Annales Geophysicae (2001) 19: 733–748 © European Geophysical Society 2001

An interpretation of the *fo*F2 and *hm*F2 long-term trends in the framework of the geomagnetic control concept

A. V. Mikhailov[1] **and D. Marin**[2]

[1]Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Troitsk, Moscow Region 142190, Russia
[2]National Institute of Aerospace Technology, El Arenosillo, 21130 Mazagon-Moguer (Huelva), Spain

Received: 20 August 2000 – Revised: 19 February 2001 – Accepted: 22 March 2001

Abstract. Earlier revealed morphological features of the *fo*F2 and *hm*F2 long-term trends are interpreted in the scope of the geomagnetic control concept based on the contemporary F2-layer storm mechanisms. The F2-layer parameter trends strongly depend on the long-term varying geomagnetic activity whose effects cannot be removed from the trends using conventional indices of geomagnetic activity. Therefore, any interpretation of the *fo*F2 and *hm*F2 trends should consider the geomagnetic effects as an inalienable part of the trend analysis. Periods with negative and positive *fo*F2 and *hm*F2 trends correspond to the periods of increasing or decreasing geomagnetic activity with the turning points around 1955, and the end of 1960s and 1980s, where *fo*F2 and *hm*F2 trends change their signs. Such variations can be explained by neutral composition, as well as temperature and thermospheric wind changes related to geomagnetic activity variations. In particular, for the period of increasing geomagnetic activity (1965–1991) positive at lower latitudes, but negative at middle and high latitudes, *fo*F2 trends may be explained by neutral composition and temperature changes, while soft electron precipitation determines nighttime trends at sub-auroral and auroral latitudes. A pronounced dependence of the *fo*F2 trends on geomagnetic (invariant) latitude and the absence of any latitudinal dependence for the *hm*F2 trends are due to different dependencies of NmF2 and *hm*F2 on main aeronomic parameters. All of the revealed latitudinal and diurnal *fo*F2 and *hm*F2 trend variations may be explained in the framework of contemporary F2-region storm mechanisms. The newly proposed geomagnetic storm concept used to explain F2-layer parameter long-term trends proceeds from a natural origin of the trends rather than an artificial one, related to the thermosphere cooling due to the greenhouse effect. Within this concept, instead of cooling, one should expect the thermosphere heating for the period of increasing geomagnetic activity (1965–1991).

Correspondence to: A. V. Mikhailov (avm71@orc.ru)

Key words. Ionosphere (ionosphere-atmosphere interactions; ionospheric disturbances)

1 Introduction

The problem of long-term variations (trends) in the ionospheric parameters is widely discussed in recent publications (see reviews by Danilov, 1997, 1998; Givishvili and Leshchenko, 1994, 1995; Givishvili et al., 1995; Ulich and Turunen, 1997; Rishbeth, 1997; Danilov and Mikhailov, 1998, 1999; Bremer, 1992, 1998; Upadhyay and Mahajan, 1998; Sharma et al., 1999; Foppiano et al., 1999; Mikhailov and Marin, 2000; Deminov et al., 2000; Marin et al., 2001). On the one hand, the world-wide network of ground-based ionosonde observations provides excellent experimental material for such an analysis, since many of the ionosondes have been operating for 3–5 solar cycles using one method of ionospheric sounding to obtain the set of main ionospheric characteristics. Most of these observations are collected and available from WDC-C at RAL (Chilton, UK) and from NGDC, Boulder, USA. On the other hand, after the model calculations of Rishbeth (1990) and Rishbeth and Roble (1992) who predicted the ionospheric effects of the atmospheric greenhouse gas concentration increase, researchers have been trying to relate the observed long-term trends in the ionospheric parameters to this greenhouse effect (Bremer, 1992; Givishvili and Leshchenko, 1994; Ulich and Turunen, 1997, Jarvis et al., 1998; Upadhyay and Mahajan, 1998). However, an analysis of many European ionosonde stations by Bremer (1998) and an analysis of a global set of ionosonde stations by Upadhyay and Mahajan (1998) has shown that the world-wide pattern of the F2-layer parameter long-term trends is very complicated and can hardly be reconciled with the greenhouse hypothesis. It should be stressed that different authors use different approaches to extract long-term trends from the ionospheric observations and the success of analysis depends, to a great extent, on the method employed. The useful "signal" is very small and the "background" is very noisy, so special methods are required to reveal a significant trend in the observed *fo*F2 and *hm*F2 variations. An approach being developed by Danilov and Mikhailov (1998, 1999), Mikhailov and Marin (2000) and Marin et al. (2001) has allowed us to find systematic variations in *fo*F2 and *hm*F2 trends unlike the other approaches (e.g. Bremer, 1998; Upadhyay and Mahajan, 1998), which result in a chaos of various signs and magnitudes of the trends at various stations. An application of this approach in *fo*F2 trend analysis resulted in a geomagnetic control concept (Mikhailov and Marin, 2000) used to explain the revealed latitudinal and diurnal variations of the *fo*F2 trends. The efficiency of this approach was also demonstrated by Marin et al. (2001) in the *hm*F2 trend analysis for many ionosonde stations in the Eurasian longitudinal sector. Briefly, the main results of the analysis by Mikhailov and Marin (2000) and Marin et al. (2001) are the following:

1. The *fo*F2 trends demonstrate a pronounced dependence on geomagnetic (invariant) latitude with strong negative trends at high latitudes and small negative or positive trends at lower latitudes for the period of 1965–1991. Contrary to this, the *hm*F2 trends show no latitudinal dependence being positive at the majority of the stations analyzed. The *fo*F2 and *hm*F2 trends are shown to be significant for most of the stations considered.

2. There are well pronounced (especially for *fo*F2) diurnal variations of the trend magnitude, while seasonal variations are rather small and may be ignored compared to diurnal ones.

3. The *fo*F2 trend analysis has shown that there exists periods with negative and positive *fo*F2 trends, which correspond to the periods of long-term increasing/decreasing geomagnetic activity. In particular, the period of 1965–1991 corresponds to the increasing geomagnetic activity, while the geomagnetic activity was decreasing during the 1955–1965 period.

4. The geomagnetic control concept has been proposed to explain main morphological features of the *fo*F2 and *hm*F2 trends revealed. This newly proposed geomagnetic hypothesis proceeds from a natural origin of the trends rather than an artificial one, related to the thermosphere cooling due to the greenhouse effect.

The aim of the paper is to provide further analysis and physical interpretation of the *fo*F2 and *hm*F2 trends within the proposed geomagnetic control hypothesis.

2 Diurnal variations at different latitudes

The final version of the method used for the F2-layer parameter trends analysis is given by Mikhailov and Marin (2000), therefore, only a fragmentary description is presented here. All available observations at about 30 European, North American and Asian ground-based ionosondes are used in the analysis by Mikhailov and Marin (2000), and Marin et al. (2001) to reveal *fo*F2 and *hm*F2 trends. The stations are located between 38° N and 81° N geographic latitude (30° N and 71° N geomagnetic latitude) and cover a broad longitudinal range, which provides the possibility to study spatial variations of the trend magnitude. Trends are analyzed for relative deviations of the observed *fo*F2 or *hm*F2 values from some model $\delta p = (p_{\rm obs} - p_{\rm mod})/p_{\rm mod}$ where p is the 12-month running mean of the monthly median *fo*F2 or *hm*F2. A regression (third-degree polynomial) of p with the sunspot number R_{12} is used as a model (Model 1). A regression of p versus R_{12} and annual mean Ap_{12} index is refered to as Model 2. Both models were used by Mikhailov and Marin (2000), and Marin et al. (2001) to find the slope K (in 10^{-4} per year) of linear trends for each station, for 12 months, and 24 LT moments. Although we are aware of the seasonal variations in trends (Danilov and Mikhailov, 1999), the later analysis has shown that diurnal variations may be much stronger than seasonal ones. Therefore, we analyze annual mean trends for selected LT hours. Averaged over 12 months the δpF2 value is found and this value is considered to be the annual mean value used in the trend analysis. The use of Model 2 was an attempt to exclude the effect of geomagnetic activity after Bremer (1998) and Jarvis et al. (1998). But our analysis (Mikhailov and Marin, 2000; Marin et al., 2001) has shown that such an inclusion of *Ap* indices to the regression, in fact, does not remove the geomagnetic effect, but only contaminates the analyzed material. Therefore, Model 1 (regression with R_{12}) is used in further analysis.

The magnitude of revealed *fo*F2 tends demonstrates strong diurnal variations depending on geomagnetic (invariant) latitude (Mikhailov and Marin, 2000). No systematic latitudinal variations were found for the *hm*F2 trends (Marin et al., 2001). Some examples of the *fo*F2 and *hm*F2 trend diurnal variations are given in Fig. 1 for auroral station Sodankyla ($\Phi_{\rm inv}$=63.59°), sub-auroral station Lycksele ($\Phi_{\rm inv}$=61.46°), mid-latitude station Ekaterinburg ($\Phi_{\rm inv} = 51.45°$), and lower latitude station Alma-Ata ($\Phi_{\rm inv} = 35.74°$). These stations are in the list analyzed by Mikhailov and Marin (2000), and Marin et al. (2001). Observations for the 1965–1991 period were used in further analysis. As in Mikhailov and Marin (2000) the $(m+M)$ year selection was used for the *fo*F2 trend analysis, where (m) represents the years around solar minima and (M) represents the years around solar maxima; all years were used to analyze *hm*F2 trends (Marin et al., 2001).

The selected stations demonstrate different diurnal variation patterns of the *fo*F2 trends (Fig. 1, left panel) which are believed (see later) to reflect different physical processes responsible for the F2-layer formation at different invariant latitudes. In general, as it was pointed by Danilov and Mikhailov (1999) and Mikhailov and Marin (2000), the *fo*F2 trends are negative at high and middle latitudes with a tendency to be small or positive at lower latitudes (e.g. Alma-Ata, Fig. 1, bot-

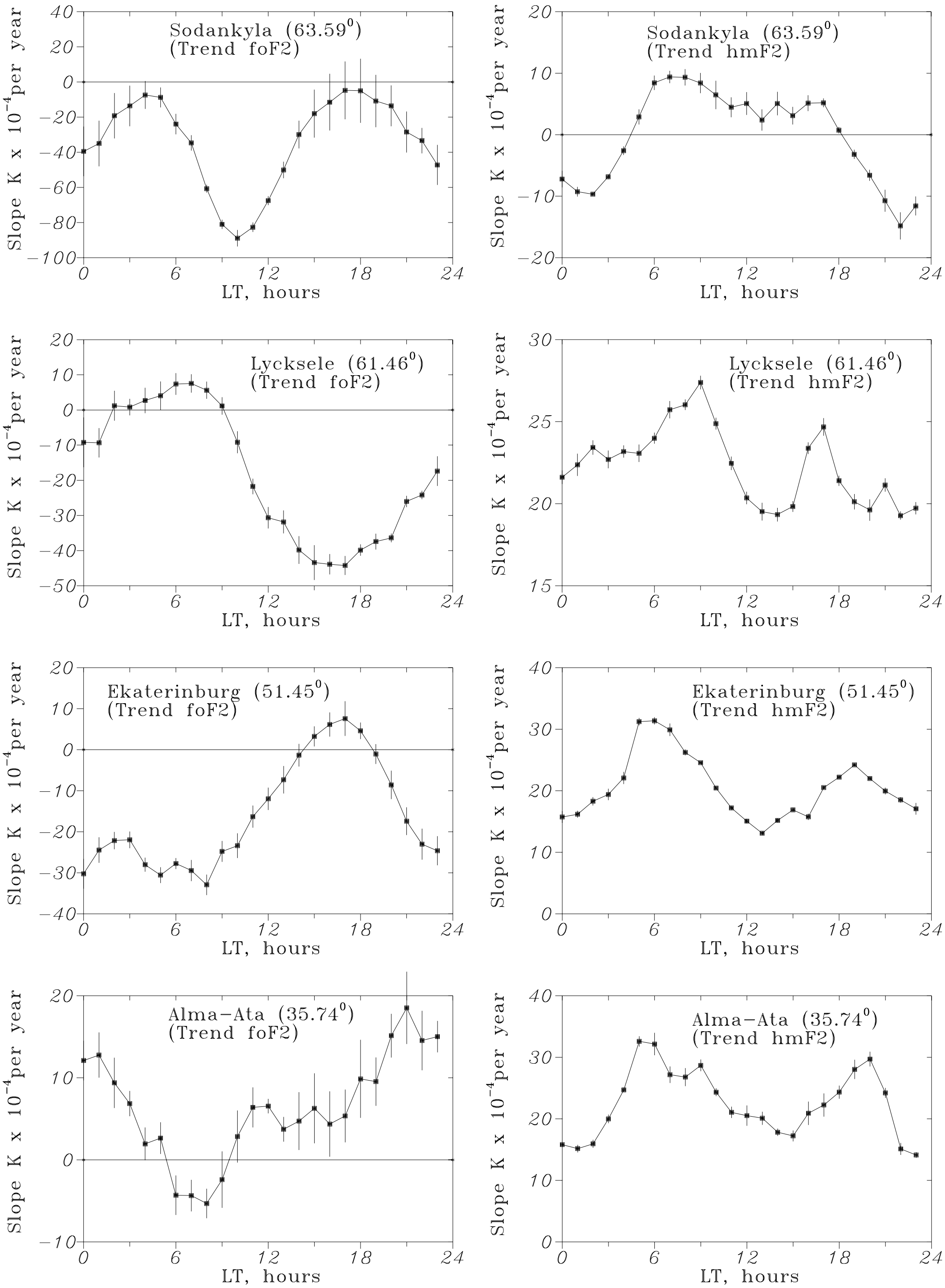

Fig. 1. Diurnal variation of annual mean slope K for *fo*F2 (left panel) and *hm*F2 (right panel) trends at auroral, sub-auroral, mid-latitude and lower latitude stations for the 1965–1991 period, invariant latitudes are given in brackets. Error bars present the standard deviation of seasonal (over 12 months) scatter in the slope K.

tom). Positive significant *hm*F2 trends for all LT are revealed at most of the stations considered (Marin et al., 2001), but at some stations, negative significant trends take place; therefore, an additional analysis is required to find out the reason. The Shimazaki (1955) formula which converts M(3000)F2 to *hm*F2, was used in our routine analysis. On the one hand, it was shown by Bremer (1992) and later confirmed by Marin et al. (2001) that *hm*F2 trends are not sensitive to the formula choice. On the other hand, an insertion of correction terms (depending on the *fo*F2/*fo*E ratio)

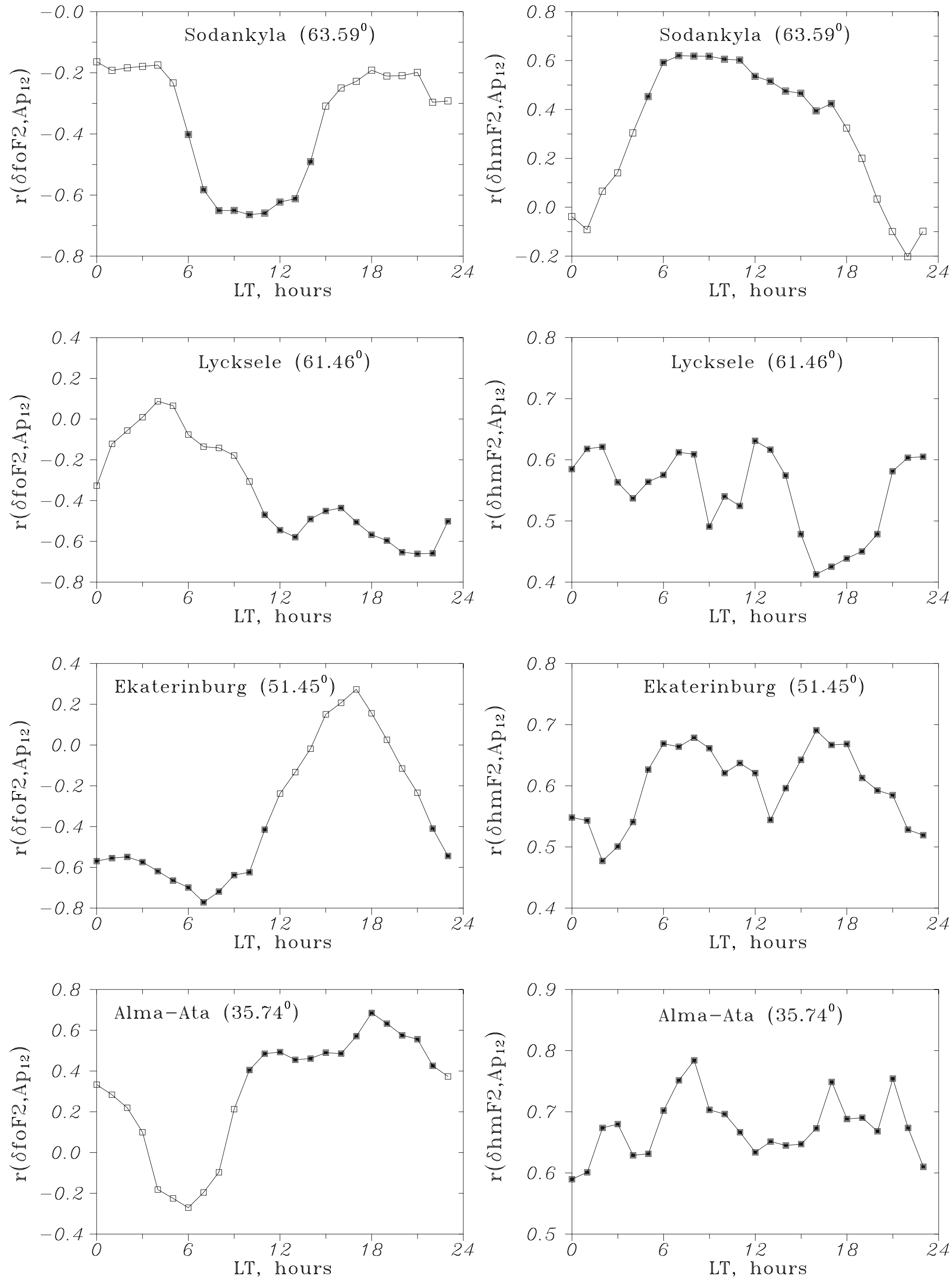

Fig. 2. Same as Fig. 1, but for correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ and $r(\delta hm\mathrm{F2}, Ap_{12})$. Solid squares are correlation coefficients significant at the 95% confidence level, open squares – the coefficients which are insignificant at this level.

to the Shimazaki (1955) formula may not be useful for the *hm*F2 trend analysis, as this ratio itself demonstrates long-term variations. The other problem with using *fo*E is in the absence of observations on many stations as well as during nighttime hours.

The revealed *fo*F2 and *hm*F2 trends may be explained in the framework of contemporary F2-layer storm mechanisms related to the thermosphere global circulation, neutral composition and temperature perturbations during disturbed periods. The relationship of the F2-layer trends with the long-term changes in the geomagnetic activity is clearly seen from diurnal variation of the correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ and $r(\delta hm\mathrm{F2}, Ap_{12})$ shown in Fig. 2, which are used in further discussion. These variations are seen to repeat the corresponding diurnal variation of the *fo*F2 and *hm*F2 trend magnitudes (Fig. 1), although the correlation coefficients (Fig. 2) are small and insignificant (open squares) at the chosen 95% confidence level for some periods of the day. Usually, as Fig. 2 shows, large correlation coefficients $r(\delta fo\text{F2}, Ap_{12})$ are significant at the 95% confidence level and the correlation may be of both signs depending on the latitude of the station considered.

Let us consider the obtained latitudinal and diurnal variations of the *fo*F2 and *hm*F2 trends (Figs. 1, 2) in the framework of the geomagnetic control concept.

2.1 Lower latitudes

Positive *fo*F2 and *hm*F2 trends are revealed both for day-and nighttime hours at the lower latitude station, Alma-Ata. An analysis of the F2-layer storm mechanisms for the lower latitude station Havana, with the same $\Phi_{\text{inv}} = 35°$ ($L = 1.5$) as Alma-Ata, was made by Mikhailov et al. (1995). According to AE-C and ESRO-4 satellite observations, geomagnetic disturbances result in an increase in the atomic oxygen absolute concentration, presumably due to the disturbed thermospheric circulation and downwelling at low latitudes, while the $R = (\text{O}/\text{N}_2)_{\text{storm}}/(\text{O}/\text{N}_2)_{\text{quiet}}$ ratio remains practically unchanged at the heights of the F2-region (Prölss and von Zahn, 1977; Skoblin and Mikhailov, 1996; Mikhailov et al., 1997). Using the well-known expression by Rishbeth and Barron (1960)

$$\text{NmF2} \cong 0.75 q_m/\beta_m \propto [\text{O}]_m/[\text{N}_2]_m \tag{1}$$

where ion production rate q_m and linear loss coefficient β_m are given at the F2-layer maximum, it was shown by Mikhailov et al. (1995) that

$$\text{NmF2} \propto \frac{[\text{O}]_1^{2/3}}{T_n^{5/6}} \left(\frac{[\text{O}]_1}{[\text{N}_2]_1}\right)^{2/3} \tag{2}$$

where all concentrations are given now at a fixed height h_1. This expression shows that NmF2 will increase provided that the absolute atomic oxygen concentration [O] increases, while [O]/[N_2] ratio may remain unchanged at any fixed level (the situation we have according to satellite observations at lower latitudes). Such [O]/[N_2] height variations are also confirmed by model calculations (Förster et al., 1999; Rishbeth and Müller-Wodarg, 1999). Thus, an [O] increase due to downwelling motion related to global storm circulation resulting from storm-induced equatorward thermospheric wind can really contribute to the positive NmF2 storm effect, while $R(\text{O}/\text{N}_2)$ ratio remains unchanged. This [O] increase provides a background NmF2 growth (see also Rishbeth, 1991; Field et al., 1998). Additional NmF2 increase is due to enhanced equatortward thermospheric wind (upward plasma drift), resulting from the auroral heating.
An increase in neutral temperature and concentrations, as well as in vertical plasma drift (due to the enhanced equatorward wind), usually taking place during disturbed periods, leads to the *hm*F2 increase. This may be seen from an approximate expression for *hm*F2 (Ivanov-Kholodny and Mikhailov, 1986)

$$hm \cong \frac{H}{3}\left\{\ln[\text{O}]_1 + \ln\beta_1 + \ln(H^2/0.54d)\right\} + cW \tag{3}$$

where $H = kT_n/mg$ is the scale height and [O] is the concentration of atomic oxygen, β is the linear loss coefficient at a fixed height h_1, W (in m/s) is the vertical plasma drift, c is a coefficient close to unity, $d = 1.38 \cdot 10^{19} \cdot (T_n/1000)^{0.5}$ is a coefficient in the expression for the ambipolar diffusion coefficient $D = d/[\text{O}]$.

The above scenario takes place in the ‘nighttime’ (relative to storm onset) longitudinal sector. In the ‘daytime’ sector, F2-layer positive storm effects with the NmF2 and *hm*F2 increase are primarily the result from the vertical plasma drift increase without changes in neutral composition and temperature (Pröls, 1995; Mikhailov et al., 1995). The main mechanism of such W increase is the background (poleward during daytime) and the storm-induced (equatorward) wind interaction. Depending on the storm intensity, this interaction may result either in a decrease of the background meridional thermospheric wind or in its reversal. In both cases, we obtain an increase in NmF2 and *hm*F2. Therefore, one should expect positive NmF2 and *hm*F2 trends for the 1965–1991 period of increasing geomagnetic activity. Our previous analysis confirms the existence of NmF2 and *hm*F2 positive trends for the majority of the day (Fig. 1, bottom).

Negative F2-layer storm effects are known to be strongest in the early morning LT sector (Wrenn et al., 1987; Pröls, 1991,1993 and references therein) due to the perturbed neutral composition with the decreased O/N_2 ratio advected towards middle and lower latitudes by the thermospheric circulation. This effect is especially pronounced at middle latitudes (see later), but takes place with strongly decreased magnitude at lower latitudes as well (see Fig. 1, around 07 LT). The area with increased [O] shifts further equatorward in this case.

Interesting results demonstrate the correlation coefficients diurnal variations (Fig. 2, bottom) which support the above discussed scenario. Large and significant coefficients $r(\delta fo\text{F2}, Ap_{12})$ are found for afternoon and evening hours when *fo*F2 trends are large at Alma-Ata (Fig. 1, bottom). This tells us that the revealed positive *fo*F2 trends are related to geomagnetic activity by the physical mechanism being discussed. Large and significant correlation coefficients $r(\delta hm\text{F2}, Ap_{12})$ are obtained for all LT moments (Fig. 2, right hand, bottom). This is due to both processes ([O] or/and W increase related to the increased geomagnetic activity) which contribute to the *hm*F2 increase, as it follows from Eq. (3).

The daytime sunlit F2-region is sensitive to the increase in [O] and W, resulting in the NmF2 increase. Therefore, the correlation coefficients $r(\delta fo\text{F2}, Ap_{12})$ are largest and significant during daytime hours (Fig. 2, left hand, bottom). The nighttime F2-region formation mechanism is different and NmF2 is less sensitive to the [O] and W variations. This results in small and insignificant (at the 95% confidence level)

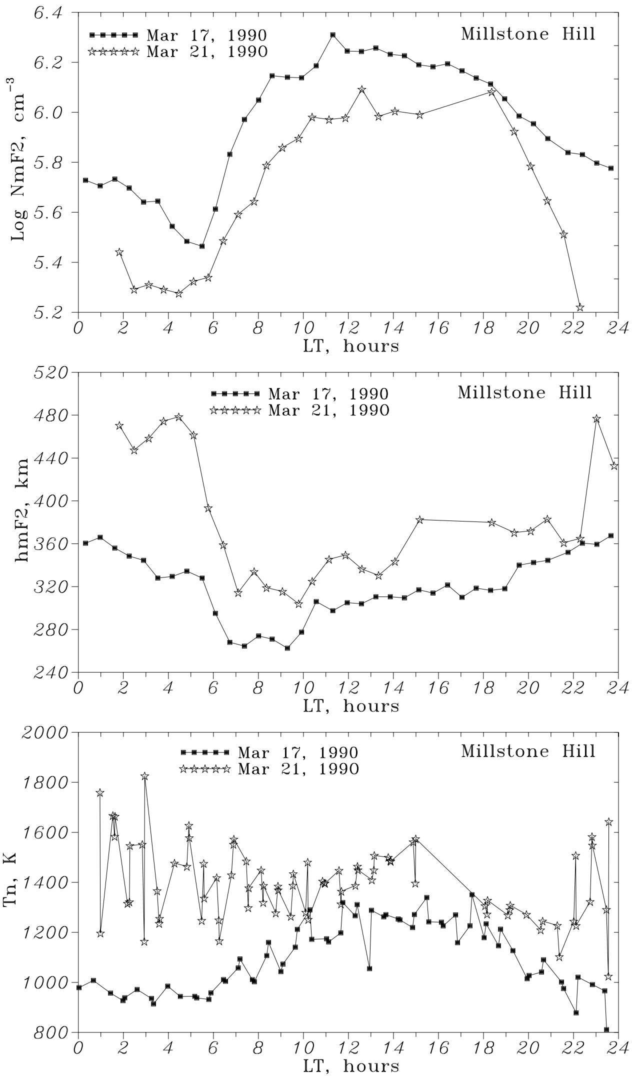

Fig. 3. Observed diurnal variations of NmF2, *hm*F2 and neutral temperature T_n estimated at Millstone Hill at 300 km for quiet 17 March 1990 and disturbed 21 March 1990 days.

nighttime correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$. In contrast, the dependence of *hm*F2 on [O] and W is practically the same during both daytime and nighttime hours. This gives large and significant $r(\delta hm\mathrm{F2}, Ap_{12})$ coefficients for the whole day (Fig. 2, right hand, bottom).

2.2 Middle latitudes

Typical mid-latitude *fo*F2 and *hm*F2 trend diurnal variations are presented by the results at Ekaterinburg (Figs. 1,2). Negative (especially at night) *fo*F2 and positive *hm*F2 (all day long) trends are obtained for most of the mid-latitude stations considered (Mikhailov and Marin, 2000; Marin et al., 2001). For better illustration of the physical mechanisms involved, let us consider Millstone Hill incoherent scatter observations for quiet 17 March 1990 ($Ap = 3$) and disturbed 21 March 1990 ($Ap = 76$) days. Millstone Hill and Ekaterinburg have close geomagnetic latitudes; therefore, such a comparison of the two stations is justified. Observed diurnal variations of NmF2, *hm*F2 and T_n at 300 km are shown for the two days in Fig. 3. The observations illustrate well-known and typical negative storm behavior for the mid-latitude F2-layer. When we pass from quiet to disturbed conditions, NmF2 decreases and *hm*F2 increases during both daytime and nighttime hours. The NmF2 decrease is more pronounced in the nighttime and early morning LT sector. The same diurnal variation is seen in the *fo*F2 trends (Fig. 1, left panel), with the correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ being the largest for the same hours (Fig. 2, left panel). Mid-latitude negative F2-layer storm effects are known to be the strongest in the post-midnight-early-morning LT sector and they are much weaker in the afternoon (Wrenn et al., 1987; Prölss, 1991,1993). As it was pointed out earlier, this is due to the disturbed neutral composition with a decreased O/N_2 ratio, which is advected towards middle latitudes during the night, rotates into the day sector being shifted back to higher latitudes by diurnal varying thermospheric circulation (Skoblin and Förster, 1993; Fuller-Rowell et al., 1994; Prölss, 1995). This effect is clearly seen in the afternoon with a tendency for the *fo*F2 trends to be even positive around 15 LT.

Contrary to the NmF2 behavior, *hm*F2 is larger for disturbed conditions. This is due to three reasons (see Eq. 3): 1) neutral temperature T_n is higher in the perturbed thermosphere. Millstone Hill T_n estimations are shown in Fig. 3 (bottom); 2) linear loss coefficient $\beta = \gamma_1[N_2] + \gamma_2[O_2]$ is higher for disturbed conditions due to higher molecular concentrations and reaction rate coefficients depending on temperature; 3) vertical plasma drift W is more positive due to an enhanced equatorward thermospheric wind in the nighttime sector, or to a decreased or even a reversal of the solar driven northward wind in the daytime LT sector (Prölss, 1993; Wickwar, 1989).

Let us consider these changes in the thermospheric parameters using Millstone Hill observations for 17 March and 21 March 1990. A self-consistent approach to the ionospheric F2-layer modelling proposed by Mikhailov and Schlegel(1997) with later modifications by Mikhailov and Förster (1999) and Mikhailov and Schlegel (2000) may be applied for daytime Millstone Hill observations to extract the set of main aeronomic parameters for the two days in question. The method uses measured $N_e(h)$, $T_e(h)$, $T_i(h)$, and $V_z(h)$ profiles to find the set of main aeronomic parameters responsible for the observed $N_e(h)$ distribution in the daytime F2-region. The calculated parameters are given in Table 1.

The results of the calculations are in agreement with the contemporary understanding of the F2-layer storm mechanisms (e.g. Rishbeth, 1991; Prölss, 1995; Field et al., 1998). The calculations show an increase in exospheric temperature T_{ex} (compare to Millstone Hill estimates at 300 km in Fig. 3), a strong enrichment of the thermosphere with heavy molecular species O_2 and N_2, and an increase in W. The latter results from some damping of the normal solar driven northward thermospheric circulation by the disturbed (southward) one.

Table 1. Calculated thermospheric parameters for quiet 17 March 1990 and disturbed 21 March 1990 days at 300 km and 13.5 LT

Date	T_{ex} K	log [O] cm^{-3}	log [O_2] cm^{-3}	log [N_2] cm^{-3}	$\beta/10^{-4}$ s^{-1}	W $m\,s^{-1}$
17 Mar 90	1310	8.955	6.909	8.364	2.63	−8.1
21 Mar 90	1502	9.065	7.386	8.697	9.26	−3.8

Atomic oxygen concentration demonstrates a small increase at 300 km (around 25%), but in fact, this means a depletion of the [O] abundance in the thermosphere as T_{ex} (and corresponding neutral scale height) is higher on 21 March (Table 1). A strong increase in [N_2], [O_2] as well as in the temperature results in a β increase by more than a factor of 3 and this is the main reason for the NmF2 decrease on the disturbed day (see Eqs. 1,2). The growth of β, W, and [O] on the disturbed day results in higher observed *hm*F2 (Fig. 3, and Eq. 3).

Therefore, the analyzed period of 1965–1991 of increasing geomagnetic activity should result in negative NmF2 and positive *hm*F2 trends, as our previous analysis has shown (Mikhailov and Marin, 2000; Marin et al., 2001). Unlike the case with lower latitudes (Alma-Ata station) where changes in vertical plasma drift and atomic oxygen concentration are responsible for the positive F2-layer storm effects, neutral composition (O/N_2 ratio) and temperature changes are supposed to be the main physical reason for the F2-layer negative storm effects at mid-latitudes (Prölss, 1995; Field et al., 1998), although the role of vibrationally excited $N_2^{\#}$ is considered in some publications as well (e.g. Pavlov, 1994; Pavlov et al., 1999). The largest neutral composition (O/N_2 ratio) perturbations take place in the post-midnight-early-morning LT sector (Prölss, 1980, 1993) and the calculated correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ are the largest for this part of the day (Fig. 2, left panel). Similar to the lower latitude case positive *hm*F2 trends and large correlation coefficients $r(\delta hm\mathrm{F2}, Ap_{12})$ take place practically all day long. As mentioned above, this is mainly due to the increase in β, T_n and W.

Therefore, the revealed mid-latitude *fo*F2 and *hm*F2 trends may be considered as the manifestation of the storm induced neutral composition, and temperature and meridional wind changes, which should take place for the period of increasing geomagnetic activity 1965–1991.

2.3 High latitudes

The situation is more complicated with the high-latitude F2-layer where close stations may demonstrate different diurnal variations of the trend magnitude. As an example, Sodankyla (67.40 N; 26.60 E; $\Phi_{\mathrm{inv}} = 63.59$ N) and Lycksele (64.70 N; 18.80 E; $\Phi_{\mathrm{inv}} = 61.46$ N) stations are shown in Fig. 1. Very strong negative *fo*F2 trends take place during daytime with the minimum shifted to the morning hours at Sodankyla. The observed *fo*F2 trends are small with a pretty large scatter during morning and evening hours. The correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ are large and significant during daytime hours (Fig. 2, left-hand, top). On the contrary, at Lycksele, the largest negative *fo*F2 trends are observed in the evening LT sector, while the trends are small during the first part of the day. Corresponding diurnal variation is seen for $r(\delta fo\mathrm{F2}, Ap_{12})$ in Fig, 2 where large and significant correlation coefficients are found for the second part of the day.

The Sodankyla station also shows an interesting and unusual *hm*F2 trend diurnal variations (Fig. 1, right-hand, top), when compared to other stations. The trends are positive although small during daytime hours, but they are negative at nighttime. The daytime correlation coefficient $r(\delta hm\mathrm{F2}, Ap_{12})$ are large and significant, while the nighttime values are small and insignificant at the 95% confidence level (Fig. 2, right-hand, top). Such unusual diurnal variations of the *hm*F2 trend magnitude are discussed later using EISCAT observations. Large positive *hm*F2 trends along with large and significant correlation coefficients $r(\delta hm\mathrm{F2}, Ap_{12})$ take place during the whole day at Lycksele (Figs. 1, 2; right-hand panels).

Let us start with the *fo*F2 trends (Fig. 1, left-hand, top). The Sodankyla station ($\Phi_{\mathrm{inv}} = 63.59°$) is located in the plasma ring or FLIZ zone (Thomas and Andrews, 1969; Pike, 1971) where an intensive F2-region ionization is produced by soft electron precipitation (Morse et al., 1971). The equatorial boundary of this zone is located at $\Phi_{\mathrm{inv}} = 61-62°$ at 00–06 MLT and at $\Phi_{\mathrm{inv}} = 63°$ at 18–21 MLT while during daytime, it shifts northward at $\Phi_{\mathrm{inv}} = 70-72°$ (Sagalin and Smiddy, 1974). This excursion of the precipitation zone explains the appearance of two peaks in the *fo*F2 trend diurnal variation (Fig. 1, left-hand, top). As the intensity of electron precipitation is highly variable in the FLIZ zone, the scatter of the trends obtained is fairly large and the correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ are small and insignificant (Fig. 2, left-hand, top) for these two periods of the day. The corpuscular ionization should be strong enough during these periods to compensate large negative effect in NmF2 due to large changes in neutral composition and temperature expected in the perturbed auroral thermosphere. The latter is seen for daytime hours when, despite direct solar photoionization, very strong negative *fo*F2 trends are observed (Fig. 1. left-hand, top).

The sub-auroral station Lycksele ($\Phi_{\mathrm{inv}} = 61.46°$) turns out to be in the FLIZ zone in the morning but not in the evening and unlike Sodankyla, there is only one (morning) peak where *fo*F2 trends are small and correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ are small and insignificant (Fig. 2, left second panel). The daytime equatorial boundary of the FLIZ zone

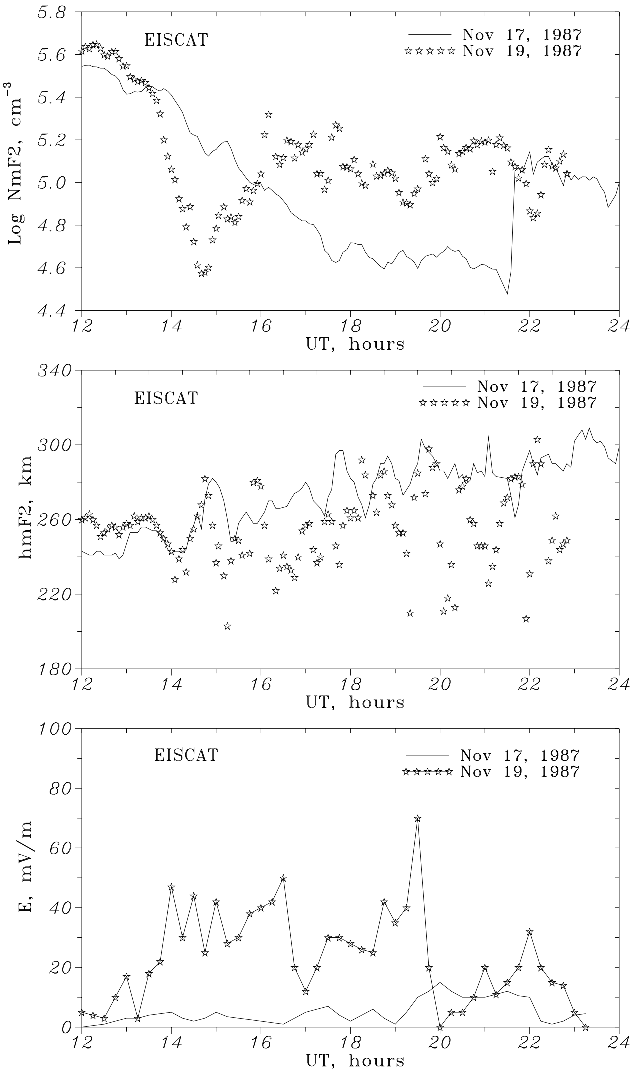

Fig. 4. Observed with EISCAT diurnal variations of NmF2, *hm*F2 and electric fields for quiet 17 November 1987 and disturbed 19 November 1987 days.

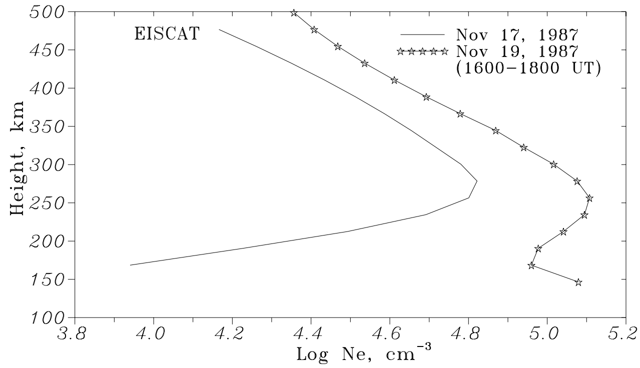

Fig. 5. Observed with EISCAT median $N_e(h)$ profiles calculated over two hours. Note the effect of strong particle precipitation in the $N_e(h)$ height distribution on 19 November.

shifts to the latitudes $\Phi_{\text{inv}} = 70 - 72°$ (Sagalin and Smiddy, 1974) and we have strong negative *fo*F2 tends resulting from the disturbed neutral composition and temperature similar to the middle latitude case. It should be kept in mind that neutral composition and temperature are perturbed for the whole day and this explains the large positive and significant *hm*F2 trends at Lycksele for all LT moments (Figs. 1,2, right second panels).

Let us analyze *hm*F2 trends at Sodankyla, where positive daytime trends and negative (although insignificant at the 95% confidence level) nighttime *hm*F2 trends are obtained (Figs. 1,2, right-hand, top). Such variations are due to specific mechanisms of the auroral F2-region formation.

Observed with EISCAT NmF2, *hm*F2 and electric field E diurnal variations are shown in Fig. 4 for quiet 17 November 1987 ($Ap = 3$) and moderately disturbed 19 November ($Ap = 12$) days. Electric fields $E \approx 20 - 40$ mV/m and an intensive electron precipitation took place on 19 November, while both characteristics were small on 17 November (some splashes of electric field took place only after 19 UT). Observed NmF2 are higher and *hm*F2 are lower on 19 November for the period of 16–22 UT, when an intensive electron precipitation is expected (Fig. 1, left-hand, top). Large scatter in the observed *hm*F2 is seen on 19 November and is obviously due to a varying precipitation intensity. Median $N_e(h)$ profiles found over the 16–18 UT period are given in Fig. 5 for the two days in question. Strong precipitation results in an enhanced electron concentration (especially in the lower F-region) as well as in a decrease in *hm*F2. Namely, this effect of the electron precipitation is the most important for our analysis. Strong plasma production at lower altitudes shifts normal *hm*F2 to lower heights (e.g. Torr and Torr, 1969). A similar situation exists for a normal mid-latitude F2-layer when daytime *hm*F2 is lower than nighttime *hm*F2dian over one hour for one and the same input parameters. This is due to strong solar photoionization at low F-region heights. As the precipitation intensity increases with geomagnetic activity (Sato and Colin, 1969; Marubashi, 1970), nighttime *hm*F2 trends are negative at Sodankyla (Fig. 1, right-hand, top) for the period of increasing geomagnetic activity of 1965–1991. Therefore, the revealed features of the NmF2 and *hm*F2 nighttime trends may be attributed to the electron precipitation effects.

Besides particle precipitation strong electric fields are an inalienable feature of the disturbed auroral F2-region. The observed increase in geomagnetic activity for the analyzed period of 1965–1991 is the manifestation of intensified electric fields in the auroral zone. Joule heating related to the electric fields results in strong perturbations of neutral composition (O/N_2, O/O_2 decrease) and neutral temperature increase (e.g. Prölss, 1980; Rishbeth and Müller-Wodarg,-1999). Therefore, by analogy with the mid-latitude case, one should expect strong negative *fo*F2 and positive *hm*F2 trends for the period in question. An additional effect working in the same direction is due to the dependence of the $O^+ + N_2$ reaction rate constant (via the effective temperature)

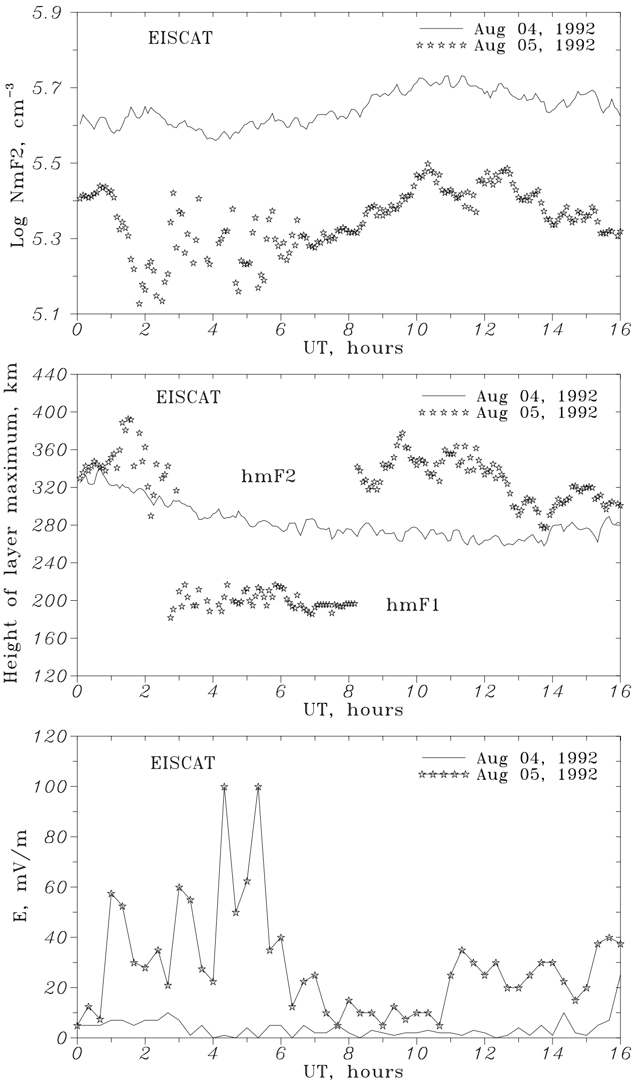

Fig. 6. Observed with EISCAT diurnal variations of NmF2, *hm*F2 and electric fields for quiet 04 August 1992 and disturbed 05 August 1992 days. Note the decrease in the height of the layer maximum after a strong electric field is switched on.

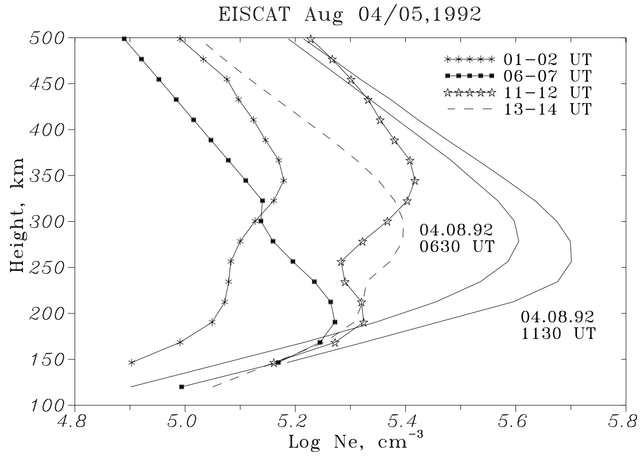

Fig. 7. Observed with EISCAT $N_e(h)$ profiles for different UT moments of the disturbed day 05 August 1992. Note the modification of normal F2-layer and formation of the layer maximum around 200 km as a reaction to the strong increase in the linear loss coefficient β. Quiet time $N_e(h)$ profiles for 04 August 1992 are shown for a comparison.

on electric field E (Schunk et al, 1975). Strong negative *fo*F2 trends (Fig. 1, left-hand, top) do take place at Sodankyla during daytime hours, the nighttime case was discussed above. But relatively small (although positive) daytime *hm*F2 trends (Fig. 1, right-hand, top) look rather strange. At least three reasons may be considered:

1) the accuracy of initial experimental M(3000)F2 values, and the M(3000)F2 to *hm*F2 conversion procedure used;
2) the effect of strong electric fields on the $N_e(h)$ height profile;
3) the effect of the auroral thermosphere depletion (due to upwelling) with atomic oxygen (Prölss, 1980).

Let us consider EISCAT observations for quiet 04 August 1992 ($Ap = 2$) and disturbed 05 August 1992 ($Ap = 35$) days which may help us analyze the problem with the *hm*F2 daytime trends. The daily mean *Ap* index was 15 on 04 August due to a disturbance which started late in the afternoon. Yet the first half of the day considered here was very quiet and we accepted $Ap = 2$ for our model calculations. Observed NmF2, *hm*F2, as well as electric field diurnal variations, are shown for the two days in Fig. 6.

The selected couple of dates demonstrates the effect of the general NmF2 decrease for the disturbed day which corresponds to the *fo*F2 negative trend (Fig. 1, left-hand, top) for the considered period of increasing geomagnetic activity of 1965–1991. The effect of the electric field switching on and off is also seen in Fig. 6. The median $N_e(h)$ profiles taken over a set of one hour observations are shown in Fig. 7 for some UT periods. Two quiet time (04 August 1992) $N_e(h)$ profiles are shown for a comparison as well. An abrupt decrease of the layer height down to 200 km (F1-layer) takes place during the morning hours on 05 August (Fig. 6, middle panel) as a reaction to the enhanced electric field (Fig. 6, bottom). Later in the morning, when E decreases and the photoionization rate increases, *hm* restores back to normal *hm*F2 values around 350 km. In the afternoon, a moderate E increase again results in the *hm*F2 decrease, when *hm*F2 turns out to be close to the 04 August values.

All observed disturbed $N_e(h)$ profiles (Fig. 7) show a strongly reduced NmF2 up to a complete disappearance of the F2-layer (0300–0800 UT period), while a pronounced F1-layer appears around 200 km height. It is obvious that the M(3000)F2 parameter, determined from routine ground-based ionosonde observations, is not reliable for such profiles. On the other hand, special care is required when taking into account the effect of the underlying ionization in the empirical formulas relating M(3000)F2 to *hm*F2. Therefore, *hm*F2 derived from M(3000)F2 may not be very reliable for such $N_e(h)$ profiles, but one may hope that this does not strongly affect M(3000)F2 monthly median values.

Table 2. Calculated at 300 km thermospheric parameters for quiet 04 August 1992 and disturbed 05 August 1992 days and two periods of the day

Date	T_{ex} K	log [O] cm^{-3}	log [O_2] cm^{-3}	log [N_2] cm^{-3}	$\beta/10^{-4}$ s^{-1}	W m s^{-1}
04 Aug 92, 06–07 UT	1088	8.546	6.807	8.241	1.84	+4.3
05 Aug 92, 06–07 UT	1332	8.345	7.422	8.593	15.6	+28.5
04 Aug 92, 11–12 UT	1158	8.645	6.793	8.279	1.96	−16.8
05 Aug 92, 11–12 UT	1263	8.537	7.235	8.512	8.77	+31.3

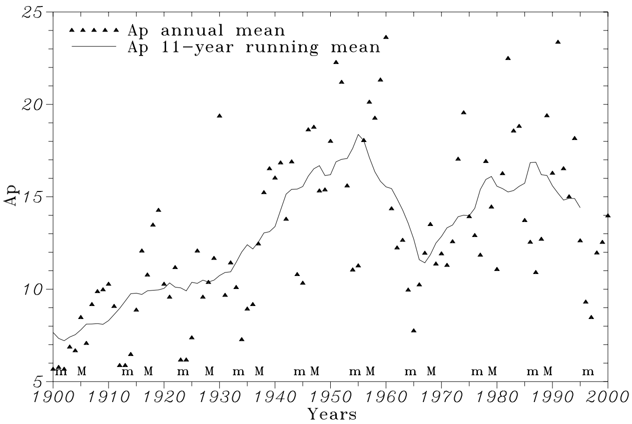

Fig. 8. Annual mean and 11-year running mean *Ap* index variations. Symbols (m) and (M) refer to years of solar cycle minimum and maximum.

To illustrate the changes in the thermospheric parameters responsible for the observed NmF2 and *hm*F2 variations under disturbed conditions, let us consider two sunlit periods around 0630 and 1130 UT for 04 and 05 August. The above mentioned method by Mikhailov and Schlegel (1997) with later modifications is used for this analysis. The two chosen UT periods correspond to the cases of a pronounced F1-layer appearance (0600–0700 UT) and to a moderately disturbed F2-layer with a pronounced *hm*F2 (1100–1200 UT); the corresponding $N_e(h)$ profiles are shown in Fig. 7. Calculated thermospheric parameters for the quiet and disturbed days are given in Table 2. The calculated T_{ex} is higher on 05 August (the disturbed day), especially for the morning period when strong electric fields were observed. The enhanced electric field produces an intensive Joule heating and an upwelling in the thermosphere. The latter is seen in the calculated vertical plasma drift W (Table 2). The upwelling motion results in a [O] decrease and a [O_2], [N_2] increase, which is also seen for the disturbed day with respect to the quiet one. Relatively small [O] decrease at 300 km (58% in the morning and 28% at around noon), in fact, corresponds to a strong decrease in the atomic oxygen abundance, as T_{ex} (and corresponding neutral scale height) is higher on 05 August (Table 2).

The thermosphere heating and upwelling results in the strong increase in [N_2] (by a factor of 2.25 in the morning and by 1.71 times around noon), and in the [O_2] increase by a factor of 4.12 and 2.77, respectively. This [N_2] and [O_2] increase, along with the increase in the O^++N_2 rate constant depending on T_n, T_i and E, results in a very strong β increase by a factor of 8.5 in the morning case, and by a factor of 4.5 around noon. Similar to the mid-latitude case, this increase in the linear loss coefficient β is the main reason for the NmF2 decrease on the disturbed day; the additional negative effect in NmF2 is related to the [O] decrease. This analysis based on EISCAT observations illustrates the physical mechanism of the strong *fo*F2 negative trend obtained for daytime hours at Sodankyla (Fig. 1, left top panel).

Electric fields via the chain of the processes mentioned above strongly affect the $N_e(h)$ height distribution and *hm*F2, accordingly. During nighttime, when direct solar photoionization is absent, or in the morning, when it is not strong enough, the loss coefficient β increase may result in a complete disappearance of the normal F2-layer and formation of the $N_e(h)$ profile with maximum around 200 km (Fig. 5, 03–08 UT period). Such a layer is composed of heavy molecular ions, NO^+ and O_2^+, as model calculations show.

Therefore, electric fields along with the earlier discussed electron precipitation effect may really contribute to the negative nighttime *hm*F2 trends at Sodankyla (Fig. 1, top right panel). During daytime hours, solar EUV ionization becomes strong enough and the F2-layer maximum is formed at usual heights, but a well-developed F1 layer still exists (Fig. 7), with the NmF2 and NmF1 values being close around 08 UT (Figs. 6,7).

Both satellite observations (Prölss, 1980) and model calculations (Table 2) show a decrease in the atomic oxygen concentration for disturbed conditions. According to Eq. (3), a decrease in [O] should compensate to some extent for the *hm*F2 growth, primarily resulting from the β, W and T_n increase on the disturbed day. This effect is not strong for the 04 and 05 August case (Δlg[O]=-0.108 and Δlgβ=0.65) and disturbed daytime *hm*F2 values are larger than the quiet time ones (Fig. 6, middle panel). But, depending on the perturbation intensity, the effect may be larger. For instance, an analysis of EISCAT observations for the period of geomagnetic storm on 10 April 1990 (Mikhailov and Schlegel, 1998) has revealed an [O] decrease by a factor of 4.3 at 300 km, with respect to the previous day. In that case, the daytime layer maximum was formed around 200 km height.

Therefore, relatively small (when compared to mid-latitude stations) daytime *hm*F2 trends at Sodankyla (Fig. 1, right top panel) may be due to a strong decrease in the atomic oxygen abundance in the perturbed auroral thermosphere.

3 Discussion

Investigation of the ionospheric trends was greatly stimulated by the model calculations of Rishbeth (1990), and Rishbeth and Roble (1992), which predicted the ionospheric effects of the atmosphere greenhouse gas concentration increase. Since then, researchers have been trying to reveal the predicted thermosphere cooling analyzing ionospheric trends (Bremer, 1992; Givishvili and Leshchenko, 1994; Ulich and Turunen, 1997, Jarvis et al., 1998; Upadhyay and Mahajan, 1998). But the world-wide pattern of the F2-layer parameter trends turned out to be very complicated and cannot be reconciled with the greenhouse hypothesis. On the contrary, the geomagnetic control concept by Mikhailov and Marin (2000), based on the contemporary understanding of the F2-layer storm mechanisms, allows us to explain the revealed morphological features of the F2-layer trends. According to this concept, there are periods of negative and positive F2-layer parameter trends corresponding to the long-term changes in geomagnetic activity shown in Fig. 8. Annual mean *Ap* indices prior 1932 were reconstructed from *aa* indices available from 1868. Years of solar cycle minima (m) and maxima (M) are marked in Fig. 8 as well, to show that such long-term variations in geomagnetic activity (presented by 11-year *Ap* index) are not related to solar cycle variations. A steady increase in geomagnetic activity took place for the period from 1900 to middle of 1950s followed by a decrease towards middle of 1960s and again an increase towards the end of 1980s. A tendency for a decrease in geomagnetic activity after 1990 is clearly seen in annual mean *Ap* values. Similar variations of geomagnetic activity can be found in Clilverd et al., (1998, their Fig. 6). Namely, these long-term variations in geomagnetic activity result in the ionospheric F2-layer long-term trends.

An example of such long-term variations is given in Fig. 9 for a mid-latitude station Slough, where ionospheric observations are available from the early 1930s. Variations of the 11-year *Ap* index are repeated in Fig. 9 (top) for further discussion. The δfoF2 variations are considered for ($M + m$) and (m) year selections (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000). Solid and dashed lines are the least squares fitting by the 4th degree polynomial (a higher degree gives practically the same results). Everywhere error bars present the standard deviation over 12 monthly values. An anti-phase type of δfoF2 and *Ap* long-term variations is seen for the period in question. The periods of increasing geomagnetic activity (before 1955 and after the end of the 1960s) are seen to correspond to negative *fo*F2 trends, while during the decreasing phase of geomagnetic activity (1955 to the end of the 1960s), a small positive *fo*F2 trend takes place. There is also a tendency for the *fo*F2 trend to switch from negative to positive after 1990, in accordance

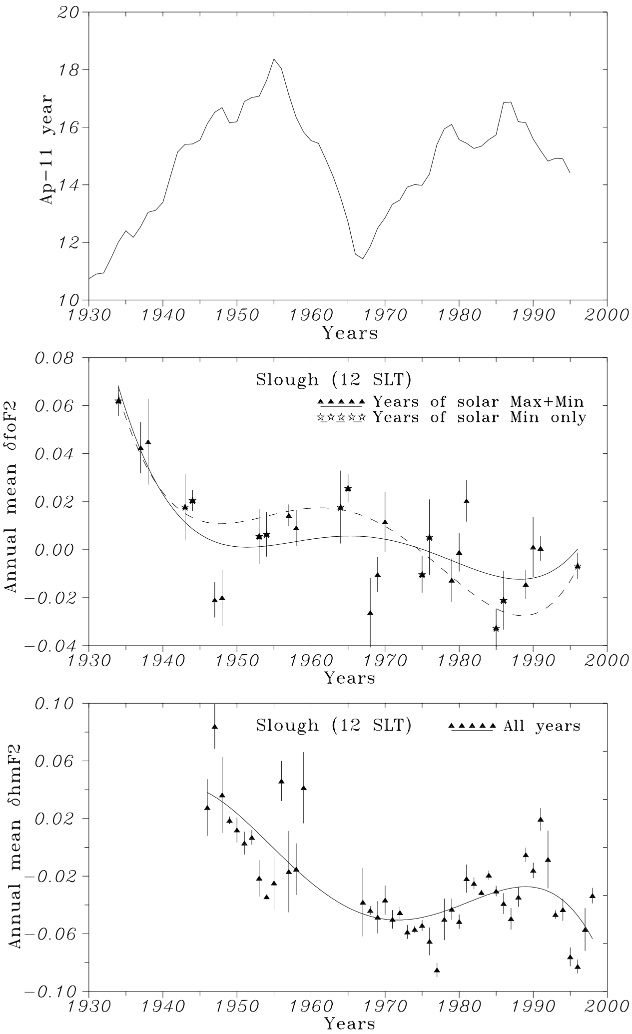

Fig. 9. 11-year running mean *Ap* index along with δfoF2 and δhmF2 long-term variations. Two year selections ($M + m$) and (m) (see text) are used for the *fo*F2 and (all years) for the *hm*F2 trend analysis. Least squares fitting curves are a 4th degree polynomials. Error bars present the standard deviation of seasonal (over 12 months) scatter.

with the change in geomagnetic activity (see Fig. 8). Different signs of the *fo*F2 trends for the periods before and after 1965 were demonstrated earlier by Mikhailov and Marin (2000) for some stations with long observational periods.

On the contrary, δhF2 demonstrates a syn-phase with *Ap* type of variations (Fig. 9, bottom). The periods with negative *hm*F2 trends before 1970 and after 1990 correspond to the periods with decreasing geomagnetic activity while a positive *hm*F2 trend takes place for the period of 1970–1990. In accordance with the analysis by Marin et al. (2001), unlike the *fo*F2 case, all years with M(3000)F2 observations may be used for the *hm*F2 trend derivation. The period between 1961–1965 is absent in Fig. 9 (bottom), as observed M(3000)F2 values for this period give unreal δhmF2 variations which have not been confirmed by observations at other stations. Physical mechanisms relating *fo*F2 and *hm*F2 trends

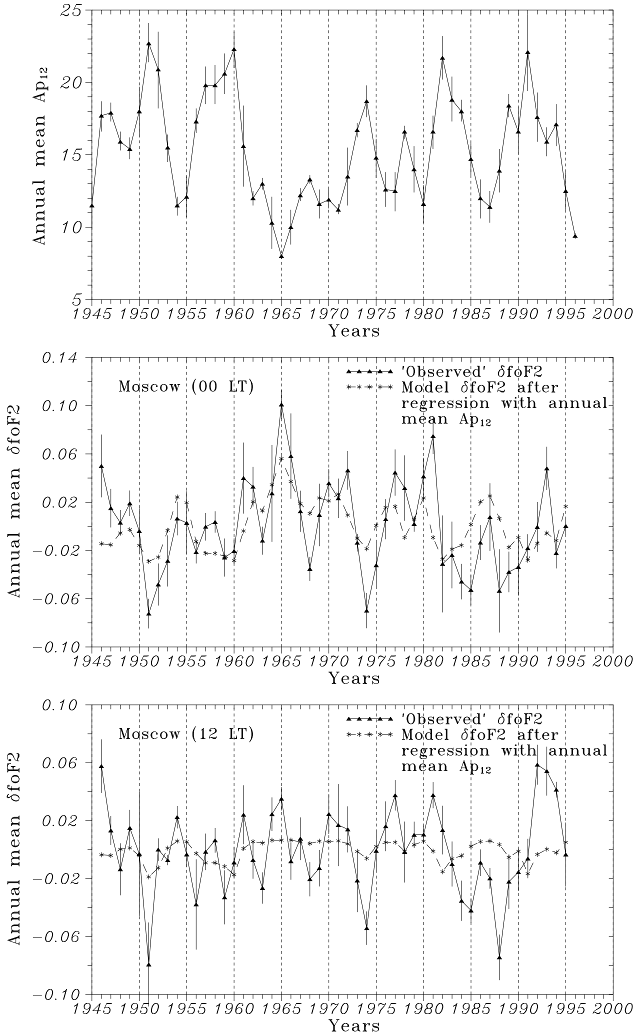

Fig. 10. Annual mean Ap_{12} and δfoF2 variations at Moscow, 00 and 12 LT. Dashed line is an attempt to remove the dependence on geomagnetic activity using δfoF2 regression with Ap_{12}. Note that observed δfoF2 variations are much stronger than model ones especially for daytime.

with geomagnetic activity variations are discussed earlier in the paper.

In the framework of the proposed geomagnetic hypothesis one should expect thermosphere heating rather than the cooling that the researchers are seaking when considering the 1970–1990 period. Indeed, from the *Ap* variations (Fig. 8), one may accept the *Ap* index increase from 12 to 16 for the period in question; such an increase in the *Ap* index, according to the thermospheric MSIS-83 (Hedin, 1983) model, results in the annual mean T_{ex} increase by about 10 K for mid-latitudes ($F_{10.7} = 140$ was used in calculations). But this heating will be followed by the thermosphere cooling, in accordance with the long-term changes in the geomagnetic activity (Fig. 8).

Although there is an obvious relationship between the F2-layer parameter trends and the geomagnetic activity, it is impossible to remove this geomagnetic effect from the trends revealed, using any conventional index (e.g. monthly or annual mean *Ap*) of geomagnetic activity, and to check if there is any residual trend (of a greenhouse origin, for instance). If it could be accomplished by using the conventional indices, the problem of the F2-layer storm description and prediction would have been solved long ago, but this has not been the case until now. This is not surprising as any global geomagnetic activity index cannot, in principle, take into account the whole complexity of F2-layer storm effects with positive and negative phases depending on the season, longitude, UT and LT of storm onset, storm magnitude, etc. Therefore, an inclusion of the *Ap* index to the regression, in fact, does not remove the dependence on geomagnetic activity, as supposed by Bremer(1998) and Jarvis et al. (1998), but only contaminates the analyzed data (Mikhailov and Marin, 2000). Indeed, according to Mikhailov and Marin (2000), and Marin et al. (2001), such an inclusion of the *Ap* index has some effect on the trend magnitude, but without changing, in principle, the main morphological features of the *fo*F2 and *hm*F2 trends. A similar result was obtained by Ulich and Turunen (1997) who did not include the *Ap* index in their study for this reason.

Figure 10 illustrates an attempt to remove the geomagnetic effect by the inclusion of the annual mean Ap_{12} to the *fo*F2 trend analysis for Moscow, 00 and 12 LT. A two-step procedure was applied. At first, $\delta fo\text{F2} = (fo\text{F2}_{obs} - fo\text{F2}_{mod})/fo\text{F2}_{mod}$ values were found and called 'observed' (Fig. 10, solid line). Then a regression (2nd degree polynomial) of these δfoF2obs with annual mean Ap_{12} was calculated and called 'model' in Fig. 10 (dashed line). The model curve is seen to follow, qualitatively, the observed δfoF2 variation for 00 LT with a correlation coefficient $r = 0.538$, which is significant at the 99% confidence level. But the observed δfoF2 variations are much larger and not reproduced completely by the model. The situation is even worse for daytime (12 LT) conditions. In this case, there is not even a qualitative agreement between the two curves ($r = 0.227$, insignificant). The same result was obtained for Ekaterinburg (Fig. 2, left panel) where significant correlation coefficients were found only for nighttime hours.

The obtained result tells us that, in fact, the geomagnetic effect is much stronger (at least during nighttime) than can be described using the Ap_{12} index. Poor δfoF2 correlation with Ap_{12} during the daytime confirms the complexity of the F2-layer storm mechanisms as mentioned earlier. For instance, mid-latitude daytime F2-layer storm effects may be due to thermospheric perturbations formed in the nighttime longitudinal sector during the preceding geomagnetic storm (Skoblin and Förster, 1993; Fuller-Rowell et al., 1994; Prölss, 1995).

On the other hand, one should keep in mind that the sunspot number R_{12}, usually used in empirical ionospheric models, is far from the best choice (Mikhailov and Mikhailov, 1999) and, in fact, it does not allow us to completely remove the dependence on solar activity being used in *fo*F2 and *hm*F2 versus R_{12} regressions. Despite special methods applied to ex-

Table 3. Annual mean slope K (in 10^{-4} per year) for the period after 1965 for the stations with close Φ_{inv}, but different D. Years of solar minimum (m) for *fo*F2 and all years for *hm*F2 trend analysis are used.

Station	Φ_{inv} deg	D deg	$\sin I \cos I \sin D$	K (*fo*F2) 12 LT (m) years	K (*fo*F2) 06 LT (m) years	K (*hm*F2) 12 LT all years	K (*hm*F2) 06 LT all years
Yakutsk	55.1	−15	−0.06	−43.4	−49.2	+15.9	+22.7
St.Petersburg	55.9	+7	+0.03	−27.3	−14.1	+10.1	+17.9
Slough	49.8	−7	−0.04	−25.3	−19.6	+17.2	+27.6
Tomsk	50.6	+9	+0.04	−20.2	−25.9	+23.2	+22.5
Khabarovsk	40.2	−11	−0.08	−5.0	−6.0	+13.5	+22.9
Novokazalinsk	39.5	+7	+0.05	−17.4	−38.0	−1.0	+15.1

tract F2-layer parameter trends the imperfection of Ap_{12} and R_{12} indices results in a fairly large δfoF2 and δhmF2 scatter (e.g. Fig.10). In practice, it was recommended (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000) to use only the years around solar minima (m) or the years around solar maximum and minimum $(M + m)$ for the *fo*F2 trend analysis. Such a selection of years allows us to avoid the hysteresis effect which takes place at the falling and rising phases of the solar cycles, and when the *fo*F2 versus R_{12} correlation is the worst. With this approach, it was possible to obtain the most consistent pattern of the *fo*F2 trends over all the stations considered. On the contrary, the same approach turned out to be inefficient when applied to the *hm*F2 trend analysis and all available years were used in the study by Marin et al. (2001). This is rather strange as the hysteresis effect takes place for M(3000)F2 solar cycle variations as well (Rao and Rao, 1969). There is currently no explanation for this effect.

A well-pronounced dependence of the *fo*F2 trend magnitude on the geomagnetic (invariant) latitude (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000) is explained by the perturbed neutral composition and temperature latitudinal dependence, as discussed earlier in the paper. Contrary to this, no systematic latitudinal dependence was revealed for the *hm*F2 trends (Marin et al., 2001). This result may be explained by the *hm*F2 dependence on the main aeronomic parameters (Eq. 3). Normally, neutral concentrations (O, O_2, N_2 at a fixed level), temperature T_n as well as vertical plasma drift W increase during disturbed periods. According to Eq. (3), this should result in an *hm*F2 increase, as all terms in Eq. (3) work in one direction. Therefore, we have positive *hm*F2 trends at middle and lower latitudes; the high-latitude case was discussed earlier. The meridional wind V_{nx} effect (via $W = V_{nx} \sin I \cos I \cos D$) becomes efficient at lower latitudes as magnetic inclination I approaches 45°. As the perturbation in β and T_n decreases and the [O] (see above) and W contributions increase towards lower latitudes, no pronounced latitudinal dependence for the *hm*F2 trend magnitude should take place, in accordance with results of our study.

In principle, some longitudinal effect in the *fo*F2 and *hm*F2 trends may be expected in the scope of the proposed geomagnetic control hypothesis. A statistical analysis by Hajkowicz (1998) of AE-index variations over two solar cycles (1957–1968 and 1978–1986) has shown that the maximum in auroral activity is largely confined to 09–18 UT, with a distinct minimum at 03–06 UT. This means that Eastern Siberia and Japan are primarily at night during the period of maximum auroral activity, whereas Europe and Eastern America are primarily at daytime. This effect, overlapping with the background solar driven thermospheric circulation (equatorward at night and poleward during daytime), may give some longitudinal effects in the F2-layer parameter trends. Another source of longitudinal variation is related to the zonal winds and longitudinally dependent magnetic declination D via the wind term in the vertical plasma drift W. Primarily negative *fo*F2 and *hm*F2 trends at longitude west of 30° E, yet positive trends east of 30° E, were revealed by Bremer (1998). A tendency for similar *hm*F2 trend separation was reported by Marin et al. (2001). Indeed, the $D = 0$ line crosses Europe along the longitude $\lambda \approx 20°$ E and the zonal wind effect cannot be excluded. But a preliminary analysis has shown that the situation is not that straightforward. Three pairs of stations with close Φ_{inv}, but different magnetic declination D, are compared in Table 3, where *fo*F2 and *hm*F2 trends from Mikhailov and Marin (2000) and Marin et al. (2001) are given for 12 and 06 LT. The results in Table 3 show that regardless of different signs of magnetic declination D, *fo*F2 trends are negative and *hm*F2 trends are positive at all stations considered (the daytime *hm*F2 trend at Novokazalinsk is insignificant), in accordance with the earlier obtained conclusions (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000; Marin et al., 2001). The expected longitudinal effect may be due to vertical plasma drift $W = (V_{nx} \cos D - V_{ny} \sin I) \sin I \cos I$ variations, where V_{nx} and V_{ny} are meridional and zonal components of the thermospheric wind. Westward $(V_{ny} < 0)$ zonal wind is strong around 06 LT, but small around 12 LT (Hedin et al., 1991). On the contrary, V_{nx} is small around 06 LT, therefore the V_{ny} effect may be expected around 06 LT. Table 3 shows that stations with negative D seem to have more positive *hm*F2 trends at 06 LT, but this is not the case for 12 LT. No definite conclusion can be drawn with respect to the *fo*F2 trends in the results given in Table 3. Therefore, if any dynamical effect due to zonal thermospheric wind exists, it is small when compared to the contribution of other aeronomic parameters.

Some European stations were shown to demonstrate negative *hm*F2 trends (Marin et al., 2001) and this was the reason to mention a longitudinal effect in the *hm*F2 trends. Their Table 2 (Model 1) shows that significant negative trends were revealed for some LT moments at Bekescsaba (46.7 N, 21.2 E), Poitiers (46.6 N, 0.3 E), Dourbes (50.1 N, 4.6 E) and Juliusruh (54.6 N, 13.4 E); the other stations may be considered as sub-auroral and auroral ones, with specific mechanisms of the F2-layer formation discussed earlier in this paper. Therefore, an additional analysis is needed for these mid-latitude stations to find out the reason for such *hm*F2 behavior. Negative *hm*F2 trends were reported for Southern hemisphere stations in the Argentine Islands and Port Stanley by Jarvis et al. (1998), and for Sodankyla by Ulich and Turunen (1997). The latter result should be discussed as it contradicts our conclusions obtained for the Sodankyla station.

It was stressed by Danilov and Mikhailov(1999), and Mikhailov and Marin (2000) that F2-layer trend results are strongly dependent on the method used to extract the trends from the ionosonde observations. Ulich and Turunen (1997) obtained a negative *hm*F2 trend, −0.39 km/year for daytime hours over the period of 1958–1994. Unlike our approach, they worked with non-smoothed absolute deviations ΔhmF2 from a model (linear regression *hm*F2 with monthly averaged $F_{10.7}$), although they applied to ΔhmF2 a running mean filter with a width of 11 years in order to suppress solar activity effects. We have used a similar approach and did obtain negative daytime *hm*F2 trends over the period in question. Regarding this,the following should be mentioned:
1) non-smoothed *hm*F2 (or *fo*F2) values show a very large scatter where a "useful signal" may just be lost. Therefore, smoothing of the initial data and working with relative (not absolute) deviations from a model was recommended for the trend analysis (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000);
2) it is known that monthly median *fo*F2 and $M(3000)$F2 parameters correlate better with smoothed (not monthly averaged) indices of solar activity (e.g. Mikhailov and Mikhailov, 1999 and references therein). That is why only 12-month running mean sunspot numbers R or $F_{10.7}$ are used in empirical F2-layer parameter modelling. Moreover, a non-linear dependence of F2-layer parameters on solar activity level provides better regression accuracy (e.g. Kouris et al., 1997) than the linear one used by Ulich and Turunen (1997);
3) as the *hm*F2 trend follows the geomagnetic activity, a separate analysis is required for different periods in the geomagnetic activity's long-term variations; the end of the 1960s and the beginning of the 1990s are the turning points in these variations. Therefore, a trend derived over the whole 1958–1994 period does not correctly present the real *hm*F2 long-term variations.

Due to these differences in approaches, the daytime *hm*F2 trends at Sodankyla obtained by Ulich and Turunen (1997) and Marin et al. (2001) have a different sign for the period of 1965–1991.

4 Conclusions

The *fo*F2 and *hm*F2 trend morphology earlier revealed by Danilov and Mikhailov (1999), Mikhailov and Marin (2000), and Marin et al. (2001), was interpreted in the framework of the geomagnetic control concept proposed by Mikhailov and Marin (2000). Latitudinal and diurnal variations of the annual mean *fo*F2 and *hm*F2 trends are the most pronounced features and their analysis was the major concern of the paper. The main results may be listed as follows:

1. The effect of long-term varying geomagnetic activity is very strong in the *fo*F2 and *hm*F2 trends. But it is impossible to remove this geomagnetic effect from the F2-layer parameter trends using conventional (monthly or annual mean *Ap*, for instance) indices of geomagnetic activity. An inclusion of Ap_{12} to the regression removes only partly the geomagnetic effect, but contaminates the analyzed material, in principle, without changing the obtained result. Therefore, any interpretation of the *fo*F2 and *hm*F2 trends should consider the geomagnetic effect as an inalienable part of the trends revealed, and this can be done based on the contemporary understanding of the F2-layer storm mechanisms.

2. Large and significant correlation coefficients $r(\delta fo\mathrm{F2}, Ap_{12})$ and $r(\delta hm\mathrm{F2}, Ap_{12})$, as well as similarity in trends and correlation coefficients diurnal variations (Figs. 1, 2) reveals the close relationship of the F2-layer parameter trends with geomagnetic activity. Both diurnal variation patterns (Figs.1, 2) clearly indicate physical processes which are usually used to explain latitudinal and diurnal F2-layer parameter storm variations. This F2-layer storm mechanism is based on the background solar driven and disturbed thermosphere circulation interaction, resulting in neutral composition and temperature perturbations.

3. There are periods with negative and positive *fo*F2, and *hm*F2 trends which correspond to the periods of increasing or decreasing geomagnetic activity. An 11-year *Ap* index can be used as an indicator of such long-term variations in geomagnetic activity. The turning points are: around 1955, the end of the 1960s and the 1980s, where *fo*F2 and *hm*F2 trends change their signs. An anti-phase for δfoF2 and syn-phase for δhmF2 type of long-term variations with *Ap* may be followed for Slough, where ionospheric observations are available from the early 1930s. Such a type of mid-latitude F2-layer parameter variations is due to neutral composition, temperature and thermospheric winds changes related to geomagnetic activity variations.

4. An existence of a pronounced dependence of the *fo*F2 trends on geomagnetic (invariant) latitude and an absence of any latitudinal dependence for the *hm*F2 trends

are due to different dependencies of NmF2 and *hm*F2 on main aeronomic parameters, the latter being latitudinal dependent during disturbed periods. In particular, for the period of increasing geomagnetic activity of 1965–1991, it may be concluded:

(a) at lower latitudes, positive (or small negative) *fo*F2 trends and positive *hm*F2 trends are primarily due to an increase in the equatorward thermospheric wind and in atomic oxygen concentration;

(b) at middle latitudes, the negative *fo*F2 trend is due to neutral composition (O/N_2 ratio decrease) and temperature increase, resulting in the linear loss coefficient $\beta = \gamma_1[N_2] + \gamma_2[O_2]$ increase. The latter, along with the enhanced T_n and equatorward thermospheric wind, determine the positive *hm*F2 trend;

(c) at sub-auroral and auroral latitudes, *fo*F2 and *hm*F2 trends are determined by strong neutral composition and temperature changes during daytime hours, while at nighttime, soft electron precipitation provides strong contribution. In the auroral zone, electric fields in addition to perturbing neutral composition and temperature via Joule heating, can strongly affect the linear loss coefficient $\beta = \gamma_1[N_2]+\gamma_2[O_2]$ via the γ_1 dependence on E. This results in very strong, negative *fo*F2 and relatively small, positive *hm*F2 daytime trends.

5. All the revealed morphological features of the *fo*F2 and *hm*F2 trends may be explained in the framework of contemporary F2-region storm mechanisms. This newly proposed geomagnetic storm concept used to explain the F2-layer parameter long-term trends proceeds from a natural origin of the trends rather than an artificial one related to the thermosphere cooling due to the greenhouse effect. Within this concept, instead of the thermosphere cooling that the researchers are seeking, one should expect the thermosphere heating for the period of increasing geomagnetic activity of 1965–1991. This period will be followed by the thermosphere cooling, in accordance with the long-term changes in geomagnetic activity.

Acknowledgements. The authors thank the Director and the staff of EISCAT for running the radar and providing the data. The EISCAT Scientific Association is funded by scientific agencies of Finland (SA), France (CNRC), Germany (MPG), Japan (NIPR), Norway (NF), Sweden (NFR), and the United Kingdom (PPARC). We are also grateful to the Millstone Hill Group of the Massachusetts Institute of Technology, Westford, for providing the data. This work was in part supported by the Russian foundation for Fundamental Research under grant 00-05-64189.

Topical Editor M. Lester thanks H. Rishbeth and another referee for their help in evaluating this paper.

References

Bremer, J., Ionospheric trends in mid-latitudes as a possible indicator of the atmospheric greenhouse effect, J. Atmos. Terr. Phys., 54, 1505–1511, 1992.

Bremer, J., Trends in the ionospheric E and F regions over Europe, Ann. Geophysicae, 16, 986–996, 1998.

Clilverd, M. A., Clark, T. D. G., Clarke, E., and Rishbeth, H., Increased magnetic storm activity from 1868 to 1995, J. Atmos. Solar-Terr. Phys., 60, 1047–1056, 1998.

Danilov, A. D., Long-term changes of the mesosphere and lower thermosphere temperature and composition, Adv. Space Res., 20, (11), 2137–2147, 1997.

Danilov, A. D., Review of long-term trends in the upper mesosphere, thermosphere and ionosphere, Adv. Space Res., 22, (6), 907–915, 1998.

Danilov, A. D. and Mikhailov, A. V., Long-term trends of the F2-layer critical frequencies: a new Approach, Proceedings of the 2nd COST 251 Workshop "Algorithms and models for COST 251 Final Product", 30–31 March, 1998, Side, Turkey, Rutherford Appleton Lab., UK, 114–121, 1998.

Danilov, A. D. and Mikhailov, A. V., Spatial and seasonal variations of the *fo*F2 long-term trends, Ann. Geophysicae, 17, 1239–1243, 1999.

Deminov, M. G., Garbatsevich, A. V., and Deminov, R. G., Climatic changes of the ionospheric F2-layer, Doklady RAN, 372, (3), 383–385, 2000.

Field, P. R., Rishbeth, H., Moffett, R. J., Idenden, D. W., Fuller-Rowell, T. J., Millward, G. H., and Aylward, A. D., Modelling composition changes in F-layer storms, J. Atmos. Solar-Terr. Phys., 60, 523–543, 1998.

Foppiano, A. J., Cid, L., and Jara, V., Ionospheric long-term trends for South American mid-latitudes, J. Atmos. Solar-Terr. Phys., 61, 717–723, 1999.

Förster, M., Numgaladze, A. A., and Yurik, R. Y., Thermospheric composition changes deduced from geomagnetic storm modelling, Geophys. Res. Lett., 26, 2625–2628, 1999.

Fuller-Rowell, T. J., Codrescu, M. V., Moffett, R. J., and Quegan, S., Response of the and ionosphere to geomagnetic storm, J. Geophys. Res., 99, 3893–3914, 1994.

Givishvili, G. V. and Leshchenko, L. N., Possible proofs of presence of technogenic impact on the midlatitude ionosphere, Doklady RAN, 334, (2), 213–214, 1994 (in Russian).

Givishvili, G. V. and Leshchenko, L. N., Dynamics of the climatic trends in the midlatitude ionospheric E region, Geomag. and Aeronom., 35, (3), 166–173, 1995 (in Russian).

Givishvili, G. V., Leshchenko, L. N., Shmeleva, O. P., and Ivanidze, T. G., Climatic trends of the mid-latitude upper atmosphere and ionosphere, J. Atmos. Terr. Phys., 57, 871–874, 1995.

Hajkowicz, L. A., Longitudinal (UT) effect in the onset of auroral disturbances over two solar cycles deduced from the AE-index, Ann. Geophysicae, 16, 1573–1579, 1998.

Hedin, A. E., A revised thermospheric model based on masspectrometer and incoherent sactter data MSIS-83, J. Geophys. Res., 88, 10170–10188, 1983.

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

Ivanov-Kholodny, G. S. and Mikhailov, A. V., The prediction of ionospheric conditions, Reidel, Dordrecht, 1986.

Jarvis, M. J., Jenkins, B., and Rodgers, G. A., Southern hemisphere observations of a long-term decrease in F region altitude and thermospheric wind providing possible evidence for global thermospheric cooling, J. Geophys. Res., 103, 20774–20787, 1998.

Kouris, S. S., Papandonious, V. Ph., Fotiadis, D. N., and Xenos, Th. D., A study on the response of *fo*F2 and *M*(3000)F2 to different indices of solar activity, Joint COST 251/IRI Workshop and Working Group Sessions Proceedings, Kuhlungsborn, Germany, 27–30 May 1997, 63–78, 1997.

Marin, D., Mikhailov, A. V., de la Morena, B. A., and Herraiz, M., Long-term *hm*F2 trends in the Eurasian longitudinal sector on the ground-based ionosonde observations, 2001 (submitted to Ann. Geophysicae).

Marubashi, K., Structure of topside ionosphere in high latitudes, J. Radio, Res. Labs, 17, 335–416, 1970.

Mikhailov, A. V. and Mikhailov, V. V., Indices for monthly median *fo*F2 and *M*(3000)F2 modeling and long-term prediction: Ionospheric index MF2, Inter. J. Geomag. and Aeronom., 1, 141–151, 1999.

Mikhailov, A. V. and Schlegel, K., Self-consistent modeling of the daytime electron density profile in the ionospheric F-region, Ann. Geophysicae, 15, 314–326, 1997.

Mikhailov, A. V. and Schlegel, K., Physical mechanism of strong negative storm effects in the daytime ionospheric F2 region observed with EISCAT, Ann. Geophysicae, 16, 602–608, 1998.

Mikhailov, A. V. and Schlegel, K., A self-consistent estimate of O++ N_2 rate coefficient and total EUV solar flux with $\lambda < 1050$ Å using EISCAT observations, Ann. Geophysicae, 18, 1164–1171, 2000.

Mikhailov, A. V., Skoblin, M. G., and Förster, M., Daytime F2-layer positive storm effect at middle and lower latitudes, Ann. Geophysicae, 13, 532–540, 1995.

Mikhailov, A. V., Förster, M., and Skoblin, M. G., An estimate of the non-barometric effect in the [O] height distribution at low latitudes during magnetically disturbed periods, J. Atmos. Terr. Phys., 59, 1209–1215, 1997.

Mikhailov, A. V. and Förster, M., Some F2-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, 249–261, 1999.

Mikhailov, A. V. and Marin, D., Geomagnetic control of the *fo*F2 long-term trends, Ann. Geophysicae, 18, 653–665, 2000.

Morse, F. A., Hilton, H. H., and Mizera, P. F., Polar ionosphere: measured ion density enhancements and soft electron precipitation, J. Geophys. Res., 76, 6099–6111, 1971.

Pavlov, A. V., The role of vibrationally excited nitrogen in the formation of the mid-latitude negative ionospheric storms, Ann. Geophysicae, 12, 554–564, 1994.

Pavlov, A. V., Buonsanto, M. J., Schlesier, A. C., and Richards, P. G., Comparison of models and data at Millstone Hill during the 5–11 June 1991 storm, J. Atmos. Solar-Terr. Phys., 61, 263–279, 1999.

Pike, C. P., A latitudinal survey of the daytime polar F-layer, J. Geophys. Res., 76, 7745–7754, 1971.

Prölss, G. W., Magnetic storm associated perturbations of the upper atmosphere: recent results obtained by satellite-born gas analyzers, Rev. Geophys. Space Phys., 18, 183–202, 1980.

Prölss, G. W., Thermosphere-ionosphere coupling during disturbed conditions, J. Geomag. Geoelectr., 43, Supp., 537–549, 1991.

Prölss, G. W., On explaining the local time variation of ionospheric storm effects, Ann. Geophysicae, 11, 1–9, 1993.

Prölss, G. W., Ionospheric F region storms, in Handbook of Atmospheric Electrodynamics, 2, edited by H. Volland, pp. 195–248, CRC Press, Boca Raton, Fla., 1995.

Prölss, G. W. and von Zahn, U., Seasonal variations in the latitudinal structure of atmospheric disturbances, J. Geophys. Res., 82, 5629–5631, 1977.

Rao, M. S. V. G. and Rao, R. S., The hysteresis variation in F2 layer parameters, J. Atmos. Terr. Phys., 31, 1119–1125, 1969.

Rishbeth, H., A greenhouse effect in the ionosphere? Planet. Space Sci., 38, 945–948, 1990.

Rishbeth, H., F-region storms and thermospheric dynamics, J. Geomag. Geoelectr, 43 (Suppl.), 513–524, 1991.

Rishbeth, H., Long-term changes in the ionosphere, Adv. Space Res., 20, (11)2149–(11)2155, 1997.

Rishbeth, H. and Barron, D. W., Equilibrium electron distributions in the ionospheric F2-layer, J. Atmos. Terr. Phys., 18, 234–252, 1960.

Rishbeth, H. and Roble, R. G., Cooling of the upper atmosphere by enhanced greenhouse gases – Modelling of thermospheric and ionospheric effects, Planet. Space Sci., 40, 1011–1026, 1992.

Rishbeth, H. and Müller-Wodarg, I. C. F., Vertical circulation and thermospheric composition: a modelling study, Ann. Geophysicae, 17, 794–805, 1999.

Sagalin, R. C. and Smiddy, High latitude irregularities in the topside ionosphere based on ISIS-1 thermal ion probe data, J. Geophys. Res., 79, 4252–4260, 1974.

Sato, T. and Colin, L., Morphology of electron concentration enhancement at height of 1000 kilometers at polar latitudes, J. Geophys. Res., 74, 2193–2207, 1969.

Schunk, R. W., Raitt, W. J., and Banks, P. M., Effect of electric fields on the daytime high-latitude E and F regions, J. Geophys. Res., 80, 3121–3130, 1975.

Sharma, S. S., Chandra, H., and Vyas, G. D., Long-term ionospheric trends over Ahmedabad, Geophys. Res. Lett., 26, 433–436, 1999.

Shimazaki, T., World wide daily variations in the height of the maximum electron density in the ionospheric F2 layer, J. Radio Res. Labs., Japan, 2, 85–97, 1955.

Skoblin, M. G. and Förster, M., An alternative explanation of ionization depletion in the winter night-time storm perturbed F2 layer, Ann. Geophysicae, 11, 1026–1032, 1993.

Skoblin, M. G. and Mikhailov, A. V., Some pecularities of altitudinal distribution of atom oxygen at low latitudes during magnetic storms, J. Atmos. Terr. Phys., 58, 875–881, 1996.

Thomas, J. O. and Andrews, M. K., The trans-polar exospheric plasma. A unified picture, Planet. Space Sci., 17, 433–446, 1969.

Torr, M. R. and Torr, D. G., The inclusion of a particle source of ionization in the ionospheric continuity equation, J. Atmos. Terr. Phys., 31, 611–615, 1969.

Ulich, T. and Turunen, E., Evidence for long-term cooling of the upper atmosphere in ionospheric data, Geophys. Res. Lett., 24, 1103–1106, 1997.

Upadhyay, H. O. and Mahajan, K. K., Atmospheric greenhouse effect and ionospheric trends, Geophys. Res. Lett., 25, 3375–3378, 1998.

Wickwar, V. B., Global thermospheric studies of neutral dynamics using incoherent scatter radars, Adv. Space Res., 9, (5)87–(5)102, 1989.

Wrenn, G. L., Rodger, A. S., and Rishbeth, H., Geomagnetic storms in the Antarctic F-region. I. Diurnal and seasonal patterns for main phase effects, J. Atmos. Terr. Phys., 49, 901–913, 1987.