Sofia	SQ	42.6	23.4	41.10	103.08
San Vito	VT	40.7	19.9	40.2	97.5
Asian chain					
Magadan	MG	60.12	151.0	50.75	210.8
Petropavlovsk	PK	53.02	158.6	44.67	219.0
Irkutsk	IR	52.5	104.0	41.1	174.8
Khabarovsk	KB	48.5	135.1	37.91	200.4
Osan	SN	37.2	127.1	26.2	195.4
Taipei (Chung-Li)	TP	25.0	121.0	13.7	189.5
American chain					
Goosebay	GS	53.3	299.6	64.61	12.07
Wallops Is.	WP	37.9	284.5	40.3	352.7
Bermuda	BJ	32.37	295.3	43.8	5.62
Dyess	DS	32.4	260.3	42.1	325.5
Eglin	EG	30.4	273.3	41.2	340.5
Puerto Rico	PR	18.5	293.8	29.96	2.49

of the Δf_0F2-plots remains at all stations, and only the oscillation amplitude is changing. It should be noted that the disturbances are positive around midnight before the magnetic storm onset and are negative during the recovery phase.

2.2. The Asian chain of stations

Fig. 2 shows the variations of Δf_0F2 over the chain of stations located near the meridian of 140°E. The growth phase of storm over this meridian corresponds to the evening hours of the local time. The fluctuations of Δf_0F2 were of a minor nature on May 14. Positive Δf_0F2 appear in the afternoon nearer to the equator (TP). During the positive phase of $D_{\rm st}$-variations on May 15 at local noon there is an increase of the values of positive Δf_0F2 at the near-equatorial station. A most dramatic effect of this storm comes from intense positive disturbances (higher than 60%) in the evening hours during the main phase of geomagnetic storm which change to negative near a minimum $D_{\rm st}$-index at subauroral and mid-latitudes. Over the stations from Magadan to Khabarovsk the disturbance changed its sign around midnight; at a lower latitude the transition from positive to negative disturbances occurs in the morning hours during the recovery phase (SN). At the near-equatorial station (TP) the intense amplitude fluctuations of Δf_0F2 were observed as early as the initial phase of the storm and during the growth phase. Unfortunately, the data gap at TP from 12 UT to 23 UT do not allow to trace the variation of Δf_0F2 during the recovery phase. On May 16, all stations observed negative disturbances of f_0F2, irrespective of the local time; their amplitude increased with decreasing latitude.

The positive peak appeared on May 15 during the main phase of storm observed at all stations and the curves of Δf_0F2-variations retained their form in this case.

2.3. The American chain of stations

Fig. 3 shows the variations of the index of ionospheric disturbance in F2 layer at the longitudes 260°–290°E. The initial phase of the storm corresponded to local midnight, the main phase and a maximum of the $D_{\rm st}$-index occurred at night and in the morning hours, and the recovery phase corresponded to the day-time in this region. Positive disturbances with amplitude of up to 30% were observed at night on May 14 at all stations of the chain, except for PR, which change to negative after midnight. In the afternoon there appeared positive Δf_0F2 as high as 40% or higher. The disturbance amplitude increased with decreasing latitude. Positive

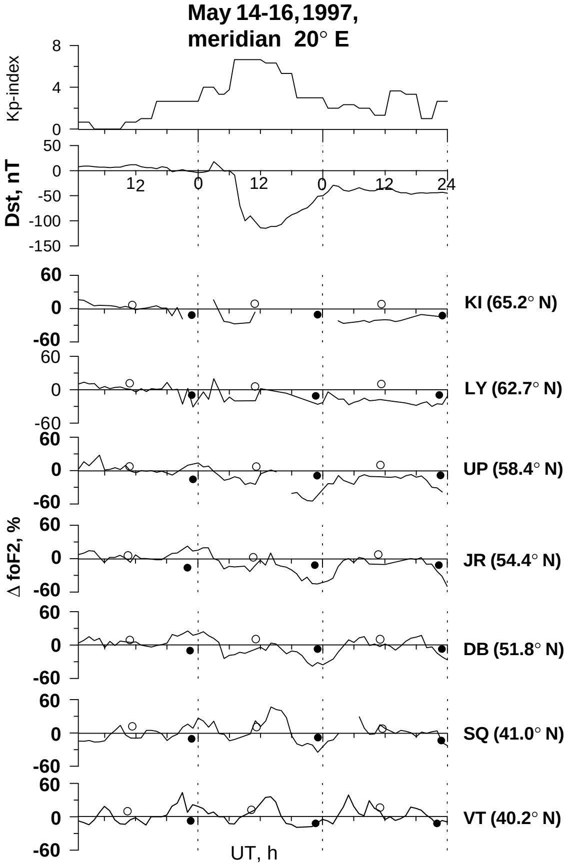

Fig. 1. Variations of the index of ionospheric disturbance of F2 layer for the stations located near the meridian 20°E. Values of the D_{st}-variation and of the K_p-index are shown at the top of the figure. Open and solid circles on the time axis correspond to local noon and midnight.

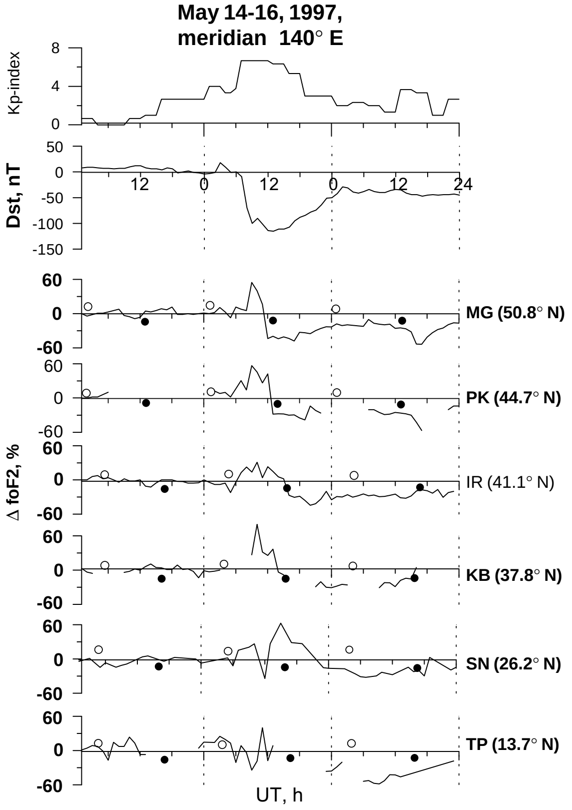

Fig. 2. Variations in the Δf_0F2 for the stations located near the meridian 140°E.

disturbances with amplitude of up to 70% were observed at the auroral zone station (Goosebay) during the main phase of the storm in the morning and day-time. They change to negative with amplitude of up to 40% in the evening sector during the recovery phase. After midnight on May 16, there recur positive Δf_0F2 whose amplitude in the morning reaches 100%. At mid-latitude during the initial phase of the storm the Δf_0F2-variations change their sign and remain negative during the main and recovery phase of the storm on 15 and 16 May. The reversal of the disturbance occurs around local midnight. The amplitude of negative disturbances does not exceed 30%. The Δf_0F2-curves also tend to retain their form by increasing the amplitude with decreasing latitude. Besides, with decreasing latitude, the oscillatory character of the disturbances is enhanced. At the (PR) station on May 15, the quasi-period is about 7 h during the main and recovery phases.

3. Discussion

Some overall regularities are suggested by considering the ionospheric disturbances on three meridians, caused by the magnetospheric storm. They imply the following features.

Prior to the storm, the European and American chains observed positive disturbances with the amplitude of up to 30%, irrespective of the local time. At the beginning of the negative storm phase, the stations of the Asian region in the evening sector observed the occurrence of positive disturbances of up to 60%, which subsequently changed to negative.

Long-duration intense negative disturbances are seen at subauroral and mid-latitudes during the main and recovery phases of the magnetic storm at all meridian chains.

Strong positive disturbances are observed at the maximum of the storm in the day time at the middle latitudes of the European chain.

The form of the curves of Δf_0F2-variations changes little with latitude. A comparison of the Δf_0F2-variations on different meridians and nearby latitudes (DB-MG-WP) and (SF-KB-EG) shows that the greatest effect of the storm in the F2 region was observed at the Asian chain.

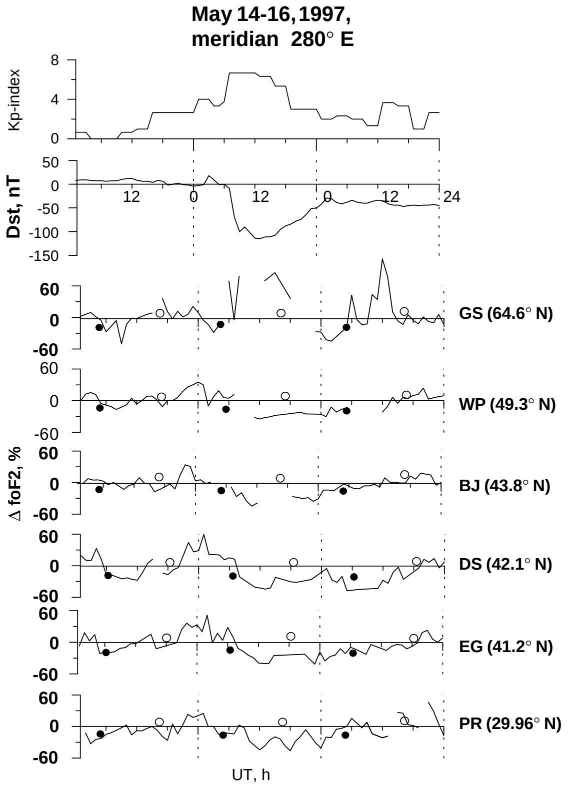

Fig. 3. The variations in the Δf_0F2 for the stations located near the meridian 280°E.

We analyzed some physical processes that cause the observed effects.

When the Δf_0F2-variations are examined with respect to the storm, at the European and American chains positive disturbances are observed to precede the storm, with maximum values around 00 UT on May 15, irrespective of the local time. At the European and American chains, respectively, these are the night and the evening hours. The occurrence of positive disturbances on May 14 can be explained by an increase of the K_p-index to 3^+. In the Asian region, no disturbances were observed before the storm, and a positive peak of Δf_0F2 occurs during the storm growth phase. Such large enhancements in N_mF2 often seen in the afternoon and evening hours represent "dusk" effect (Buonsanto, 1999). The fact that there was no disturbance with increasing of the K_p-index on this meridian is associated with the forbidden time for the occurrence of ionospheric disturbances in the day-time (Danilov, 1985). "Dusk" effect in the development of the disturbance was observed in the North-Eastern region of Russia, based on the vertical, oblique-incidence and backscatter sounding data (Pirog et al., 2001; Zherebtsov et al., 1999). Using the experimental data from the Millstone Hill IS radar, Foster (1995) suggested a mechanism for the positive peak of Δf_0F2 in the evening hours ("dusk" effect), associated with the formation of the main ionospheric trough. Magnetic storms can be accompanied by an intense (> 100 mV/m) polarization electric field if the injected ions of the plasma sheet lie more equatorward than the electrons. This gives rise to a latitudinally narrow polarization jet band or a subauroral drift of ions (Galperin et al., 1986). The region of fast convection develops a deep, narrow trough in the F region, whereas equatorward of it the antisunward directed plasma flow from a later LT and lower latitudes leads to an increase in electron density during the initial phase of the storm. One can suppose that the clearest manifestation of this mechanism was observed on May 15, 1997 at 08–12 UT at the Asian chain.

The changes of the neutral composition to the molecular component can cause a decrease in electron density in the day-time during the storm (Matsushita, 1959; Prolss et al., 1991), because they lead to a strong decrease in the production of O^+ ions and to an increase of its losses. Changes in composition are produced by the neutral wind predominantly in the region of Joule heating. Liu et al. (2000) studied the variations of high-latitude ionosphere on May 15, 1997 and showed that the large depletion in N_e of auroral oval was caused by strong electric fields, peaked to 120 mV/m during the storm main phase. As a result, this large electric field caused strong Joule heating in the ionosphere, thereby heating the ions from about 900° to nearly 2000°K. Simultaneously, the heating in the F2 region resulted in an increase of neutral temperature and an upwelling of the neutral gas, providing enriched concentrations of molecules in the F2 region. As a consequence of the heating in high latitudes, the large-scale thermospheric circulation can be taken to be the source of enrichment with oxygen and nitrogen molecules, causing a decrease in atomic oxygen in the F2 region at other latitudes. Both processes contribute to the F2 region depletion mainly by increasing the recombination rate of O^+ ions.

Anomalous increases in the ionization density at middle latitudes and anomalous increases in the neutral gas density at low latitudes are prominent features of ionospheric storms. Both anomalies can have a common origin and are caused by traveling atmospheric disturbances (TAD) (Prolss and Ocko, 2000). During magnetospheric storms, energy is injected into the polar upper atmosphere. The sudden energy addition launches a TAD which propagates with high velocity (600 m/c) towards the equator, either directly or via the pole. An essential feature of such a TAD is that it carries along equatorward-directed winds of moderate magnitude (150 m/c). At middle latitudes, these meridional winds drive the ionization up the inclined magnetic field lines and cause an uplifting of the F2 layer. Since the ionization losses (which are proportional to the N_2 and O_2 densities) decrease much faster with height than the ionization production (which are proportional to the O density), this will lead to the increase in the ionization density, i.e. to positive ionospheric storms (Prolss et al., 1991).

As it has been pointed out above, a significant increase in electron density during the main storm phase, observed at the Asian chain of mid-latitude stations ("dusk" effect), is an important feature of the manifestation of this storm in the North-Eastern region of Russia. Several mechanisms were considered to explain this effect (Buonsanto, 1998). According to Klimenko and Namgaladze (1977), the reversal of the electric zonal wind from eastward to westward provides a positive disturbance in electron density approximately by a factor of 2, followed by a negative disturbance of the same magnitude. An analysis of the experimental data on the May 26–27, 1990 magnetic storm from the Millstone Hill radar, and modeling result of the electron density distribution during the concerned storm showed that electric fields and the neutral wind are the main mechanisms that are responsible for the "dusk" effect, and for taking into account the fuller change of all N_e-variations it is important to have a combination of all concerned mechanisms including TAD, the inclusion of vibrationally excited ions, the motion of high-density plasma from higher latitudes, and the neutral composition variation (Schlesier and Buonsanto, 1999).

In order to explain the increase in electron density during the main phase of the storm in the evening time observed at the Asian chain of stations, we made an attempt to estimate the effective meridional neutral wind from the deviations of the layer heights.

The peak height, h_mF2, was determined by the empirical formula derived by Shimazaki (1955)

$$h_m\mathrm{F2}\ (\mathrm{km}) = 1490/M(3000)\mathrm{F2}\ (\mathrm{MHz}) - 176,$$

where $M(3000)$F2 is maximum usable frequency for a path of 3000 km by F layer reflection.

There are more exact formulas, but they require the F layer critical frequency, and this parameter is not always available, as our concern is only with the relative variations, the inaccuracy in the determination of the values of h_mF2 is not all that important.

Variations of the effective meridional neutral wind ΔU_x are calculated by the technique suggested by Forbes et al. (1988)

$$\Delta U_x = \Delta h_m\mathrm{F2}/\alpha\ (\mathrm{m/s}),$$

where

$$\alpha = 2[1 + 0.25\cos 2\pi/24(t-14)]\sin I\cos I\ (\mathrm{km/s}),$$

t is the local time (hours), and I is the angle of magnetic dip.

The coordinate axes are directed: x—southward (equatorward), y—eastward, and z—upward.

This effective meridional wind can be caused both by a change in the neutral wind regime under disturbed conditions and by the influence of zonal electric fields. The effective meridional wind, in turn, causes a vertical plasma drift which is related to the meridional wind and with electric zonal fields by the relations

$$\Delta V_{zU} = \Delta U_x \sin I \cos I$$

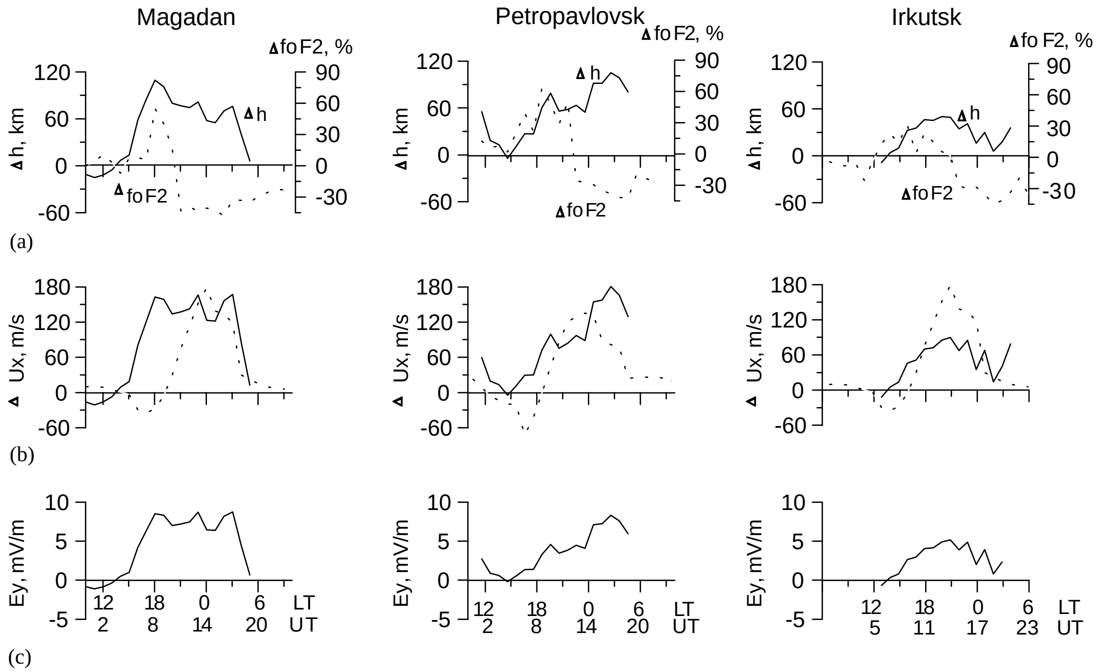

Fig. 4. The variations in Δf_0F2 and Δh_mF2 during the main phase of storm (a). The variations of the effective meridional neutral wind determined from the deviations of heights of F2 layer maximum (solid line) and the model HWN-90 (dashed) (b). The variations of east–west electric field (c).

and

$$\Delta V_{zE} = (E_y/B_0)\cos I.$$

Since changes in the F2 layer peak height can be produced both by meridional neutral wind variations U_x and by the effect of the east–westward electric field E_y, their contributions E_y and U_x to the vertical drift V_z are not possible to separate without additional independent information.

If it is assumed that the difference (ΔV_z) is caused only by the influence of the electric field, then its value (in mV/m) can be estimated as

$$E_y = \Delta V_z B_0/\cos I,$$

where ΔV_z is determined as ΔV_{zU}.

Naturally, this calculation gives the very approximate values of east–west electric fields, but it allows to estimate the possible mechanisms that control over the distribution of electron concentration during the ionospheric storm.

Fig. 4 plots the deviations of critical frequencies and peak height of the F2 layer from an undisturbed level (a), and the variation of the effective meridional neutral wind for three stations of the Asian chain (b). It is evident that at the beginning of the main phase of the storm the variations Δh_mF2 and Δf_0F2 are of the same sign. With a further development of the storm, the height and frequency variations are changing out of phase. It should be noted that the largest deviations of F2 layer peak heights were observed at subauroral station Magadan (16–22 LT). Furthermore, the dashed line in Fig. 4b plots the variations of the meridional neutral wind calculated from the empirical model of neutral winds HWM-90 (Hedin et al., 1991). The figure shows that these variations are generally similar. It is worth noting that the enhancement of the effective meridional wind ΔU_x, inferred from the deviations of Δh_mF2, starts significantly earlier than the enhancement calculated in the HWM-90 model; this is especially evident for station Magadan. The vertical drift that is caused by the meridional neutral wind would not ensure such an increase of the height. Based on this, one is led to suggest that this growth of the layer height could be caused by a vertical drift produced by an electric field of a magnitude of 5–8 mV/m. Such fields were obtained during the magnetic storm of January 20–21, 1989 (Reddy et al., 1990) and May 26–27, 1990 (Schlesier and Buonsanto, 1999). Our estimates of the east–west electric field are similar to the variations of the field obtained by other authors.

4. Conclusion

The analysis of the variations in F2 layer critical frequencies at three chains of ionospheric stations located on different meridians has permitted us to identify the following overall regularities and differences:

(1) long-lasting intense negative disturbances during the growth and recovery phases of the storm at subauroral and mid-latitudes;
(2) positive disturbances at the European and American chains observed prior to the storm, irrespective of the local time;
(3) the positive peak of Δf_0F2 at the Asian chain during the growth phase of the storm in the evening hours (“dusk” effect);
(4) the similarity of the form of Δf_0F2-variations at each chain at different latitudes and
(5) the greatest effect of the storm on the F region is observed at the Asian chain.

Our obtained differences of the Δf_0F2-variations in different longitudinal sectors can be caused both by the local time of the storm sudden commencement and by magnetic dip. It is no mere chance that the greatest differences are observed on the meridian of 140°E where the difference between the geographic and magnetic poles is the largest.

The evolution features of the mid-latitude ionospheric storm that were pointed out in items 1, 2 and 4 correspond to the established understanding of this phenomenon. It has been reported that the “dusk” effect, mentioned in item 3, was observed at Millstone Hill and in the East-Siberian region. Its origin is yet imperfectly understood. Of interest is the fact that regions where the “dusk” effect is observed are recorded in opposite longitudinal sectors. The result, pointed out in item 5, is a new one and can be considered as the main contribution of this paper to current community knowledge on ionospheric storm effects.

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