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Response of ionosphere to the great geomagnetic storm of September 1998: Observation and modeling

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Abstract

We present the results derived from investigating of the ionospheric effects of the great geomagnetic storm on September 24–27, 1998 based on analyzing the data obtained at ionospheric stations located in the region of Siberia and the Far East. For the sake of comparison we have also introduced the data from some European stations. In addition to the vertical-incidence sounding data the measurements from the Irkutsk incoherent scatter radar are used. It is obtained that the intense negative disturbances during the main phase of the storm are observed at all stations under investigation. A comparison of the foF2 variations for the two meridians shows that even with a relatively small difference of longitudes (45°), the recovery phase has substantial differences of ionospheric disturbances. On September 26, the positive disturbances are observed and persist the following day at all stations except Salekhard and the Norilsk chain. At the Norilsk chain and at Salekhard the negative disturbances recurred after positive disturbances. The sign reversal of disturbance during the recovery phase extends over in the further displacement from the west to the east. An interpretation of the measurements includes their comparing with the results of calculations in terms of a numerical model of the ionosphere and plasmasphere. The modeling results are in the satisfied agreement with the measurements. According to the model calculations the sign of the ionospheric disturbance is changed from negative to positive as the result of combined effects of corpuscular and photo ionization. The sign of ionospheric disturbance is determined by a local time at which the magnetic storm has begun.

Keywords: Ionosphere; Plasmasphere; Atmosphere; Ionospheric storm; Geomagnetic disturbance; Incoherent scatter; Electron density; Electron and ion temperature; Numerical model of the ionosphere and plasmasphere

1. Introduction

The ionospheric storm is a complex set of phenomena in the mid-latitude ionosphere, which arises as a response to a disturbance of the geospace during magnetospheric storms. Extensive research on ionospheric storms has been underway for over four decades now, and the main processes governing the mechanism responsible for the formation and evolution of an ionospheric disturbance have been essentially understood at present (Prölss, 1993; Buonsanto, 1999). At subauroral and mid-latitudes, these processes include primarily the interaction of ionospheric plasma with equatorward propagating disturbances of the thermospheric wind and the composition of the neutral atmosphere, as well as the effects of expansion (toward low latitudes) of the areas of energetic electron precipitation and magnetospheric convection (Buonsanto, 1999). As a result of the numerous experimental and theoretical investigations, it has been ascertained that the character of the ionospheric response to a particular geomagnetic storm depends quite crucially on the sequence and intensity of the effects of these factors under given geophysical conditions. For that reason, interpretation of observational data on every ionospheric storm is of independent scientific interest and constitutes a rather challenging problem.

Let us take a brief look at the mechanism responsible for the influence of a thermospheric disturbance on the mid-latitude ionosphere. About 10–20 min after the onset of

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the magnetic storm, the auroral oval begins to expand toward lower latitudes, and this expansion is accompanied by a rapid heating of the high-latitude thermosphere at the rate proportional to the increase of the AE-index (Emery et al., 1999). As a result of such impulsive heating, the atmosphere generates strongly longitudinally extended large-scale gravity waves with a period of 1–3 h. Propagating in the thermosphere from high to low latitudes, they alter the number–density composition of the thermosphere and neutral wind parameters. According to measurements, during magnetospheric storms the meridional thermospheric wind velocity V can be as high as ≈500–800 m/s, whereas under quiet conditions $V \approx$ 100–200 m/s (Emery et al., 1999; Buonsanto et al., 1999; Hagan, 1988). The equatorward enhancement of the wind causes the F2 layer to go up and the charged particle density in its maximum to increase, which is commonly called the *positive phase* of the ionospheric storm (Rishbeth, 1998; Namgaladze et al., 2000). It should be noted that the disturbed (“stormy”) circulation, in addition to causing the F2 layer to go up, plays an important role in thermospheric composition variation. Thus, the horizontal wind transports composition disturbances from the polar to middle and low latitudes, while intense, stormy, vertical drifts lead to a decrease (upward flows) or an increase (downward flows) in atomic oxygen density in the lower thermosphere (Buonsanto, 1999; Rishbeth, 1998; Burns et al., 1991). Since the electron density near the F2 region maximum NmF2 $\propto$ R = [O]/[N2], and the value of the number–density composition R usually decreases at the time of geomagnetic disturbances, the most typical feature of the ionospheric storm is the decrease of NmF2 that is called the *negative phase*. We emphasize that usually both *positive phase* and negative phase are properties exhibited by initial stage (main phase) of magnetic storm. Thus, the currently generally accepted picture of the ionospheric storm evolution consists of two stages, one of which is associated with an enhancement of the equatorward directed meridional wind, and the other reflects variations in neutral composition. Depending on the intensity of the magnetospheric disturbance and on the local time of its onset, the behavior of the ionosphere at these stages can be essentially different.

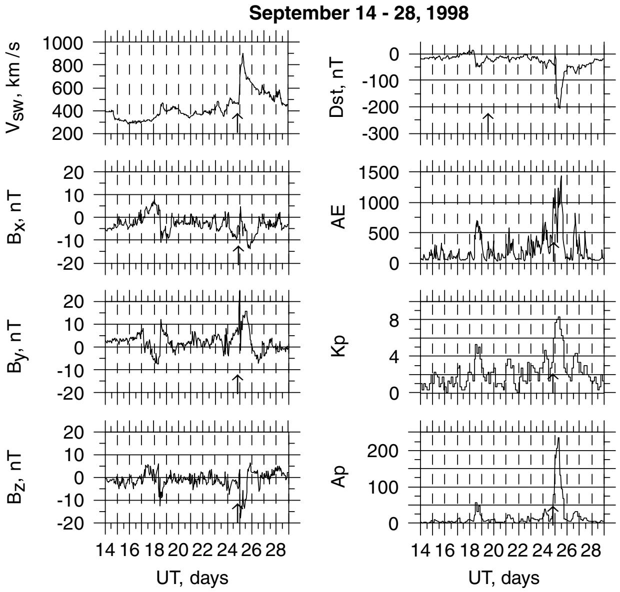

Fig. 1. Variations of solar wind parameters and geomagnetic activity indices over the period of September 14–28, 1998. The arrows indicate the SSC time.

2. Data analysis

This paper presents results derived from interpreting the ionospheric observational data obtained during the great geomagnetic storm occurred on September 25, 1998. The magnetic storm under investigation is caused by a disturbance of the solar wind propagating with the velocity of ~850 km/s at $B_z \approx -18$ nT. The first contact of this disturbance with the Earth’s magnetosphere (sudden commencement) occurs at ~23.45 UT on September 24. Fig. 1 shows the variations of geomagnetic activity indices and parameters of solar wind for the period 14–28 of September, 1998. As is evident from Fig. 1, during the storm the planetary index of geomagnetic activity K_p is as high as ~8.5, and the D_{st} index is ~ -207 nT. The main phase of the storm that lasts from 02.00 to 10.00 UT on September 25, shows strong variations of both the horizontal and vertical components of the geomagnetic field vector. The storm is accompanied by a powerful X-ray flare of class M. According to the observations from the Defense Meteorological Satellite Program (DMSP) satellites, in the Asian sector of the northern hemisphere the equatorial boundaries of the auroral oval and the areas of magnetospheric convection are displaced during the main phase of the storm to the geographical latitudes of ~60° and ~55°, respectively. During the concerned storm total absorption periods are of short duration, and variations of critical frequencies of the layers are often observed at mid-latitudes and in the zone of the main ionospheric trough. The situation at auroral stations is more complicated, where blanketing sporadic E layers are observed along with the absorption and it results in the absence of reflections in the F2 layer.

The data used for the present study are the hourly values of the F2 layer critical frequency from ionospheric stations listed in Table 1. It is evident from the list that eight of them are located along the *Yakutsk* and the *Norilsk* meridians, and one station (Magadan) is to the east of these two chains. Tixie, Zhigansk, and Norilsk refer to the auroral zone, Magadan, Yakutsk, and Tunguska lie in the region of the main ionospheric trough, and Khabarovsk and Novosibirsk are mid-latitude stations. Furthermore, our comparison uses the data from Central Asian station Almaty, and four stations located approximately between the geomagnetic latitude of 50–60 °E (the West Siberian station Salehard and three European stations).

Fig. 2 presents the variations of the D_{st} index and critical frequencies foF2 for September 24–27 at the stations of the

Table 1
List and locations of ionospheric stations

Station name	Geographic		Geomagnetic	
	Latitude	Longitude	Latitude	Longitude
Lycksele	64.7	18.8	62.7	111.4
Tixi	71.58	129.0	61.03	192.95
Norilsk	69.20	88.26	58.71	165.7
Salekhard	66.60	66.70	57.65	149.82
Zhigansk	67.00	123.4	56.00	188.5
Juliusruh/Rugen	54.6	13.4	54.4	99.06
Chilton	51.53	358.7	51.8	78.8
Yakutsk	62.0	129.6	50.99	194.1
Tunguska	61.40	90.0	50.83	165.61
Magadan	60.12	151.0	50.75	210.8
Novosibirsk	55.02	83.00	44.61	157.79
Khabarovsk	48.5	135.1	37.91	200.4
Almaty	43.25	76.92	33.64	152.19

Yakutsk and Norilsk chains. Almaty is included in the Norilsk chain because the difference in geographical longitude of the stations is small, less than 13°. The variations of foF2 in the quiet day on September 22 ($K_p < 3$, $D_{st} > -20$ nT) are used as the quiet level.

2.1. Yakutsk chain

The main phase of the storm in this region corresponds to the morning and daytime hours. A common feature of all stations, irrespective of their location, is an abrupt decrease in F2 layer critical frequencies during the main phase of the storm on September 25. The lack of data for that day, as shown above, is caused by the occurrence of powerful sporadic layers, which blanketed the F-region.

A closer examination reveals that significant negative disturbances were observed as early as September 24 with a decrease of the D_{st} index to -70 nT; this was especially true in regard to the stations of the Yakutsk meridian. At Tixi the negative disturbances alternate with the absence of reflections because of the Es layer blanketing. At Yakutsk and Zhigansk in the evening hours there is observed a drastic decrease of foF2, "break-down of the diurnal variation", which is likely to be caused by the appearance over the station of the main ionospheric trough during its rapid equatorward displacement at the time of the storm. The negative phase of a significantly lower intensity, however, persists during the recovery phase at Tixi in daytime, and a sharp increase of the F2-layer critical frequency is observed at night. In daytime of September 27 the ionization level is close to the quiet level. At Zhigansk and Yakutsk the recovery phase on September 26 shows a significant excess of foF2 over the quiet level: by 2–3 MHz in daytime, and by 4–5 MHz at night. This positive disturbance continues also in daytime of September 27 but at Zhigansk the "break-down of the diurnal variation" appears again in the evening and results in the negative disturbance. Nighttime positive disturbances coincide with the new disturbance in the D_{st} index. This

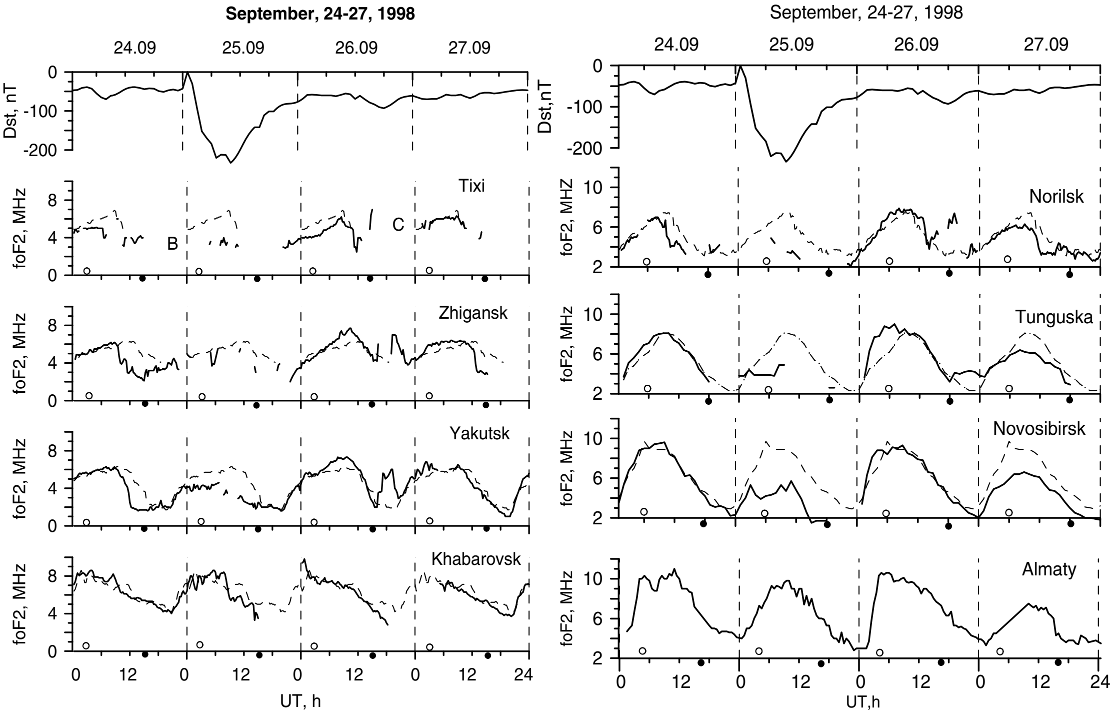

Fig. 2. Variations of the D_{st} index and critical frequencies of the F2-layer for September 24–27, at the stations of the Yakutsk and Norilsk chains. The dashed line shows the diurnal variation of foF2 in the quiet day and the solid line corresponds to the current values of foF2. Open and solid circles on the time axis correspond to local noon and midnight.

suggests that they are likely to be associated with the increase in the intensity of precipitating auroral particle fluxes.

The small fluctuating variations of ΔfoF2, positive in daytime, and negative in the evening and at night, are observed at Khabarovsk during the main phase. The lack of data for the time interval from 15 to 24 UT on September 25 interferes with the complete picture of disturbances for this station. It can be pointed out that a sharp ionization peak is observed in the morning hours of September 26, whereas critical frequencies in daytime approach the quiet level. A decrease of the F2 layer critical frequencies typical of the appearance of the main ionospheric trough over the station recurs in the evening on September 25 and 26.

2.2. Norilsk chain

At the Norilsk stations chain the situation is more uniform. On September 24 at Norilsk, the decrease of the D_{st} index is also followed by a "break-down of the diurnal variation" and later by blanketing Es-layers. At a maximum of the storm, as on the Yakutsk meridian, negative disturbances with larger amplitudes are observed both at high and middle latitudes. During the recovery phase on September 26 Norilsk and Tunguska show positive disturbances during daytime and at night. In Novosibirsk the variations of foF2 agree closely with the quiet level. On September 27 the disturbances were negative again at all stations. Unfortunately we have not Almaty data on 22 September (the quiet level) but the current values of foF2 are consistent with the variation at other stations.

2.3. Longitudinal effect

A comparison of the foF2 variations for meridians shows that even with a relatively small difference in longitudes (45°), the recovery phase has substantial differences of ionospheric disturbances. We decided to look into the extent to which these differences extend. To do this, we have also introduced data from some European stations.

Fig. 3 presents the variations of the F2-layer critical frequencies for the longitudinal chain of stations located at geographic longitudes from 0° to 150°E and along nearly geomagnetic latitudes of about 55°N. At Chilton (extreme western point of the chain) negative disturbances (as low as 2 MHz) are observed on September 24; the next day, during the main phase they increase greatly in amplitude (4 MHz). During the recovery phase in the night hours the disturbances remain negative till the morning; after that, foF2 recovers a quiet level. The positive disturbances (2 MHz) are observed after local noon both on September 26 and 27. Such variations are observed at the next stations of the chain (Juliusruh Rugen and Lycksele) located at 15° and 20° to the east. With a further eastward advance the absence of reflections because of the Es layer blanketing and the total absorption prevent to obtain the picture of the disturbances on September 25 at Salekhard. At Tunguska the intense negative disturbances and the total absorption are observed in the main phase of the storm. During the recovery phase, the ΔfoF2 are positive on September 26 and negative on September 27 at both of these stations. At Yakutsk the picture of disturbances is similar to that observed at European stations, except for the night peak on September 26. And, finally, at Magadan there are no positive disturbances during the recovery phase, and the F2-layer critical frequencies remain low till September 28.

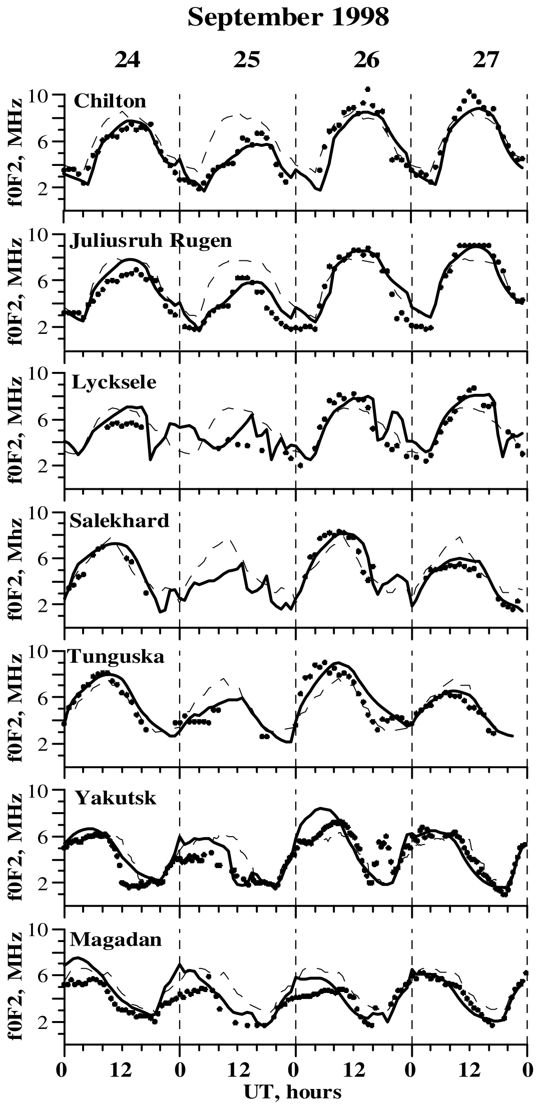

Fig. 3. Variations of the foF2 for September 24–27, at the longitudinal chain of stations. Close dots – observational values; dashed lines – quiet level; solid lines – results of modeling.

3. Discussions

Our analysis of ionospheric response to the great geomagnetic storm at the Yakutsk and the Norilsk meridians and at the longitudinal chain nearly geomagnetic latitudes of about 55 °N revealed the dependence of ionospheric disturbances both on the latitude and longitude. The longitudinal effect is of prime interest.

The negative disturbances at the longitudinal chain during the main phase of storm are observed at all stations except Salekhard where any information about F2 layer is absent. During the recovery phase on September 26 the positive disturbances are marked in daytime at all stations except Magadan. At night they are observed only at the stations of Siberia. European stations observed the small negative disturbances at night.

On September 27 the disturbances over Magadan are still negative, but the foF2 restores gradually to an undisturbed level. At Yakutsk and European stations disturbances are positive. At stations Tunguska and Salekhard the disturbances are again negative. A similar situation is noticed during the geomagnetic storm of October 18–19, 1995 (Kurkin et al., 2001). As there is shown in that study the stations from Salekhard to Magadan observed the negative ionospheric disturbance during the main phase of the storm, the positive disturbances on the following day during the recovery phase and then negative ones.

Usually the formation of the negative phase during the storm can be caused by disturbances of the neutral gas composition (Prölss, 1993). Large-scale circulation in the thermosphere as a consequence of the heating at high latitudes can be taken as the source of enrichment with atmospheric molecules. An increase in concentration of molecular species leads to a decrease in electron density as a consequence of an increase of losses (Prölss, 1993; Danilov, 1985). There is no consensus of opinion regarding the origin of long-lasting (as long as four hours) positive ionospheric disturbances to date. Fuller-Rowell et al. (1994) on the basis of thermospheric–ionospheric global circulation model suggested that these disturbances were caused by neutral composition variations. Any increase of the O/N_2 ratio must cause an enhancement of the ionization, i.e., a positive ionospheric storm. Other investigations leaning to a greater extent on observations indicate that the positive disturbances are caused rather by meridional winds (Prölss, 1993; Rishbeth, 1998; Bauske and Prolls, 1998). According to Mikhailov et al. (1995) the positive storm effects of long duration occur when the enhanced equatorward winds lift the ionization to greater heights at a time when production takes place still. This mechanism works best during the daytime. They also found that an increase in the O density is more important in causing positive storm effects than an increase in the O/N_2 ratio.

The transition of negative disturbances during the main phase to positive disturbances during the recovery phase seems to be caused by fluctuations of thermospheric composition. Such neutral composition variations after the magnetic storm were presented in the paper (Illes-Almar et al., 1987).

It is more difficult to explain the foF2 variations from stations of Norilsk chain and at Salekhard during the recovery phase of the storm when negative disturbances recurred after positive disturbances. Pulinets et al. (1996) also found that during the displacement from the east to the west there exists a boundary at about 55 °E where the phase of critical frequency deviations changes its sign. It should be emphasized that in our investigation the differences in critical frequency variations are observed during the recovery phase only. In accordance with observations by Irkutsk IS radar during the period of September 24–26 a positive disturbance in the ionosphere was recorded on September 26 as well (Zherebtsov et al., 1999). For interpreting of the sign reversal of disturbance a numerical simulation of the ionospheric response to this magnetic storm was carried out.

4. Results of modeling

The numerical model for ionosphere–plasmasphere coupling that was developed at the ISTP SB RAS (Tashchilin and Romanova, 2002) is used to interpret the observational data on the ionospheric response to the magnetospheric disturbance of September 24–27, 1998. The model is based on the numerically solving system of nonstationary balance equations of particles and thermal plasma energy within closed geomagnetic flux tubes whose bases are anchored at 100 km altitude. The reference spectrum of EUV solar radiation from (Richards et al., 1994) is used to calculate the photoionization rates of thermospheric species and the energy spectra of primary photoelectrons. A global empirical model of the thermosphere, MSIS-86, is used for space–time variations in neutral temperature and in densities of the thermospheric constituents, whereas the velocities of the horizontal thermospheric wind are determined in terms of the HWM-90 model. Values of the integral flux and average energy of the precipitation electrons, which are needed for calculating the auroral ionization rates, are taken in accordance with the global empirical model of precipitation (Hardy et al., 1987). The electric field of magnetospheric convection is calculated in accordance with an empirical model of the potential distribution (Sojka et al., 1986).

The response of the ionosphere to the magnetic storm under consideration is reproduced by calculating the variations of plasma parameters throughout the entire geomagnetic tube which base in the northern hemisphere is located at different points with geographical coordinates of ionospheric stations from the Table 1. The calculations are performed for the period of time from September 14–27, 1998. During this period the level of solar activity was increased ($F_{10.7} \approx 120–145$).

In the previous paper (Tashchilin et al., 2002) the study of the mid-latitude ionospheric response to the strong geomagnetic disturbance under consideration has been implemented from the comparison data measured by Irkutsk incoherent scatter (IS) radar and results of numerical modeling. It was showed that negative phase of this ionospheric storm aroused principally because of the variations the thermospheric composition. In addition, the initial theoretical analysis of Irkutsk radar measurements has given the chance to fit the solar EUV fluxes as well as thermospheric parameters to conditions of the storm under consideration. In the study we use a specified set of correcting factors to performance the model interpretation of the ionospheric response to the magnetic storm September 24–27, 1998. The Fig. 3 presents the overall picture of ionospheric storm course in European and Asian regions. At each plot a calculated variations of foF2 for the longitudinal chain of stations are showed as solid lines. These modeling results are in satisfied agreement with the measurements (dots in the figures).

In the present paper with help of modeling calculations the most attention has been focused on the reason why the positive ionospheric disturbances appeared during the early recovery phase. For this purpose we will analyze the calculated courses of ionospheric parameters for two locations: Lycksele and Salekhard in detail. In Fig. 4 calculated time-varying ionospheric parameters at the peak of F2 layer (electron density NmF2 and height of peak $h_{\max}$) with energy flux of the precipitation electrons (Pe) are shown for four drifting plasma tubes. Two tubes pass over Lycksele at the 1200 UT September 26 as well as on September 27. Two other tubes pass over Salekhard at the same instants of time. According to Fig. 4 it is evident that in the tube passing over Lycksele on September 26 at 1200 UT plasma is produced by the photoionization for sunlight intervals or by corpuscular ionization during unlit periods. Because these plasma sources operate against the background of almost recovered thermosphere the total ionization rate has the ability to form a positive ionospheric disturbance. The daily increase of NmF2 is created by the same manner on September 27. It should be noted that during the recovery phase a moderate substorm occurred on September 26. In this case ionosphere over Lycksele is undisturbed because Lycksele is placed in the daily zone when substorm has begun (~16.00 LT).

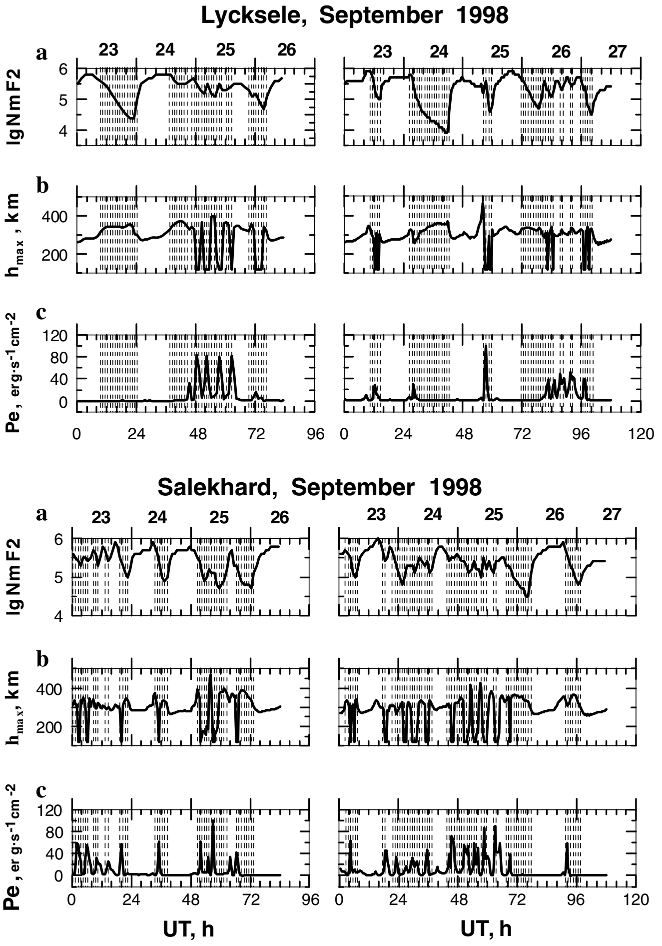

Fig. 4. Variations of the ionospheric parameters for two drifting plasma tubes passing over Lycksele and Salekhard at the 1200 UT on September 26 as well as on September 27. (a) Electron density NmF2; (b) height of F2-layer; (c) energy flux of the precipitation electrons.

In Salekhard the positive disturbance on September 26 is created under the action of corpuscular and photo ionization as well as over Lycksele. But on September 27 the ionospheric disturbance over Salekhard is negative. The cause of that transformation resides in the fact that Salekhard is placed in the evening sector when substorm has just begun (~19.50 LT). According to the current view of ionosphere generation this case aids to formation of negative ionospheric disturbance (Danilov, 1985).

5. Conclusions

By analyzing the ionospheric effects observed during a strong geomagnetic storm on September 24–27, 1998 using data from ionospheric stations located in the region of East Siberia and the Far East and comparing them with ionospheric disturbances from European stations we are able to identify common regularities and differences:

1. Intense negative disturbances during the main phase of the storm were observed at all stations under investigation.
2. At all other stations except Salekhard and the Norilsk chain, during the early recovery phase on September 26, there appeared positive disturbances, which persisted the following day.
3. At stations of the Norilsk chain and at Salekhard the disturbances were again negative on September 27.
4. According to the model calculations the sign of the ionospheric disturbance is changed from negative to positive as the result of combined effects of corpuscular and photo ionization. The sign of ionospheric disturbance is determined by a local time at which magnetic storm has begun.

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