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Ionospheric F2-layer storms

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Abstract

Morphology of midlatitude and equatorial F2-layer storms as well as recent publications on storm mechanisms are summarized. Ground-based ionosonde, incoherent scatter and satellite observations are used to specify the processes responsible for the observed F2-layer storm effects. The interaction of background (solar-driven) and storm-induced (due to high-latitude energy inputs) thermospheric circulation patterns may be considered as the principal mechanism explaining the main features of the midlatitude F2-layer storm effects. Vertical ExB plasma drifts are responsible for main NmF2 perturbations in the equatorial F2-region.

Key words: Midlatitude and equatorial ionosphere, F2-layer storms, Disturbed thermosphere, ExB drifts.

1. INTRODUCTION

Ionospheric F2-layer perturbations can be registered with ground-based ionosondes as deviations of F2-layer critical frequency, foF2 from median or quiet time values. The deviations may be of both signs – so called «positive» and «negative» F2-layer disturbances. Observations of this phenomenon and its relation with geomagnetic storms were first reported by Anderson (1928), Hafstad and Tuve (1929), Appleton and Ingram (1935), Kirby *et al.* (1935). Vertical sounding ionogram reduction usually gives the increase of the F2-layer maximum height, hmF2 and changes in the electron density height profile, Ne(h) compared to prestorm conditions. Strong reduction of electron density in the F2-layer maximum during negative storms helps to occur a pronounced F1-layer; when NmF1 > NmF2 we speak about G-conditions (King 1962). In the beginning of ionospheric researches the idea of plasma redistribution with height was proposed as a possible F2-layer storm mechanism. But afterwards direct total electron content (TEC) observations have shown that electron concentration does change in the whole F2-region during disturbed periods (e.g. Titheridge and Buonsanto, 1988). F2-layer storms is a world-wide feature lasting from some hours to some days. This is a very interesting and important link in the complex chain of solar-terrestrial relations. On the other hand, F2-layer storms are of practical interest as they may severely degrade HF radio communication. A great number of publications is devoted to morphology, physical interpretation, modelling and prediction of the F2-layer storms. A comprehensive review on the problem was made by Prölss (1995, with 420 references therein).

Despite the long history of F2-layer storms investigation many features of this phenomenon still are not clear to say nothing of adequate predictions with a sufficient accuracy. This is due to the fact that F2-layer storms result from many related processes in the magnetosphere, ionosphere and upper atmosphere. The lack of current information on solar wind parameters, ionospheric electric fields and currents, high latitude particle precipitations unable one the make a «deliberate» forecast of the F2-layer storms using so called physical models. An attempt to apply modern 1-3D theoretical models of the F2-region to predict even the simplest quiet time NmF2 and hmF2 daily variations gave overall unsatisfactory results (Anderson *et al.*, 1998). Negative F2-layer storm effects which are the most crucial for HF radio-wave communication cannot be satisfactory modelled without special fitting of aeronomic parameters for each particular ionospheric storm (e.g. Richards *et al.*, 1989, 1994a; Richards and Wilkinson, 1998). Therefor, an empirical approach to the foF2 short-term prediction based on statistical methods is still should be recommended for practical use (e.g. Muhtarov *et al.*, 1998; Marin *et al.*, 2000). On the other hand, some features of the F2-layer storms may be reproduced fairly well with global theoretical models (e.g. Fuller-Rowell *et al.*, 1996; Rishbeth and Field, 1997; Field *et al.*, 1998; F(rster *et al.*, 1999; Rishbeth and Muller-Wodarg, 1999).

The problem of F2-layer storms is so extensive that it cannot be considered more or less completely in a short review. Therefor only midlatitude and equatorial F2-region electron concentration (mainly NmF2 and hmF2 parameters) variations will be considered. The results of morphological analysis based on long-term ground-based ionosonde observations are summarized below. Physical mechanisms of main F2-region storm effects are considered using model calculations along with ground-based ionosonde, satellite and incoherent scatter observations.

2. SOLAR CYCLE AND SEASONAL VARIATIONS

An analysis by Zevakina (1971) of positive and negative storms occurrence on Moscow station over the solar cycle (1957-1967) has shown the following. Negative disturbances prevail at high solar activity. Maximum in their occurrence is shifted by two years in accordance with the same time shift in geomagnetic activity with respect to the maximum in sunspot numbers. There is a tendency at all levels of solar activity for increasing the number of positive storms in winter and equinoxes with minimum number in summer. There is also a tendency for negative storms to be more frequent during equinoxes and this may be attributed to the equinoctial increase in geomagnetic activity. According to other numerous observations, midlatitude negative NmF2 disturbances take place during the main phase of geomagnetic storms in all seasons except winter, when positive perturbations are very probable (Matuura, 1972; Mendillo and Klobuchar, 1974; Basu *et al.*, 1975; Essex 1979; also references in Prölss, 1995). Positive F2-layer disturbances are observed at lower and equatorial latitudes in all seasons during the main phase of magnetic storms (Obayashi and Matuura, 1970; Matuura, 1972; Kane, 1973). Background NmF2 increase over the monthly median or the prestorm reference level and individual NmF2 upsurges above this background level are typical of the F2-layer positive storm effect at lower latitudes during daytime hours.

The intensity of F2-layer negative storm effects during the main phase may be related with D_{st}-index variations (Zevakina and Kiseleva, 1985). The stronger magnetic disturbance the lower geomagnetic latitude where negative storm effects are registered. Worldwide ionosonde network observations analysis has shown (Besprozvannaya, 1983) that in summer this boundary is systematically lower compared to winter time. During summer strong geomagnetic disturbances with D_{st} = 300-350 nT negative storm effects may be observed at latitudes as low as Φ_{inv} = 25-30^0. On the other hand, the perturbation propagation velocity does not show any pronounced seasonal dependence, but is related to the rate of energy dissipation in the auroral zone which roughly is proportional to dD_{st}/dt (Besprozvannaya, 1983). Typical propagation velocity of storm effects is some hundred m/s (Prölss, 1995).

3. SPATIAL DISTRIBUTION

As an example of F2-layer storm spatial distribution the Jan 24-26, 1974 disturbed period is shown in Fig.1 for American and European longitudinal sectors. This is a typical of isolated moderate magnetic storm with a well-defined storm commencement (SC) on Jan 25 around 0500 UT. Observed D_{st} and AE-index variations for this period are shown in Fig. 9. Couples of stations with close geomagnetic latitudes are selected in two longitudinal sectors. Strong negative storm effect is seen in Winnipeg (high latitudes) during sunlit hours. In Boulder (midlatitudes) a well pronounced positive upsurge (positive phase) takes place before noon followed by a negative storm phase. At lower midlatitudes (Havana) strong positive foF2 storm perturbations are seen during afternoon hours. An equatorial station Huancayo demonstrates a stable positive storm effect during daytime. This is a typical pattern of latitudinal distribution of F2-layer storm effects but only for «nighttime» longitudinal sectors where the storm onset took place during nighttime hours. But only positive storm effects take place in the European («daytime») longitudinal sector at high and middle latitudes. This was a daytime sector during the storm onset. Unlike the midlatitude Boulder station in the American sector, the positive storm phase is not followed by a negative one in the European sector. Irregular foF2 variations are seen at low-latitude (Alma-Ata) and equatorial (Kodaikanal) stations. Therefor, F2-layer storms demonstrate a complex longitudinal pattern depending on local time of the storm onset (see also Pr(lss, 1995 for references). Physical mechanisms of such longitudinal differences are considered below. Along with such LT control there exists a longitudinal/UT effect in the onset of auroral disturbances (Hajkowicz, 1998) which should result in a systematic differences between European and Asian sectors. A statistical analysis 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, Japan and Australia are mostly at night during the period of maximum auroral activity whereas Europe and Eastern America are mostly at daytime.

4. DEPENDENCE ON LOCAL TIME

Morphological studies have shown that midlatitude negative F2-layer perturbations are usually observed to follow magnetic storms started during the preceding night, while positive storm effects are generally associated with increased geomagnetic activity in the local daytime sector (e.g. Appleton and Piggot, 1952; Martyn 1953; Jones 1971; Pr(lss 1993a). The results of analysis on 31 ionosonde stations (420 cases) by Prölss and von Zahn (1978) and on 10 stations (217 cases) given in a review by Danilov and Morozova (1985) show that negative storm commencements are the most frequent in post-midnight-early-morning LT and very rare in the noon and afternoon hours. This is a very important trait of the negative F2-layer storm morphology for understanding the physical mechanism of this phenomenon.

Positive perturbations may start in any LT sector. An analysis by Zevakina and Kiseleva (1978) for about 100 F2-layer storms at high solar activity has revealed positive storms of two types. Type I of perturbations are referred to those followed by quiet ionospheric conditions like in the European sector during the Jan 25 1974 storm period (Fig.1, right hand side). Positive disturbances of type II are followed by negative storm effects like in Boulder (Fig.1, left hand side). It was confirmed that summer positive disturbances were rare in comparison with other seasons. The disturbances of type I were more frequent in the night (19-06 LT), while those of type II – during daytime. The duration of perturbation of type II is shorter than of type I, but its amplitude is larger. Perturbations of type II are accompanied by larger hmF2 increase. Generally positive disturbances are more frequent at low geomagnetic activity: $10 < \Sigma Kp < 20$, AE_{max} = 200-400 nT, D_{st} = 10-30 nT.

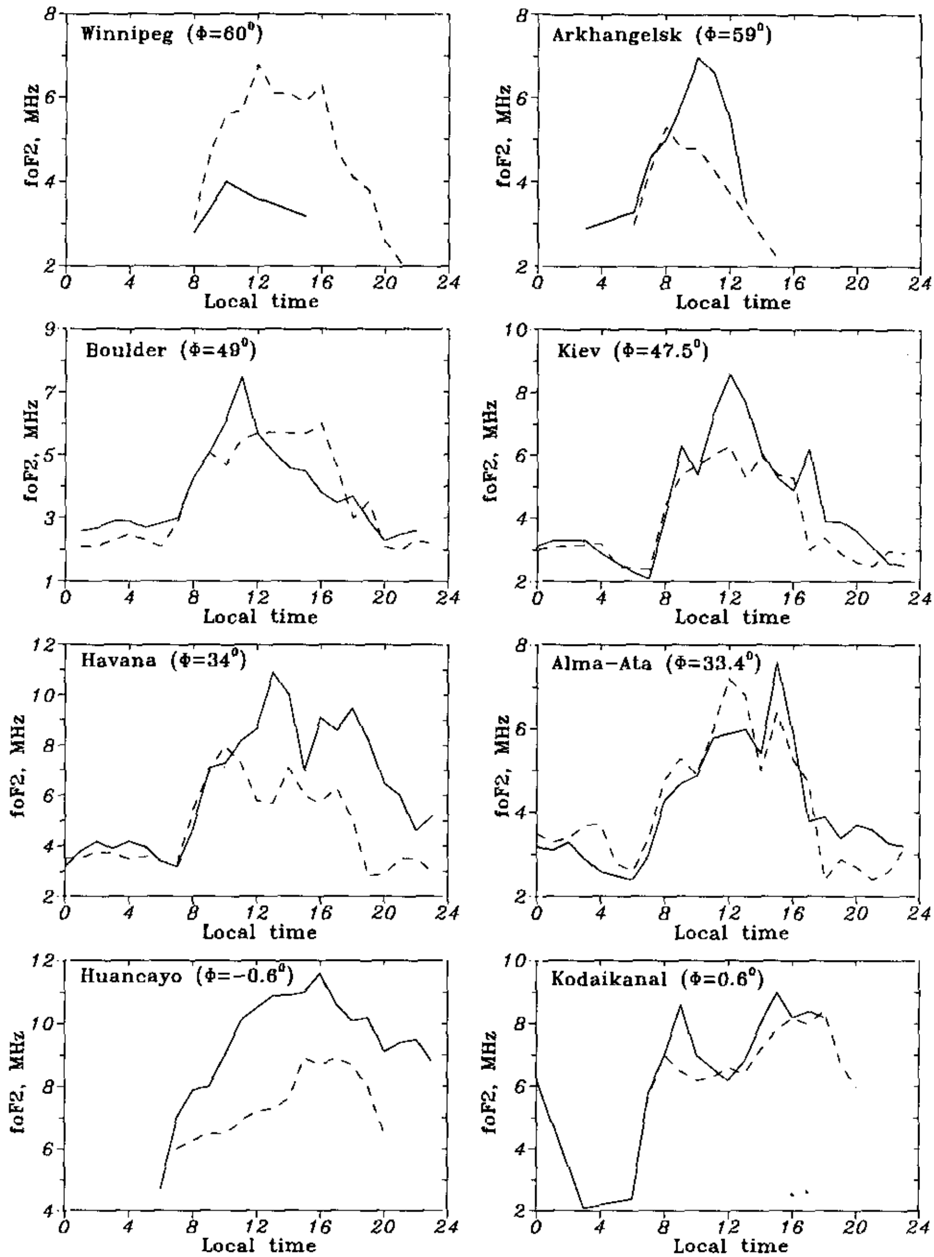

Figura 1. Longitudinal difference in F2-layer storm effects during the Jan 24-25, 1974 geomagnetic disturbance. Stations in American and European sectors with close geomagnetic latitudes are compared. Quiet-time Jan 24 (dashes) and disturbed Jan 25 (solid) foF2 variations are shown.

Positive disturbances in the equatorial F2-region do not coincide on time with high- and midlatitude positive perturbations, therefor one may think that their origin is different. An analysis of 94 storms on the equatorial station Ibadan for the period of 1956-1966 (Adeniyi, 1986) has shown that 90% of all disturbances during daytime and 50-60% during nighttime are positive both at high and low solar activity. Well pronounced negative perturbations are also observed in the equatorial F2-region, but physical mechanisms of negative as well as positive disturbances differ from midlatitude ones (see below).

5. NEGATIVE DISTURBANCE MECHANISMS (MIDLATITUDES)

Among 16 possible physical processes analyzed by Prölss (1995) and 5 processes considered by Rishbeth (1991) which may contribute to the midlatitude F2-layer negative storm effect, thermospheric neutral composition changes with O/N_2 ratio decrease are believed to be the main one. This is confirmed both by direct comparison of R(Nm) = $NmF2_{storm}/NmF2_{quiet}$ and $R(O/N_2)$ = $[O/N_2]_{storm}/[O/N_2]_{quiet}$ (Prölss, 1980; see also Forbes *et al.*, 1996; Zuzic *et al.*, 1997) and 3D model calculations (Fuller-Rowell *et al.*, 1996; Rishbeth and Field, 1997; Field *et al.*, 1998; Förster *et al.*, 1999; Rishbeth and Muller-Wodarg, 1999). Seaton (1956) was the first who suggested that negative storm effects were caused by changes (a decrease) in the thermospheric atomic/molecular ratio during geomagnetic storms. Such neutral composition changes (mainly O/N_2 ratio) alter the balance between electron production and loss rates resulting in the NmF2 decrease. Disturbed global circulation driven by high-latitude energy inputs (Joule heating and particle precipitations) superimposed on the quiet solar-driven circulation is the main mechanism of thermospheric composition changes. This was proposed by Duncan (1969) and confirmed afterwards by many others (see Prölss, 1995; Rishbeth, 1998 and references therein). Unlike the suggestions by Seaton (1956) (an increase of $[O_2]$) and by Chandra and Herman (1969) (a decrease of [O]) now it is established that both effects take place (Prölss, 1980; Zuzic *et al.*, 1997).

The other mechanism often mentioned in relation with F2-layer negative storm effect is the $O^+ + N_2$ reaction rate increase due to vibrationally excited N_2^* (Richards *et al.*, 1989; Pavlov, 1994; Pavlov *et al.*, 1999). Although taking into account N_2^* sometimes helps to get closer model calculations to measurements (e.g. Pavlov and Buonsanto, 1997) there are problems with reproducing negative storm phase and a correction of MSIS model neutral composition is required to match model results to the observations (Richards *et al.*, 1989; Richards *et al.*, 1994a; Richards and Wilkinson, 1998). Moreover it was stressed that the inclusion of vibrationally excited N_2^* actually worsens the agreement between modelling and observations (Richards *et al.*, 1994a, b). An analysis by Mikhailov and Schlegel (2000) based on EISCAT observations has shown that recent flowing afterglow laboratory measurements of this reaction rate coefficient by Hierl *et al.* (1997) may be used in a wide temperature range (up to T_{eff} = 1400 K) in F2-region calculations without any special N_2^* effects taking into account.

To illustrate the discussed mechanisms of F2-layer negative disturbances let us consider some examples. We start with an isolated moderate geomagnetic storm during Jan 06-11, 1997. Millstone Hill IS observations during this event were analyzed by Mikhailov and Förster (1999). This was deep solar minimum conditions with monthly $F_{10.7}$ = 73. A quiet time interval of Jan 06-09 (Ap = 3-11) was followed by a moderate geomagnetic storm on Jan 10 with Ap = 32 resulting in a well pronounced negative storm effect during daytime hours with NmF2 reduction by a factor of 2.0-2.5 and hmF2 increase by 30 km on average (Fig. 2). The variations of all parameters are very close to each other for the four prestorm quiet days, so Jan 09 with Ap = 5 was chosen as a reference one. The observed and calculated Ne(h) profiles for quiet and disturbed days are given in Fig. 2 (bottom graph). A self-consistent method by Mikhailov and Schlegel (1997) for daytime F2-region modelling was applied to find the set of main aeronomic parameters responsible for the observed Ne(h) distribution. Calculated parameters of the T_n(h) profile, [O], [O_2], [N_2] extrapolated to the height of 120 km as well as vertical plasma drift W, and O/N_2 ratio at the 300 km height are given in Table 1.

Table 1. Calculated thermospheric parameters for the Jan 06-10,1997 storm period. Vertical plasma drift W and O/N_2 ratio are given at the 300 km height Also are shown [O], [O_2], [N_2] extrapolated to the 120 km height. The second lines give the corresponding MSIS-83 values.

Date 1997	*Time (UT)*	T_{ex} (K)	T_{120} (K)	$lg[O]_{120}$ (cm^{-3})	$lg[O_2]_{120}$ (cm^{-3})	$lg[N_2]_{120}$ (cm^{-3})	*S* (km^{-1})	*W* (m/s)	O/N_2
Jan 06	1730-1930	826	354	10.882	10.637	11.482	0.028	−16.5	7.62
	(1830)	756	346	10.874	10.648	11.486	0.032		-9.20
Jan 07	1700-2000	845	335	10.899	10.711	11.418	0.027	−17.5	8.59
	(1830)	788	361	10.852	10.669	11.486	0.030		-7.40
Jan 08	1700-2000	780	334	10.850	10.637	11.487	0.026	−16.6	8.45
	(1830)	780	358	10.856	10.664	11.485	0.031		7.78
Jan 09	1630-1900	870	334	10.838	10.713	11.451	0.025	−16.8	6.88
	(1745)	761	348	10.870	10.663	11.491	0.032		8.71
Jan 10	1700-1930	982	368	10.605	10.849	11.646	0.025	−6.7	1.71
	(1815)	814	371	10.841	10.696	11.491	0.029		6.37

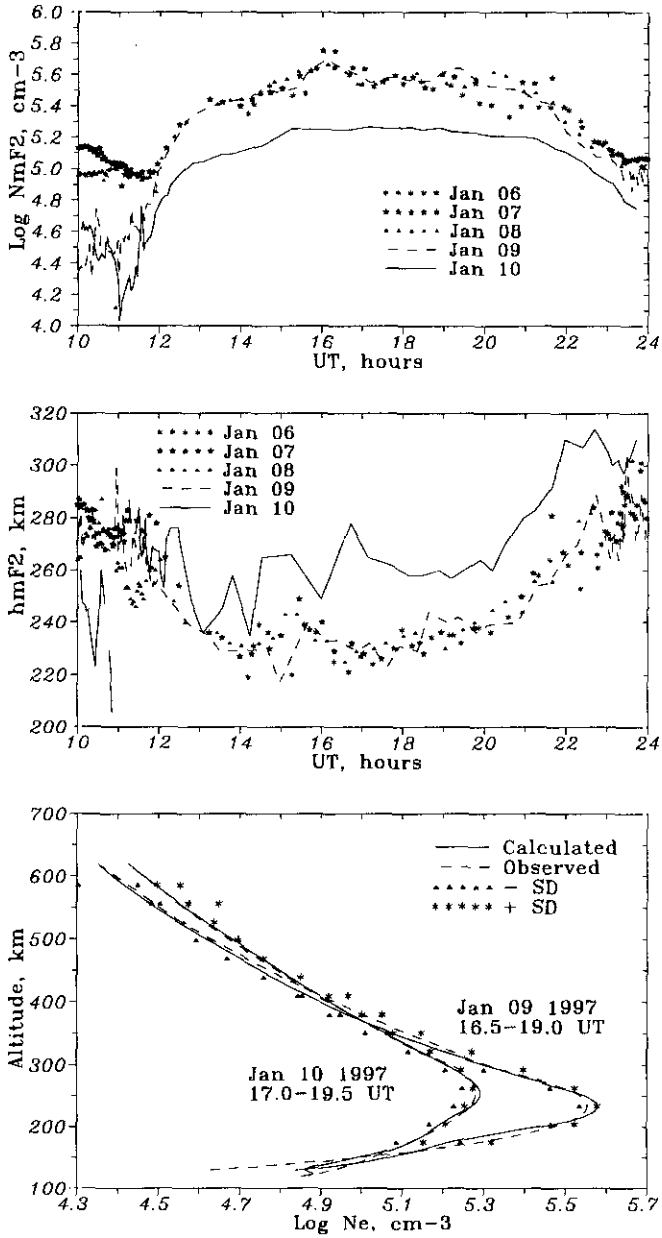

Figura 2. Observed NmF2 and hmF2 variations for daytime hours during the Jan 06-10, 1997 (solar minimum) disturbed period. Also observed and calculated Ne(h) profiles for quiet Jan 09 and disturbed Jan 10 days are shown (bottom panel).The standard deviations of the observed values are indicated. Calculated profiles closely match the observations on both days.

In the F2 region (300 km height) the O/N_2 ratio is in acceptable agreement with MSIS predictions (18% is the average difference for quiet days), but is less by a factor of 3.72 on Jan 10. Vertical plasma drift resulted from the northward thermospheric wind is about the same for the quiet days, but is decreased essentially for the disturbed day. This is in line with the present day understanding of the thermosphere circulation pattern changes during geomagnetically disturbed periods. Thus the main reason for the observed N_mF2 negative storm effect on Jan 10 is the $O/(N_2+O_2)$ ratio decrease in the thermosphere. The calculated $[N_2]$ and $[O_2]$ increase on Jan 10 with respect to Jan 09 is a factor of 3.61 and 3.66, respectively, while [O] decreased by 11%. Neutral composition is seen to demonstrate typical storm time variations. The thermosphere is depleted with atomic oxygen and enriched with molecular species. This is due to the changes in the global thermospheric circulation carrying the disturbed neutral composition from the auroral latitudes as well as to neutral gas upwelling resulted from the disturbed equatorward neutral wind at the initial phase of the storm. It should be stressed that changes in neutral composition and temperature (not predicted by modern thermospheric models) seem to be the only way to explain the observed electron density decrease in the daytime F2-region. The consideration of vibrationally excited N_2^*, (Pavlov, 1994; Pavlov and Buonsanto, 1997) as a plausible mechanism for the F2-layer negative storm effects is not applicable to winter solar minimum conditions in question.

The storm onset took place during night time (around 06 UT) in the American longitudinal sector. So, the storm-induced thermospheric wind (due to high-latitude energy inputs) coincides with the background pole-to-equator thermospheric circulation and this helps the increased auroral N_2/O ratio to spread towards midlatitudes resulting in negative storm effects at latitudes of Millstone Hill during the following daytime hours in accordance the disturbed global circulation mechanism mentioned above.

The Jan 06-10, 1997 was a moderate F2-layer disturbance with the NmF2 decrease by 2-2.5 times. During severe geomagnetic storms the NmF2 drop may be much larger with G-condition occurrence when NmF2 < NmF1. Millstone Hill observations during such a very strong geomagnetic storm on April 06-12, 1990 (solar maximum) with Ap = 124 were analyzed by Mikhailov and Foster (1997). During this event F2-layer maximum practically disappeared at usual heights and F1-layer constituted the ionospheric maximum during daytime hours. The electron concentration at the F2-layer heights dropped by a factor of 10 with respect to quiet time prestorm conditions. Observed NmF2 and hmF2 variations for this period are shown in Fig. 3. April 07 with Ap = 8 was used as a reference quiet day. As above the method by Mikhailov and Schlegel (1997) was used for the analysis. Observed and calculated Ne(h) profiles for quiet and disturbed days are given in Fig. 3 (bottom panel).

The ionospheric parameter variations are given in Fig. 4. The position of the F2-layer maximum on April 10 is very approximate, so N_mF2 and h_mF2 are given by dashes in Fig. 4. Daytime N_mF2 in accordance with Rishbeth and Barron

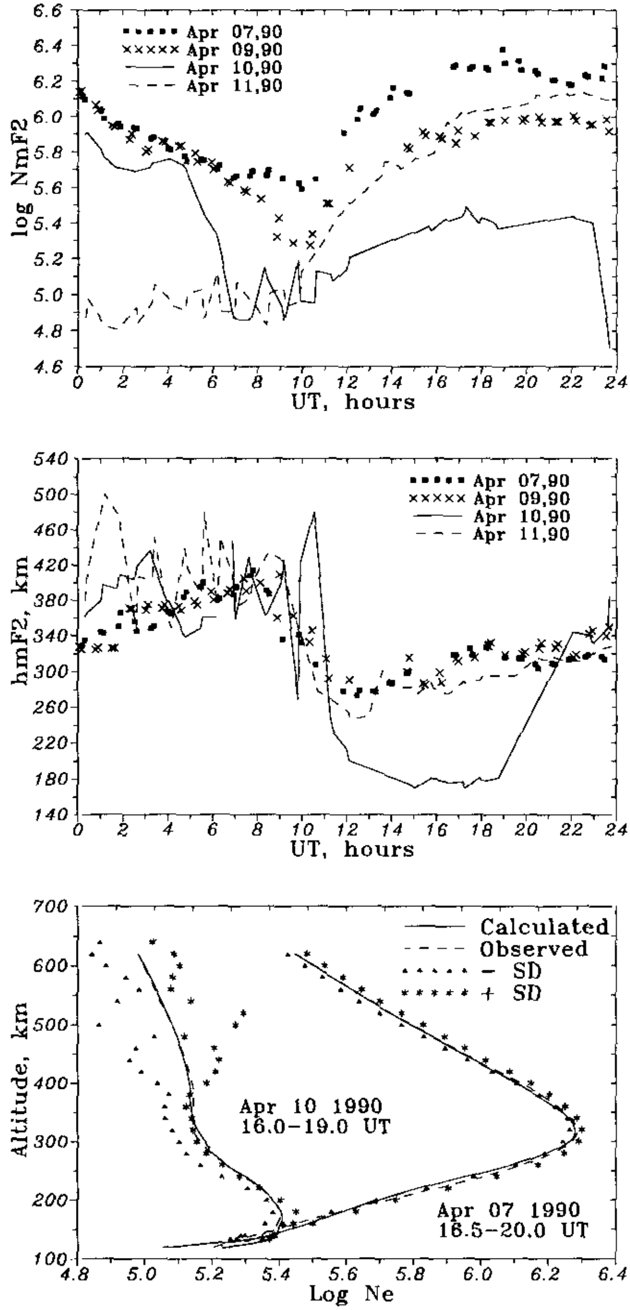

Figura 3. Same as Fig. 2, but for a severe storm on April 07-11, 1990 during solar maximum.

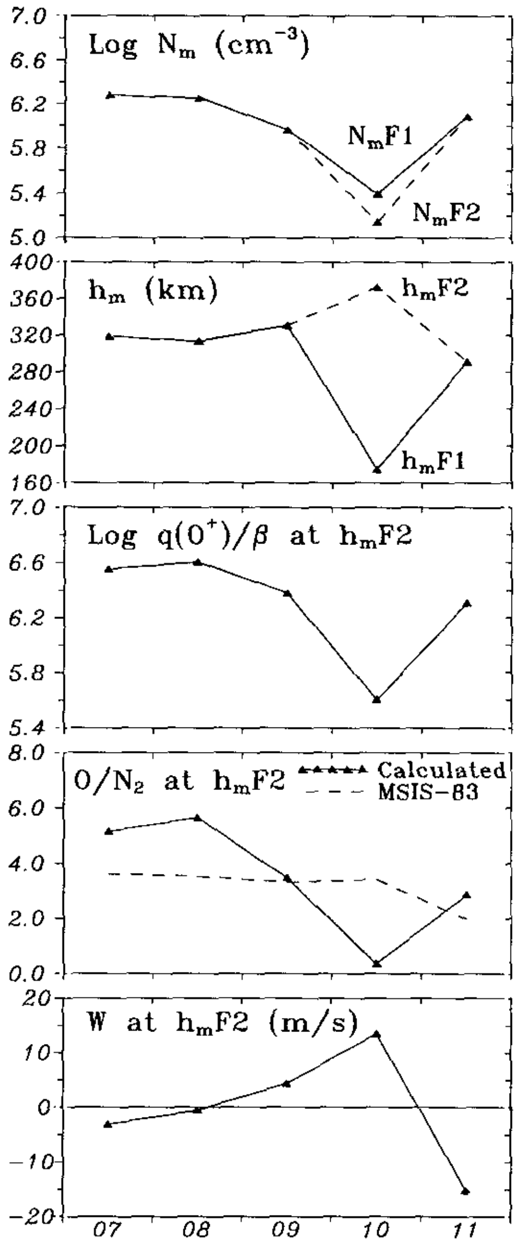

Figura 4. Observed variations of log Nm and peak height hm are presented for the April 07-11,1990 period along with calculated log $q(O+)/\beta$ and O/N_2 ratios and vertical plasma drift at the height of F2-layer maximum. The MSIS-83 model O/N_2 prediction is shown for comparison (dashes). Figures along the x axis are dates of April 1990.

(1960) closely follows the $q(O^+)/\beta$ variation at the h_mF2 height. The $q(O^+)/\beta$ ratio is controlled mostly by the O/N_2 ratio, and the relationship of N_mF2 with O/N_2 during geomagnetic storms is a well-established (Prölss, 1980, 1995). A comparison with the MSIS-83 model predictions shows that the model does not describe properly the O/N_2 relative variations during the considered period. The O/N_2 ratio decrease for April 10 relative to April 07 predicted by MSIS-83 is only 6% at our best estimate of the F2-layer peak height while the decrease required to fit the observations is more than a factor of 14. On the other hand, the absolute O/N_2 values are close to the MSIS-83 prediction for April 09 and April 11. Such a strong $q(O^+)/\beta$ decrease on April 10 mainly resulted from the [O] decrease by a factor of 6 and molecular $[N_2]$ and $[O_2]$ species increase by the factors of 3 and 16, respectively (Fig. 5). This type of neutral composition change is typical of the auroral zone where strong Joule heating results in atmospheric upwelling followed by a decrease in light atmospheric species and increase in heavy species abundance (e.g. Prölss and Fricke, 1976; Trinks *et al.*, 1976; Prölss, 1991). The reason for such changes may be local Joule heating as strong electric fields up to 75 mVm^{-1} were observed at Millstone Hill during morning hours. On the other hand, perturbed neutral composition and temperature (Fig. 5) may have been transferred from high latitudes by a strong equatorward wind during postmidnight hours (Buonsanto *et al.*,1992). So the main reason for the observed tenfold decrease in electron concentration at the F2-layer heights on April 10 appears to be the strong decrease in the ionization rate due to an [O] decrease and an increase of the O^+ recombination rate. The linear loss coefficient $\beta={}_{\gamma 1}[N_2] + {}_{\gamma 2}[O_2]$ has increased at h_mF2 heights by 4.2 times on April 10 with respect to the prestorm day of April 07. The calculated vertical plasma drift W (presumably resulting from the meridional thermospheric wind) is more positive for more disturbed days (Fig. 4) in accordance with the present day understanding of the global circulation pattern but becomes strong negative on April 11. The reason for such change in the thermospheric wind direction is not clear, but this is important for further discussion. Indeed, a fast recovery of all thermospheric parameters on April 11 to the April 09 level (Fig. 4, 5) is puzzling after such strong perturbations on April 10. However, according to Prölss (1995) the idea that composition perturbations, once they have been generated, «rotate» with the Earth is only schematic. Actually, the disturbance bulge will be pushed around by winds and may move back and forth in latitude. Such effects were confirmed by the storm simulation (Fuller-Rowell *et al.*, 1994) as well as by ESRO-4 data analysis (Skoblin and Förster, 1993). So the strong northward thermospheric wind calculated for April 11 (Fig. 5) may provide an explanation for the rapid changes in the thermospheric parameters on April 11, the disturbance bulge was just shifted to higher latitudes. The calculated exospheric temperatures T_{ex} (Fig. 5) are close to the MSIS-83 model predictions and Millstone Hill estimates for all days other than April 10 when MSIS-83 gives T_{ex} by 570 K lower. T_{ex} calculations clearly show to a strong atmospheric heating on the disturbed day of April 10.

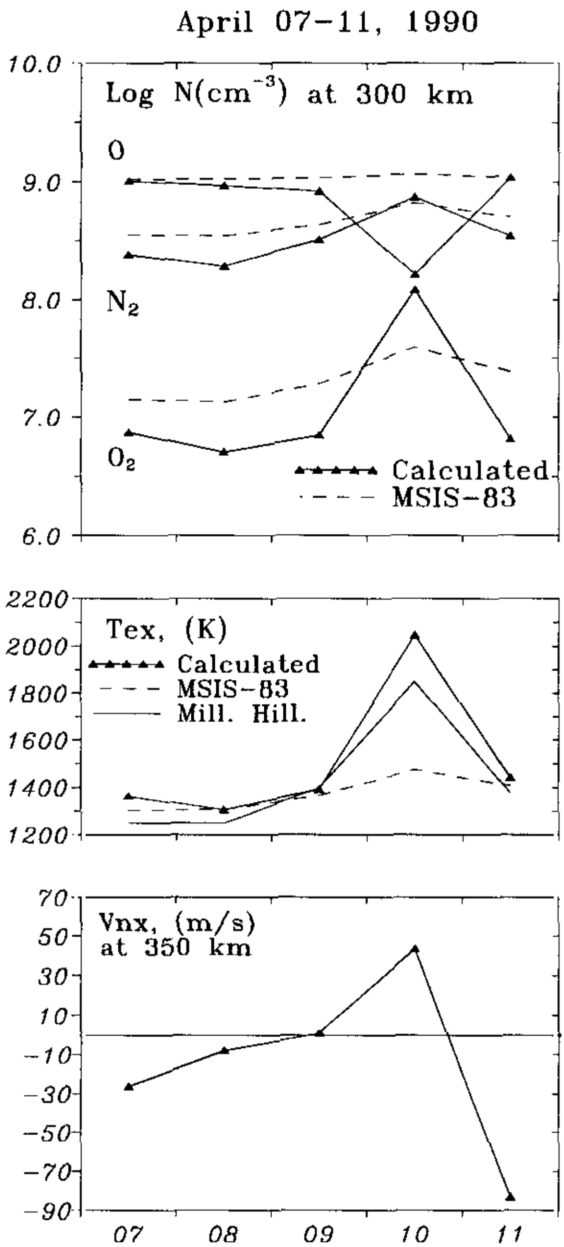

Figura 5. Calculated neutral composition at 300 km and exospheric temperature T_{ex} are compared to MSIS-83 model predictions (dashes). Millstone Hill estimate of Tex is shown as well (solid), and calculated meridional thermospheric wind (bottom panel, positive to the south), is shown. Figures along the x axis are dates of April 1990.

Both analyzed cases of midlatitude negative storm effect resulted from neutral composition and temperature changes in accordance the accepted concept. But at high-midlatitudes daytime F2-layer negative storm effects may have different origin although they look similar to midlatitude ones.

Such an example of strong negative disturbance in the daytime F2-region demonstrate EISCAT observations on April 03, 1992 (Mikhailov and Schlegel, 1998). Despite EISCAT is located in the auroral zone, F2-region during daytime (sunlit) hours may be considered as typical of midlatitude one controlled by local processes (Farmer *et al.*, 1984; Lathuillere and Brekke, 1985). The April 1992 period is very suitable for the analysis as it includes three previous quiet days, so April 02 can be used as a reference. On April 03, 1992 a steep upsurge of the westward ExB drift started after 1000 UT, peaked around 1200-1400 UT at values of about 2000 m/s, and then subsided down to 1000 m/s. Therefor, a mean value of 1700 m/s ($E \approx 85$ mV/m) may be accepted for the analyzed period 1400-1500 UT. Observed N_mF2 and h_mF2 variations during daytime hours are shown in Fig. 6. The disturbed day of Apr 03 is characterized by an increase in h_mF2 and a strong decrease in N_mF2 in comparison with the previous quiet days. Such h_mF2 and N_mF2 variations are similar to midlatitude negative F2-layer storm effects resulting from changes of neutral composition and temperature, but the mechanism of this negative disturbance is different. According to observations N_mF2 was reduced by a factor of 6.4 and h_mF2 increased by about 40 km.

Electron density profiles resulting from model calculations in comparison with the observed $N_e(h)$ profiles are displayed in Fig. 6 (bottom panels). The calculated variations of the neutral composition during the March 31-April 03 period (Fig. 7) are not strong. This may be attributed to the fact that the considered period (1400-1500 UT) was relatively close to the beginning of the geomagnetic storm at about 1000 UT. Much more time is usually required for changes in the neutral composition. Therefor, observed strong N_mF2 reduction from April 02 to April 03 (by a factor of up to 6.4) is not resulted from neutral composition changes: the O/N_2 ratio equals to 5 on April 02 and 4.7 on April 03 at the h_mF2 height. Also Fig. 7 reveals only small neutral composition changes at 300 km altitude. On the other hand the linear loss coefficient $\beta = \gamma_1[N_2] + \gamma_2[O_2]$ for O^+ ions increased by a factor of 5 at the F2-layer maximum height. This results from a large increase in γ_1 by more than a factor of 10 due to its dependence on the electric field (Schunk *et al.*, 1975). Therefore, the very large negative F2-layer storm effect on April 03, 1992 is mainly a consequence of the strong electric field ($E \approx 85$ mV/m), rather than of changes in neutral composition.

The observed steep upsurge of the electric field produced not only negative disturbance at the latitudes of EISCAT, but a daytime trough in latitudinal distribution of N_mF2. Fig. 8 shows the observed latitudinal variation of N_mF2 along a chain of European ionosonde stations for the same time interval. Negative storm effect due to the high-latitude electric field is seen extended down

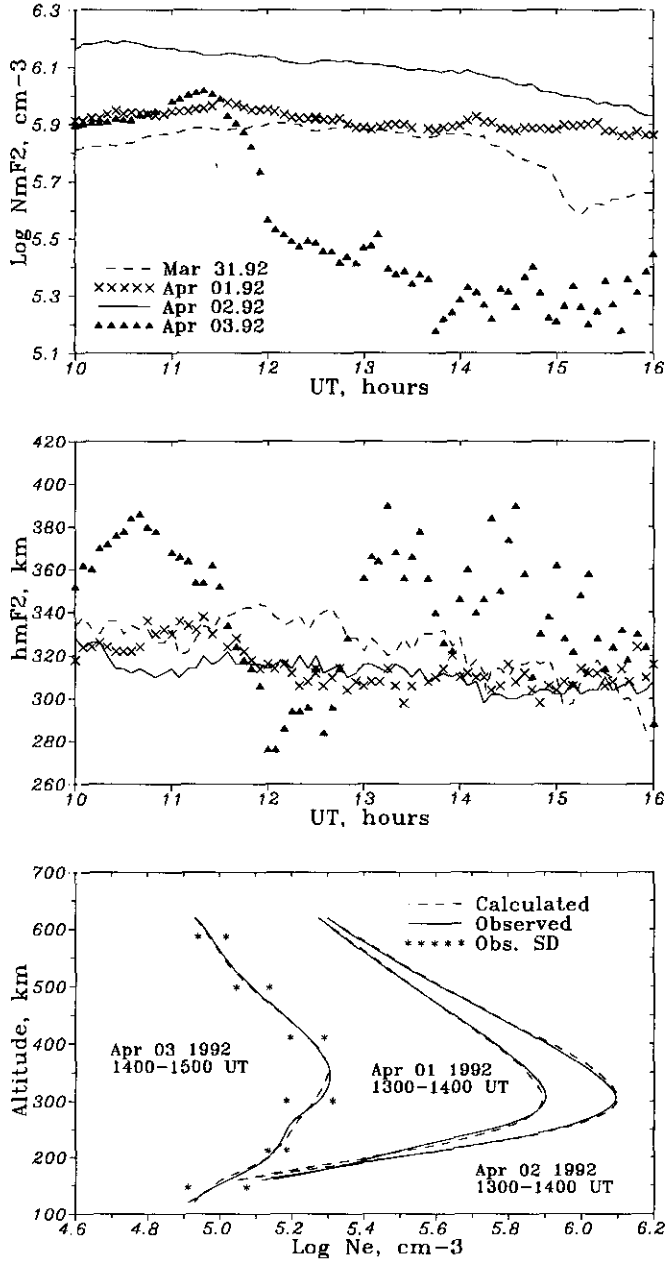

Figura 6. Observed by EISCAT NmF2 and hmF2 variations for March 31-April 03, 1992 during day-time hours. Also, observed (together with a band of standard deviations) and calculated Ne(h) profiles for two geomagnetically quiet (April 01,02) and disturbed April 03 days. Compare to Figures 2 and 3.

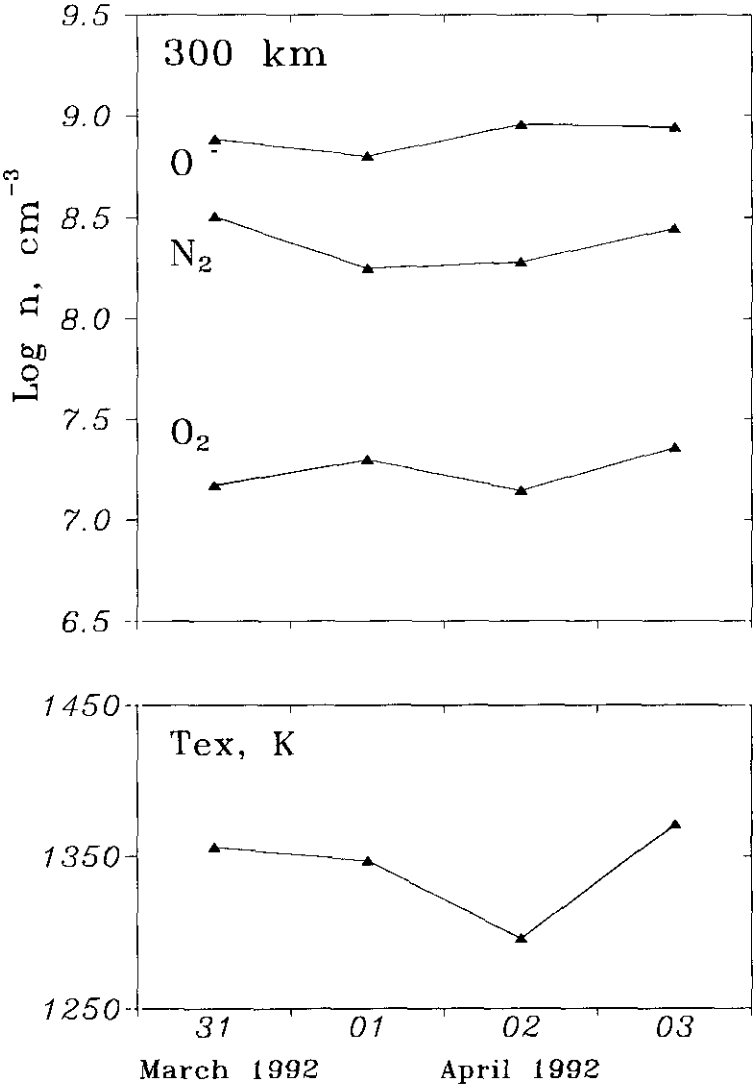

Figura 7. Calculated neutral composition (at 300 km) and exospheric temperature T_{ex} for the March 31-April 03, 1992 disturbed period.

to latitudes of Uppsala ($\Phi = 58^0$) and a small N_mF2 reduction is seen even at the midlatitude station Kaliningrad. Therefore April 03 provides an excellent example of a daytime negative storm effect resulted from an enhanced electric field.

6. POSITIVE DISTURBANCE MECHANISMS (MID- AND LOWER LATITUDES)

Among 15 processes listed by Prölss (1995) and 4 processes mentioned by Rishbeth (1991) equatorward-directed winds associated with traveling atmospheric disturbances (TADs) followed by changes in global thermospheric circulation as well as an increase in the atomic oxygen concentration may be considered as the main processes responsible for the midlatitude daytime F2-region positive storm effects. Let us consider these mechanisms analyzing the Jan 24-26, 1974 storm period (Fig. 1) as it was done by Mikhailov *et al.* (1995).

Figure 9 demonstrates D_{st} and AE index variations for Jan 24-26, 1974 storm period with the SC on Jan 25, at 0500 UT. This storm period was chosen

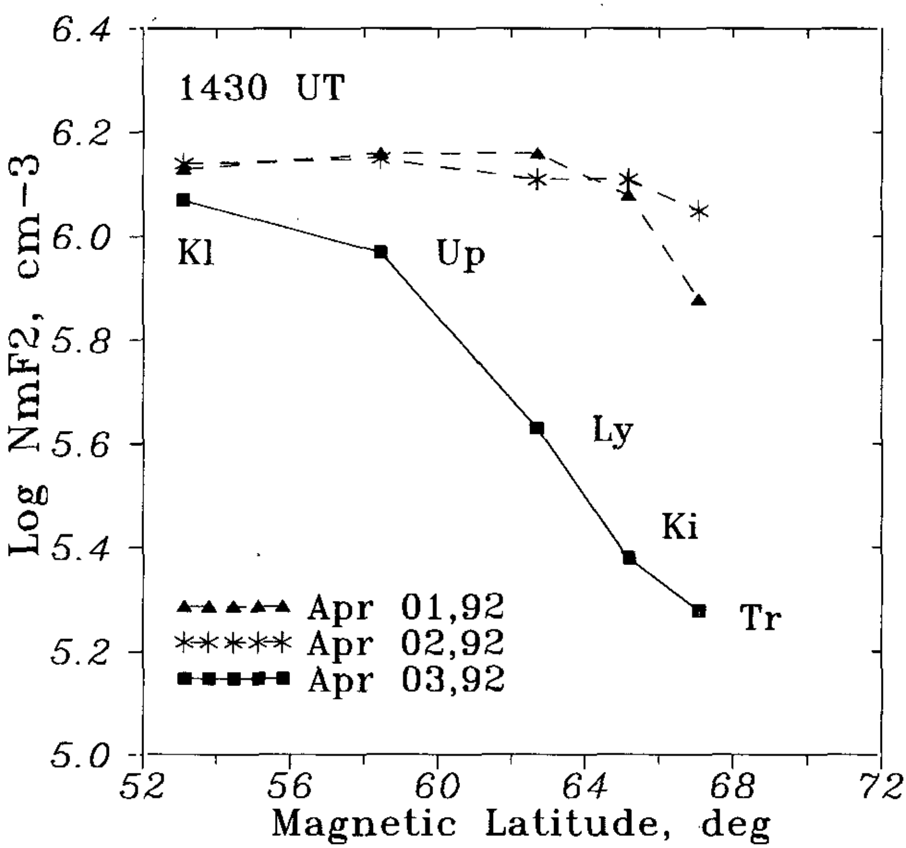

Figura 8. Observed NmF2 latitudinal variation for the chain of European ionosonde stations: Kaliningrad, Uppsala, Lycksele, Kiruna and Tromso (EISCAT location). Daytime trough is produced by enhanced electric field.period.

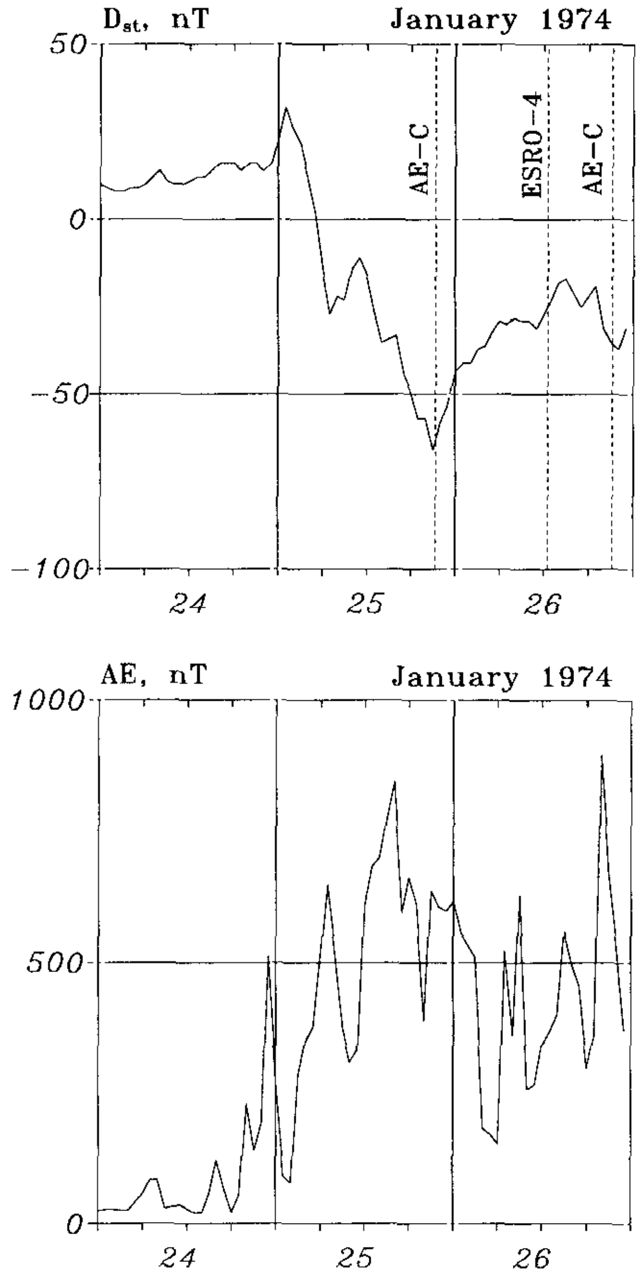

Figura 9. Dst- and AE-index variations for the Jan 24-26, 1974 storm period. Three consecutive AE-C and ESRO-4 passages in the American longitudinal sector are indicated. Time axis is in UT.

for the following reasons. First, this was an isolated moderate magnetic storm with well-defined SC and AE-index increases up to 900 nT. Second, very pronounced positive storm effects were observed at lower latitudes in the American sector and at middle latitudes in Europe. Third, neutral composition data from two satellites ESRO-4 and AE-C are available. In accordance with storm onset, we mark the American sector as «nighttime» as SC took place around local midnight and the European sector as «daytime» as SC falls on morning hours.

Neutral composition changes measured by two satellites in the American longitudinal sector along with MSIS-83 model predictions are shown in Fig. 10. All the data are reduced to 250 km. The orbit for prestorm quiet day of Jan 22 was chosen as a reference to analyze ESRO-4 data. The MSIS-83 model is seen to represent quiet time variations fairly well (see also Fig. 12), and so it may be used with some confidence as a reference for AE-C storm time measurements, as AE-C data are not available for quiet prestorm days. Both satellites demonstrate a pronounced [O] increase at lower latitudes while $R(N_2/O) = (N_2/O)_{storm}/(N_2/O)_{quiet}$ ratio remains practically unchanged at the F2-region heights. Latitudinal variation of $R(N_2/O)$ is shown in Fig. 10. It should be stressed that such a situation takes place in a wide range of heights along the satellite orbits. Such a distribution of neutral composition implies a non-barometric law for atomic oxygen distribution presumably caused by downwelling related to disturbed thermospheric circulation (Skoblin and Mikhailov, 1996; Mikhailov *et al.*, 1997; Förster *et al.*, 1999; Rishbeth and Muller-Wodarg, 1999).

Figure 11 illustrates the observed NmF2 and hmF2 (from ionogram reduction) variations for Havana (23 N, 278 E, $\Phi_{inv} = 34.2$). Quiet-time NmF2 and hmF2 values for Jan 24, 1974 were used as a reference level. A pronounced NmF2 positive storm effect is seen during sunlit hours on Jan 25. Background NmF2 increase and an upsurge after 12 LT followed by a downfall at 1500 LT are observed in NmF2 daytime variations. The hmF2 variations are very strong. For further analysis median NmF2 and hmF2 values for day-time hours of Jan 24 and Jan 25 were found. They turned out to be those observed just around 1600 LT, i.e. the time of AE-C measurements. These median values are: lgNmF2 = 5.68 and hmF2 = 244 km for Jan 24 and lgNmf2 = 5.97 and hmF2 = 300 km for Jan 25.

Let us estimate NmF2 positive storm effects resulting from observed neutral composition changes and storm induced equatorward thermospheric wind. According to the well-known expression by Rishbeth and Barron (1960)

$$N_mF2 = 0.75 * q_m / \beta_m \propto [O]_m / [N_2]_m \qquad (1)$$

where ion production rate q_m and loss coefficient β_m are given at the F2-layer maximum. In this case NmF2 varies along with $[O]_m/[N_2]_m$ ratio but hmF2 also

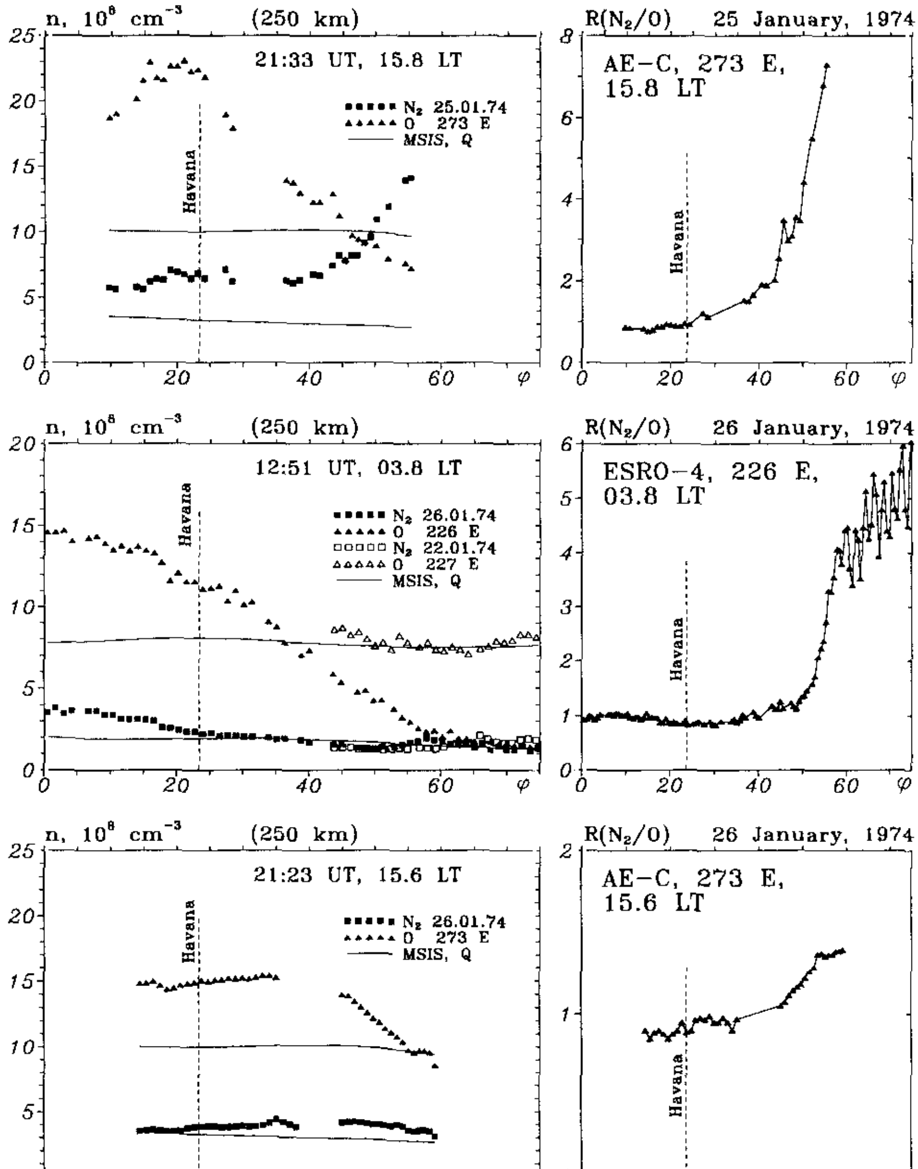

Figura 10. Latitudinal variations of [O] (triangles), [N_2] (squares) reduced from the height of satellite orbit to 250 km and (N_2/O)storm/(N_2/O)quiet at 250 km for three consecutive satellite passages in the American sector. *Filled symbols* indicate disturbed and *open symbols* show quiet-time prestorm conditions. The *solid line* represents the MSIS-83 model quiet-time variations.

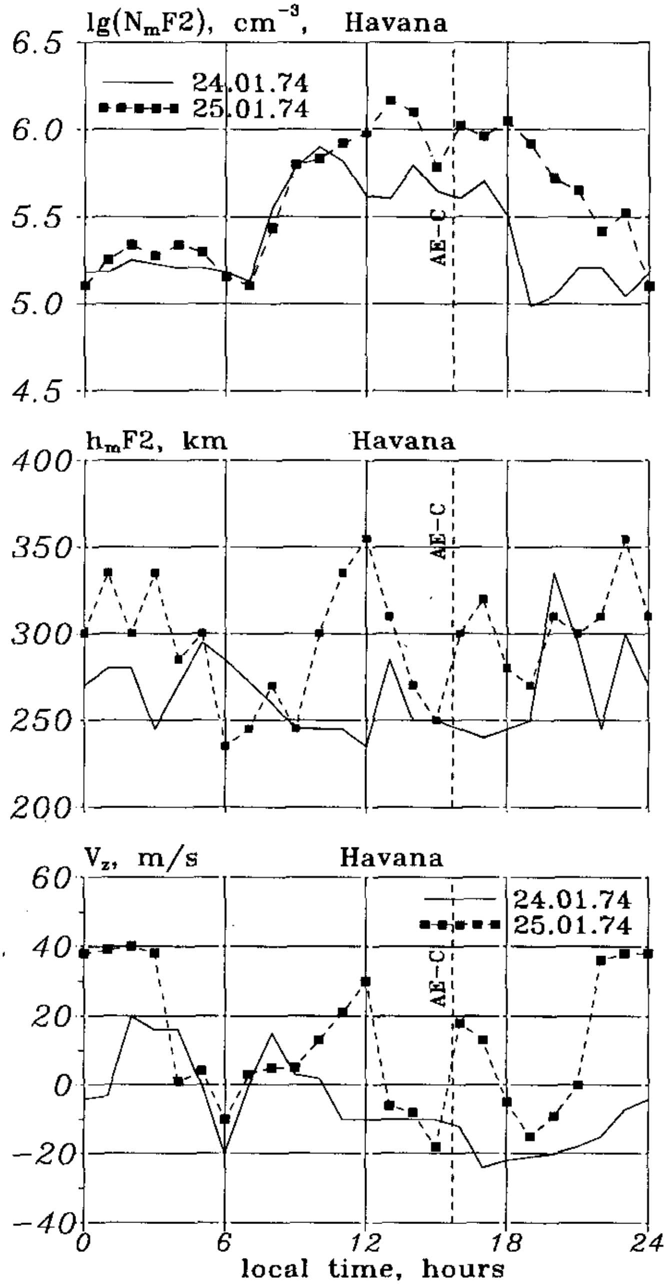

Figura 11. Observed log NmF2 and hmF2 variations for disturbed Jan 25 and quiet-time Jan 24, 1974 days at Havana, along with calculated Vz daily variations.

varies as we pass from quiet to disturbed thermosphere. For convenience we re-write this expression for a fixed height h_1 (Mikhailov *et al.*, 1995)

$$N_m F2 \propto \frac{[O]_1^{2/3}}{T_n^{5/6}} * \left(\frac{[O]_1}{[N_2]_1} \right)^{2/3} \tag{2}$$

This expression shows that NmF2 will increase provided the absolute atomic oxygen concentration [O] increases, while $[O]/[N_2]$ may remain unchanged at any fixed level – the situation we have according to satellite data. NmF2 varies as $[O]^{0.67}$ according to the simplified expression (2). An accurate numerical continuity equation solution, taking into account all the processes responsible for the F2-layer formation and the real thermosphere, gives a little steeper dependence as $[O]^{0.83}$. Thus an [O] increase at lower latitudes due to downwelling motion resulting from storm-induced equatorward thermospheric wind, can really contribute to the positive NmF2 storm effect while $R(N_2/O)$ ratio remains unchanged.

To estimate the quantitative contribution of $\Delta[O]$, $\Delta\beta$, ΔT_n, and ΔV_z to the observed ΔNmF2 and ΔhmF2 storm effect, we use more precise expressions for idealized daytime stationary F2-layer model (Ivanov-Kholodny and Mikhailov, 1986) These expressions resulted from an analytical solution of the continuity equation for electron concentration in the F2-region

$$\Delta \lg N_m F2 = \frac{4}{3}\Delta \lg[O] - \frac{2}{3}\Delta \lg \beta + \frac{2}{3}\Delta \lg H - \frac{1}{3}\Delta \lg(0.54d) + \Delta \lg J_0 \tag{3}$$

$$\begin{aligned} \Delta h_m F2 = {} & \frac{2.3H_s}{3}\left\{ \lg([O_s]\beta_s) + \lg(H\frac{2}{s}/0.54d_s) \right\} \\ & - \frac{2.3H_q}{3}\left\{ \lg([O_q]\beta_q) + \lg(H\frac{2}{q}/0.54d_q) \right\} \end{aligned} \tag{4}$$

where [O] is the atomic oxygen concentration, and β is the loss coefficient at any fixed height, H is the atomic oxygen scale height, J_o is the ionization efficiency, $d = 1.38(10^{19}(T_n/1000)^{0.5}$ is the diffusion coefficient and q and s indices correspond to quiet and storm conditions. We can extract the explicit dependence on T_n in the expression (3), and assuming $\Delta \lg J_o = 0$ for neighboring days, we can write

$$\Delta \lg N_m F2 = \frac{4}{3}\Delta \lg[O] - \frac{2}{3}\Delta \lg \beta + \frac{2}{3}\Delta \lg H - \frac{1}{3}\Delta \lg(0.54d) + \Delta \lg J_0 \tag{5}$$

This expression does not depend on height for any isothermal atmosphere in which scale heights for [O] and β are related as H(O) = 2H(β).

Let us consider the physical mechanism of the positive storm effect in the «nighttime» (relative to the storm onset) American sector. All the thermospheric parameters are reduced to a fixed height of 250 km with the help of the MSIS-83 model which was normalized by AE-C measured [O], $[N_2]$ and T_n. The aeronomic parameters at 250 km and 1600 LT used in calculations, are shown in Table 2.

Table 2. Aeronomic parameters at 250 km and 1600 LT used in the calculations.

Date	T_n *K*	*[O]* cm^{-3}	$[O_2]$ cm^{-3}	$[N_2]$ cm^{-3}	γ_1 $cm^{-3}\,s^{-1}$	γ_2 $cm^{-3}\,s^{-1}$	β s^{-1}
Jan 24	845	9,81 + 8	1,68 + 7	3,29 + 8	6,35-13	8,94-12	3,59-4
Jan 25	1.096	2,23 + 9	3,50 + 7	6,64 + 8	1,07-12	7,45-12	9,71-4

Scale heights of neutral gases and some other parameters at the height of hmF2 necessary for further discussion are shown in Table 3

Table 3. Scale heights of neutral gases and parameters at hmF2 height.

Date	*H(O)* *km*	$H(N_2)$ *km*	$[O]_{max}$ cm^{-3}	$[O_2]_{\mu\alpha\xi}$ cm^{-3}	$[N]_{\mu\alpha\xi}$ cm^{-3}	$(O/N_2)_{max}$	P_{max} *Pa*
Jan 24	48,4	27,7	1,11 + 9	2,15 + 7	4,09 + 8	2,71	1,80-4
Jan 25	62,8	35,9	1,00 + 9	7,12 + 6	1,65 + 8	6,06	1,77-4

Now we can write down the contribution of various terms in Eq (5) to Δlg NmF2 in Table 4.

Table 4. The contribution of various terms Eq. (5) to Δlg NmF2.

$4/3\Delta\lambda\gamma[O]$	$\angle 2/3\Delta lg\beta$	$1/2\Delta lgTn$	*Sum*	*ΔlgNmobs*	*Wind contr.*
0.476	–0,288	0,056	0,244	0,290	0,046

Apart from neutral composition and temperature changes, vertical plasma drift due to thermospheric wind may cause the NmF2 variations. The difference between $\Delta lgNm_{obs}$ and the sum of the contributions of [O], β and T_n equals 0.046 (see Table 4) and this may be ascribed to the vertical drift effect. According to Ivanov-Kholodny and Mikhailov (1986, formula (2.43)) this vertical drift contribution corresponds to $\Delta Vz = 5.1\ ms^{-1}$. This value can be checked using the observed $\Delta hmF2 = 56$ km and Eq.(4). From Eq.(4) it follows that the sum of the contributions of $\Delta[O]$, $\Delta\beta$ and ΔT_n to Δhm is equal 48 km. Thus the vertical drift contribution to Δhm equals 8 km and this corresponds to $\Delta Vz = 5.2\ ms^{-1}$ (Ivanov-Kholodny and Mikhailov, 1986, Eq.(2.44)). Therefor, ΔV_z derived from two expressions is self-consistent.

The survey of the results presented in Table 4 shows that atomic oxygen concentration variation contributes largely to the observed background ΔNmF2 increase i.e. it may be regarded as the main reason for the prolonged positive storm effect. The averaged daytime vertical drift contribution to this background NmF2 and hmF2 increase is rather small – about 10% in NmF2 and 8 km in hmF2. Therefor, our analysis confirms the suggestion by Rishbeth (1991) that atomic oxygen concentration increase provides the main contribution to the positive storm effect but only in the «nighttime» sector as in the «daytime« sector the mechanism is different (see below). On the other hand, the NmF2 surge after 1200 LT followed by a NmF2 downfall at 1500 LT results from TAD passage over Havana. The F2-layer is non-stationary during this period and cannot be analyzed with the help of the analytical approach described above. A non-stationary continuity equation numerical solution was derived to get an idea of real vertical drift variations. Observed hmF2 were fitted by Vz and resultant Vz daily variations are shown in Fig. 11 (lower graph). Observed NmF2 daily variations were used as an independent check for our Vz calculations.

Let us consider the European longitudinal sector («daytime» relative to the storm onset) where pronounced positive storm effects took place during the Jan 25, 1974 geomagnetic storm (Fig. 1). Unlike the midlatitude American sector these positive storm effects were not followed by negative disturbances during day-time hours (positive storm of type I).

Observed daily NmF2 and hmF2 (from ionogram reduction) for Jan 25 in comparison with quiet day of Jan 24 variations for Juliusruh observatory (54.6 N, 13.4 E, $\Phi_{inv} = 54.4$) are shown in Fig. 12. Atomic oxygen [O], molecular nitrogen $[N_2]$, as well as the $R(N_2/O)$ ratio observed by AE-C in the European sector at about 1500 LT on Jan 25, are shown on the right-hand side of Fig.12. Quiet-time MSIS-83 model variations are given as well. Such a comparison with MSIS-83 model is valid because ESRO-4 observations in the same longitudinal sector on Jan 22 (prestorm day) coincide with MSIS-83 model for quiet-time conditions (right-hand side of Fig.12, bottom box) Calculated by fitting model hmF2 to the observed ones vertical plasma drift daily variations are shown in Fig. 12 (bottom panel).

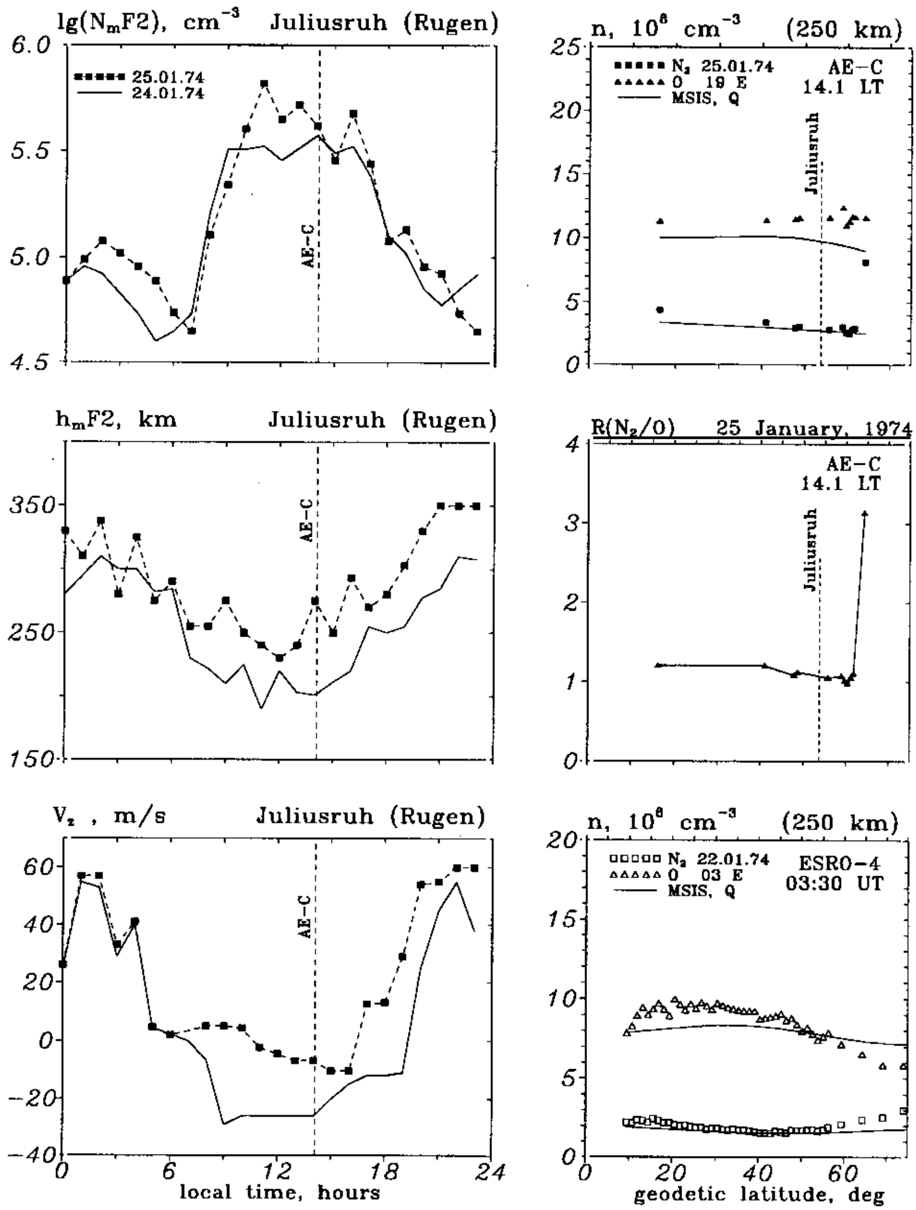

Figura 12. Observed log NmF2 and hmF2 variations for disturbed Jan 25 and quiet-time Jan 24, 1974 periods, along with calculated vertical plasma drifts for Juliusruh (left-hand side). Latitudinal variations of [O], [N_2] and R(N_2/O)storm/(N_2/O)quiet at 250 km measured by AE-C in the European sector on Jan 25. The bottom panel shows [O] and [N_2] concentrations measured by ESRO-4 on prestorm quiet day of Jan 22, 1974 in the same European sector compared to the quiet-time MSIS-83 model.

Unlike the American («nighttime») longitudinal sector, neutral composition perturbations turned out to be restricted to the higher latitude region (Prölss, 1995) as the storm onset took place in the day-time sector and no perturbation of neutral composition was observed at middle latitudes in Europe during sunlit hours (so called «forbidden time» for the negative storm onset, see above). The calculated vertical plasma drift is seen to become more positive just after the storm onset (about 0600 LT) for Jan 25 compared to quiet day of Jan 24, when we have the usual daily variations of wind pattern with poleward thermospheric wind during day-time hours. Therefor, on one hand, the background daytime (equator-to-pole) and storm-induced (pole-to-equator) thermospheric wind interaction results in disturbed neutral composition restricted to high latitudes. On the other hand, it decreases normal poleward meridional wind and makes vertical plasma drift more positive. This increased vertical plasma drift may be considered as the principal cause for the positive storm effect in the sunlit winter mid-latitude F2-region as the neutral composition remains unchanged.

There is an additional cause making easier the positive storm effect to occur in winter. Winter thermosphere is cold and the neutral scale height is small. So one and the same hmF2 displacement due to the vertical drift results in more NmF2 changes in winter compared to any other season as in winter the F2-layer turns out in the thermosphere with more abundant atomic oxygen. It may be shown that ΔlgNmF2/ΔVz is systematically higher in winter compared to summer in the whole range of plausible vertical plasma drifts Vz (see also Prölss, 1995).

7. DISCUSSION OF THE STORM MECHANISMS

Solar EUV ionizing flux, thermospheric neutral composition and winds are known to be the principal aeronomic parameters which control the daytime F2-region. The analysis of AE-C and ESRO-4 neutral composition data along with calculated meridional thermospheric wind for quiet-time and storm conditions, leads to the conclusion that the interaction of background thermospheric circulation (resulted from solar heating) and storm-induced circulation (due to high-latitude energy inputs) is the main physical process giving rise to the variety of storm effects in the mid- and lower latitude sunlit F2-region.

The mechanism of the F2-layer storm positive effect is different to some extent in the «nighttime» and «daytime» (relative to the storm onset) longitudinal sectors. The storm-induced (equatorward) thermospheric wind coincides with that of the background in the nighttime sector and disturbed neutral composition spreads far towards low latitudes. Upwelling and horizontal advection leads to $R(N_2/O)$ increase at high and middle latitudes, and this results in the negative storm effect during the following day. Downwelling at lower latitudes leads to an increase in [O] and $[N_2]$ absolute concentrations, while the $R(N_2/O)$ ratio remains practically unchanged at the heights of the F2-layer (Fig. 10). The absence of any noticeable $R(N_2/O)$ variation at lower latitudes, according to satellite observation and recent 3D model calculations (Förster et al., 1999; Rishbeth and Muller-Wodarg, 1999), was obviously the reason why neutral composition changes were not considered as a source of positive storm effect (Prölss, 1995). However, the theory of F2-layer formation gives different dependencies of NmF2 on [O] and $[N_2]$. The growth of atomic oxygen absolute concentration [O] (when $R(N_2/O)$ is unchanged at the heights of F2-region) does contribute to the positive storm effect appearance (see Table 4). The stability of the $R(N_2/O)$ ratio at lower latitudes implies the influence of some other processes apart from thermospheric expansion due to temperature increase (Mikhailov *et al.*,1997), and this was emphasized by Prölss (1982). The downwelling motion of atomic oxygen is the most probable process.

It is important to emphasize that the increase of absolute atomic oxygen concentration (low-latitude case) provides only a background NmF2 increase. Additional effects are related to the equatorward thermospheric wind changes. Strong NmF2 and hmF2 variations observed in 1200-1600 LT (Fig. 11) are caused by TAD passage resulting in vertical drift changes up to (20-30 ms^{-1}. This TAD was launched by enhanced auroral heating (AE -index upsurge around 1700 UT, Fig. 9) and its passage is seen on other American ionosonde stations, e.g. Boulder (Fig. 1). Apart from such TADs effects (Prölss, 1995) a general (background) increase of storm induced equatorward wind exists. According to our model estimates, this results in (Vz of about 5 ms^{-1} for the disturbed day of Jan 25. This vertical drift averaged over day-time hours also contributes to the positive NmF2 effect, but the contribution is fairly small compared to the Δ[O] effect.

Such small vertical drift allows the F2-region isobaric concept by Rishbeth and Edwards (1989) to be efficient in this case. Gas pressure does not practically change at hmF2 (see Table 3). The isobaric concept allows to estimate NmF2 variations (when vertical drifts are small), but it says nothing about the contribution of various aeronomic parameters to these NmF2 variations. Indeed, atomic oxygen concentration did not change at the hmF2 (see Table 3) and one may conclude that the atomic oxygen production rate did not change also (see Eq. (1)). Thus, observed NmF2 increase was due to the loss rate decrease as $[N_2]$ decreased at hmF2 (see Table 3). In fact, this is not so, as the thermosphere enrichment with atomic oxygen is the main reason for the positive storm effect and this is clearly shown by our calculations (see Table 4) .

All our estimates were made assuming the validity of barometric law, while downwelling results in a non-barometric height distribution for atomic oxygen. Indeed, only in this case, $R(N_2/O)$ may be unchanged in a wide range of heights. An estimate of the downwelling on atomic oxygen height distribution (Mikhailov *et al.*, 1997) shows that we may expect an additional 25-35% increase in [O]. Thus the conclusion regarding the leading role of atomic oxygen in positive storm effects will only be enforced. On the other hand, the winter midldtitude F2-layer positive storm effect in the «daytime» sector results only from vertical plasma drift changes, as [O] and [N_2] absolute concentrations remain unchanged.

According to Zevakina and Kiseleva (1978) midlatitude positive disturbances are more probable at low magnetic activity. This is clear, as the background thermospheric circulation turns out to be a little dampened by moderate auroral heating, but not reversed. In this case, we have no changes of neutral composition at middle latitudes but increased vertical plasma drift only – the situation is similar to that for the Jan 25 1974 storm in the European sector (Fig. 12). When geomagnetic activity (and auroral heating) elevates, the area of increased N_2/O ratio spreads further to the equator and negative NmF2 disturbances appear at middle latitudes, while the area of positive NmF2 perturbations shifts to lower latitudes. The nighttime sector with pole-to-equator background thremospheric wind, as well as summer season conditions when daytime poleward thermospheric wind is weakened, are preferable for such a spread of increased N_2/O ratio towards lower latitudes (e.g. Prölss and von Zahn, 1977) .

Thus the mechanism of interaction between background (solar-driven) and storm-induced (due to high-latitude energy inputs) thermospheric circulation with subsequent changes in neutral composition and temperature enables to understand the main morphological features of daytime midlatitude F2-layer storm effects.

With regard to the nighttime F2-layer the situation looks more complicated because additional processes are involved. Nighttime F2-layer is lifted by the solar-driven equatorward meridional thermospheric wind high enough from the region of strong recombination. The characteristic time of NmF2 changes with respect to recombination ($\tau_{chem} \approx 1/\beta_{max}$) is more than 10 h and NmF2 is not very sensitive to changes in neutral composition. Therefor, additional storm-induced pole-to-equator thermospheric wind carrying perturbed neutral composition may result in further hmF2 increase only without noticeable changes in NmF2. Only in the morning when vertical plasma drift (related to the equatorward meridional wind) decreases, the F2-layer shifts down and plunges into the disturbed neutral composition with high N_2/O ratio. The recombination rate increases resulting in the negative F2-layer storm effect usually observed in the early morning hours (Prölss and von Zahn, 1978).

Nighttime NmF2 variations mainly result from the balance between plasma influx from the plasmaspheric tube of force and recombination. Variations in plasmaspheric flux may result in large NmF2 night-to night changes (up to factor of 7) even in quiet geomagnetic conditions (Mikhailov and Förster, 1999). Such strong NmF2 variations are comparable with severe F2-layer storm effects. Plasmaspheric fluxes are controlled by many processes and plasma compression (decompression) in a magnetic tube of force under the action of ExB drift is one of the them. Therefor, nighttime F2-layer storm mechanisms require further considerations.

8. F2-LAYER STORMS AT GEOMAGNETIC EQUATOR

A survey of ionospheric storms in the equatorial F2-region for the period of one solar cycle (Adeniyi, 1986) shows that the positive disturbances predominate (about 90% of all the cases) during the main and recovery phases of the geomagnetic storms. Positive F2-layer storm effects prevalence during geomagnetic disturbed periods was mentioned in (Matuura, 1972; Chandra *et al.*, 1973; Sharma and Hewens, 1976; Rajaram, 1977). However negative F2-layer storm effects may take place during severe magnetic storms (Kane, 1973; Turunen and Rao, 1980; Adeniyi, 1986) .

The formation of equatorial F2-layer is known to be under strong control of ExB drift and many morphological features of the F2-layer are related to zonal Ey electric field variations. Electric field observations in American (Fejer, 1981, 1991) as well as in Indian sectors (Viswanathan *et al.*, 1987; Namboothiri *et al.*, 1989; Scherliess and Fejer, 1997) show the decrease of eastward (during sunlit hours) electric field Ey resulting in positive foF2 storm effect. Negative F2-layer storm effect is usually attributed to the enhancement in the eastward Ey resulting in the increased plasma uplift from the equatorial F2-layer, NmF2 decrease and the equatorial anomaly enhancement (Raghavarao and Sivaraman, 1973; Turunen and Rao, 1980; Adeniyi, 1986). A special case of negative F2-layer storm effect caused by strong downward plasma drift (westward Ey) is considered by Mikhailov and Leschinskaya (1991). Thus equatorial F2-layer disturbances are supposed to be caused by electric field variations. Meanwhile neutral gas composition changes take place in the equatorial F2-region during geomagnetic disturbances as well (Prölss, 1982, Prölss, 1993b) and they may contribute to the F2-layer storm effect as it was shown by Mikhailov *et al.* (1994). To estimate the effects of electric field and neutral composition variations three disturbed days of Sep 15,16 and 23, 1973 were chosen for the analysis. These days were marked by pronounced F2-layer disturbances at equatorial ionosonde station Huancayo (12 S, 284.7 E) and ESRO-4 measurements were available in the American longitudinal sector as well. Moderate geomagnetic disturbances with AE up to 600 nT and Dst down to –30 nT took place on Sep 15 and 16 while stronger geomagnetic variations with AE up to 1500 nT and Dst down to –60 nT were registered on Sep 23. Figure 13 shows observed and monthly median foF2 variations for three days in question as well as hmF2 derived from M(3000)F2 parameter. Pronounced, stable negative (–2MHz on Sep 15) and positive (+3 MHz on Sep 16) foF2 storm effects took place during sunlit hours. Sept 23 gives a different type of variations with a pronounced positive foF2 effect before noon followed by a sharp foF2 decrease afternoon.

A theoretical model by Leschinskaya and Mikhailov (1984) was used in the calculations. It was shown that a simple form of the electron concentration continuity equation could be used in the vicinity of geomagnetic equator to describe the electron density distribution

$$\frac{\partial n}{\partial t}+\left(\frac{2D_a}{r}+V_z\right)\frac{\partial n}{\partial r}+\left\{\frac{2D_a}{r}\left(\frac{\partial lnT_e}{\partial r}+\frac{1}{H}\right)+\frac{6V_z}{r}+\beta\right\}n=q \qquad (6)$$

where n – electron concentration equals to [O^+], D_a – ambipolar diffusion coefficient; r – geocentric distance; V_z – vertical E x B plasma drift; Te – electron temperature; H – plasma scale height; β – loss linear coefficient; q – EUV ionization rate.

The MSIS-83 model neutral concentrations used in calculations were normalized by those measured by ESRO-4 and the vertical plasma drift, Vz is the only unknown parameter which can be found provided that the observed NmF2 and hmF2 are specified. The calculated vertical drifts for three days are shown in Fig.13. The results of calculations may be analyzed with the help of an analytical expression resulted from the analysis of the continuity equation (6) numerical solution (Leschinskaya and Mikhailov, 1985)

$$\Delta \lg NmF2 = 1.0\Delta \lg[O] - 0.48\Delta \lg\beta - 7.75*10^{-2}\Delta\sqrt{V_z} + \lg\frac{I_1}{I_2} \qquad (7)$$

where [O] and $\beta = \gamma_1[N_2] + \gamma_2[O_2]$ are specified at any fixed height (e.g. 400 km), Vz (m s^{-1}, positive upward) and I – EUV solar flux. All necessary aeronomic parameters used in calculations as well as quantitative contribution of various terms of Eq. (7) to ΔlgNmF2 are listed in Tables 5 and 6. The most stationary period of the day around 14 LT was chosen for the analysis of Sep 15, 16 and 11 LT (just before foF2 drop, Fig. 13) for Sep 23.

Table 6 shows that neutral composition changes may provide a major contribution to the observed ΔNmF2 variations, for example on Sep 23. Vertical

Table 5. Aeronomic parameters at 400 km used in the calculations.

Date	*lg[O], cm^{-3}*	*lgβ, s^{-1}*	*V_z, m s^{-1}*
Ref. day, 14 LT	7,87	–5,42	13
Sep. 15, 14 LT	7,87	–5,46	35
Sep. 16, 14 LT	8,01	–5,27	1
Ref. day, 11 LT	7,77	–5,76	18
Sep. 23, 11 LT	8,08	–5,39	15

Table 6. The contribution of various terms (7) to ΔlgNmF2

Date	*Sep. 15*	*Sep. 16*	*Sep. 23*
1,0Δlg[O]	0,0	0,14	0,31
–0,48Δlgβ	0,02	–0,07	–0,17
$-7{,}75 * 10^{-2}\Delta\sqrt{V_z}$	–0,18	0,20	0,03
$\lg I/I_{ref}$	0,0	0,0	0,04
ΔlgNm	–0,16	0,27	0,21
ΔlgNm (obs)	–0,16	0,27	0,23

plasma drift, however, is the main reason of the observed negative storm effect of Sep 15 and positive effect on Sep 16. Surely sharp changes of the vertical drift after 12 LT on Sep 23 is the reason for the observed afternoon foF2 fall. It should be mentioned that essential atomic oxygen positive contribution turns out to be compensated by half due to $[N_2]$ concentration increase resulting in the loss process enhancement.

The calculated vertical drifts (Fig.13) are quite different for three days in question. There is a strong upward Vz of about 40 m s^{-1} (Ey = 1 mVm^{-1}) on Sep 15 which is more than twice that the quiet time Vz. Irregular variations of Vz around zero take place on Sep 16 and V_z is close to quiet time variations before noon followed by a sharp upsurge of Vz up to 60 m s^{-1} (1.5 mVm^{-1}) at 13 LT on Sep 23.

The reality of calculated drifts is confirmed by vertical drifts measurements at Jicamarca incoherent back-scatter facility and by ground-based magnetic field observations as well. According to (Fejer, 1981,1991; Scherliess and Fejer, 1999) equinoctial quiet daytime (14 LT) vertical drift is about 13 ms^{-1} at low level of solar activity and it may reach 60 – 70 ms^{-1} during disturbed periods (Woodman, 1970; Woodman *et al.*, 1972) .

The observed ground-based H-component magnetic field variations may serve as an independent check of the calculated vertical F2-layer drifts because of close relation between electric fields in the equatorial E and F2 ionospheric regions (Balsley and Woodman, 1969; Fejer *et al.*, 1976; Vikramkumar *et al.*, 1987). Such an analysis of ΔH variations was made for three days in question by Mikhailov *et al.*, (1994) and ΔH relative variations were shown to be close to the calculated variations in Vz.

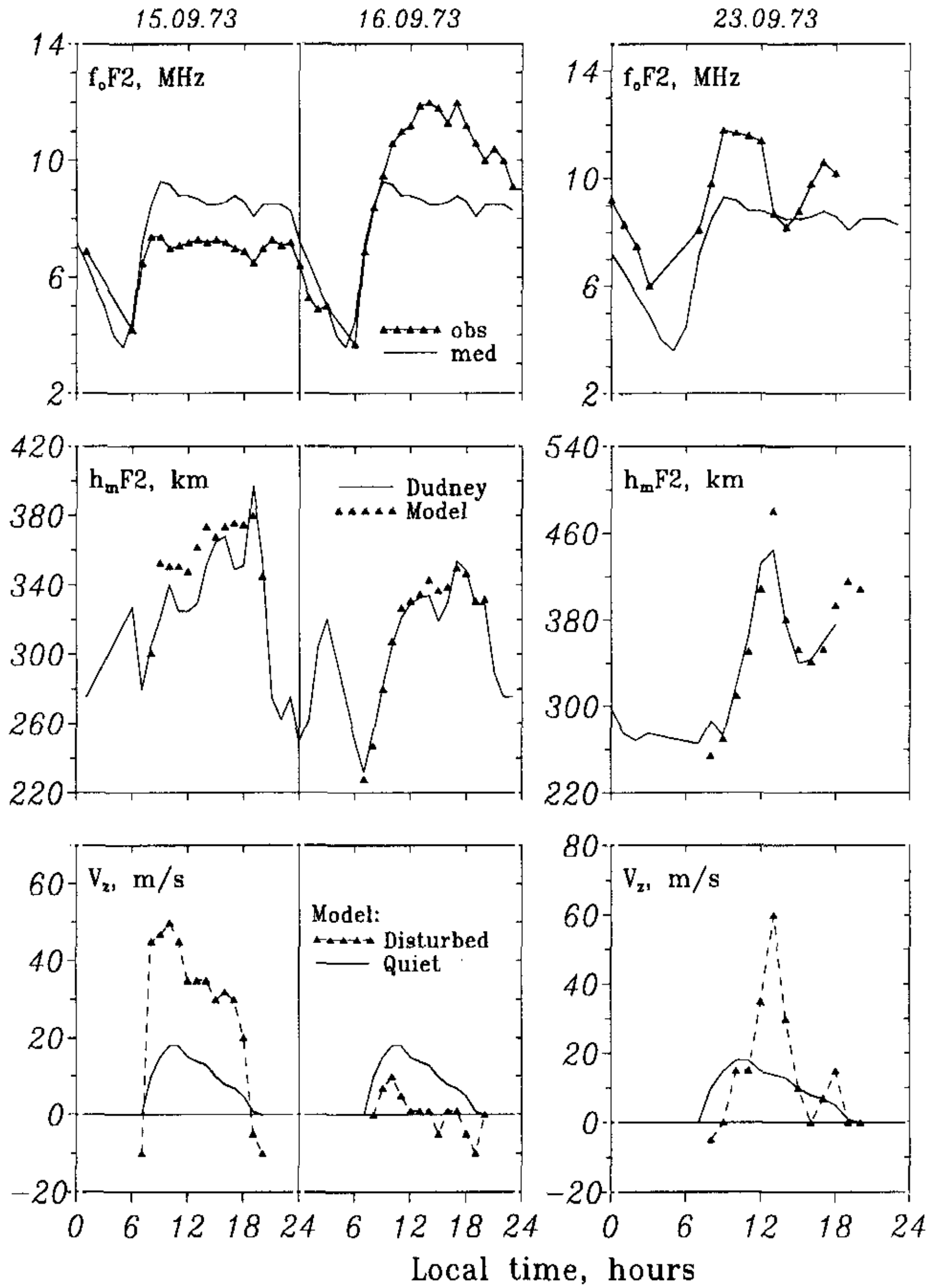

Figura 13. Observed foF2 and calculated hmF2 variations together with calculated vertical drifts. Monthly median foF2 (solid line) and Vz quiet-time variations are shown for comparison.

Usually equatorial F2-layer disturbances are related as mentioned above to the ExB drift variations since storm neutral composition changes are not that impressive as at high and middle latitudes. Besides, O/N_2 ratio (which is believed to define NmF2) practically does not change at lower latitudes during storm periods (see above). According to a theory of the equatorial F2-layer formation the NmF2 dependence on [O] and $[N_2]$ is different (see Eq.(7)) resulting in a positive NmF2 storm effect despite unchanged O/N_2 ratio similar to mid-latitude F2-region (see above). However half of this [O] positive effect is compensated by $[N_2]$ increase resulting in loss process enhancement (Table 6).

Let us consider ExB vertical drift effects. Observations of day-time vertical plasma drifts and F2-layer parameter variations in American (Fejer, 1981,1991) and Indian (Chandra, 1973; Rajaram, 1977; Viswanathan *et al.,* 1987) equatorial ionosphere show that as a rule, the usual eastward Ey electric field decreases during storm periods. The decrease of upward plasma drift results in NmF2 increase, day-time «bite-out» and equatorial anomaly disappearance (Rajaram, 1977; Alex *et al.,* 1988). Thus the decrease of regular eastward Ey is an effective mechanism of the positive F2-layer storm effect which is clearly seen in Figure 13 for Sep 16. An increase of the eastward Ey, resulting in negative storm effects, is usually observed during severe magnetic storms (Raghavarao and Sivaraman, 1973; Turunen and Rao, 1980; Adeniyi, 1986). Figure 13 demonstrates such an effect for the afternoon hours on Sep 23. But the same mechanism may work at low level of magnetic activity as shown in Fig. 13 for Sep 15.

The equatorial zonal Ey electric field and vertical plasma drifts are known to be closely related to B_z component of interplanetary magnetic field (IMF) variations (Reddy *et al.,* 1979; Gonzales *et al.,* 1979; Sastry, 1988; Deminov and Deminova, 1988; Fejer, 1991; Mikhailov *et al.,* 1996). Zonal westward electric field perturbations during day-time hours are often associated with rapid northward changes of IMF (Fejer, 1991). The case we have after 15 UT on Sep 16 and after 13 UT on Sep 23 (Fig.13). Eastward Ey perturbations are associated with sudden increases in convection (southward turning of Bz). This takes place during day-time hours on September 15 and around 17 UT on Sep 23. Close relation between AE-index and changes of Bz component was demonstrated by Kane (1974). The reversal of Bz from northward to southward is a necessary and sufficient condition for AE changes (Kane, 1974; Mikhailov *et al.,* 1996). Thus Bz of IMF and AE index variations may be useful for the equatorial F2-layer storm effects explanation.

Summarizing the results of the analysis one may conclude that generally vertical ExB plasma drift defines the type (positive or negative) of NmF2 storm effect. Negative NmF2 perturbations usually are caused by increased vertical (upward) drifts (eastward Ey increase). Ionospheric plasma is uplifted by this drift from the F2-region, then drifts along the magnetic field lines apart from the geomagnetic equator (so called fountain effect). Neutral composition changes observed at equatorial latitudes are insufficient to produce negative NmF2 disturbances. A very strong downward drift (westward Ey) also may result in negative NmF2 effect (Mikhailov and Leschinskaya, 1991) when F2-layer is pushed down to lower height where recombination is strong.

Usually, a decrease of the upward drift or moderate downward drifts carrying plasma from the topside to the F2-layer maximum result in a positive NmF2 effect. Atomic oxygen [O] concentration increase observed in the equatorial thermosphere during magnetically disturbed periods may essentially contribute to the positive NmF2 storm effect provided that vertical drift variations are small.

9. CONCLUSIONS

Ionospheric F2-layer storms is a very interesting and challenging global scale upper atmospheric phenomenon being studded for more than 60 years since its discovery. An obvious progress has been achieved for the last decades in understanding the physical processes responsible for many F2-layer storm effects. Ground-base ionosonde and incoherent scatter ionospheric observations, satellite measurements of neutral atmosphere parameters along with 1-3D theoretical modelling of the coupled thermosphere-ionosphere system enable to establish a hierarchy in a long list of processes contributing to the F2-layer storm effects. Neutral composition changes with decreased [O] and increased [N_2] and [O_2] along with enhanced T_n are believed to be the main reason of the midlatitude F2-region negative storm effect. These perturbations of the thermospheric parameters result from changes in the thermosphere global circulation caused by high-latitude energy inputs (Joule heating and particle precipitations) during geomagnetically disturbed periods. This mechanism based on the interaction of background (solar-driven) and storm-induced thermospheric circulation systems enables to explain the main negative storm features: latitudinal and longitudinal dependence, seasonal and local variations (Field *et al.*, 1998). The other effects related to vibrationally excited N_2, electric fields, plasmaspheric fluxes etc. are not that important at midlatitudes during daytime and easily may be compensated in model calculations by additional small changes in neutral composition.

Situation with the midlatitude positive storm effect is not that clear. The main question concerns the increased [O] and the storm-induced equatorward thermospheric wind contributions to the daytime F2-layer positive storm effect. According to Rishbeth (1991) the [O] increase provides the main contribution to effect while Prölss (1993b,1995) supposes that TADs and the equatorward thermospheric wind are the main reason of the F2-region positive perturbations. Our analysis shows that both processes may be responsible for the observed storm effects depending which longitudinal sector («nighttime» or «daytime» with respect to the storm onset) we consider. Such longitudinal differences may be successfully explained in the framework of the same disturbed global circulation mechanism.

There is still a problem with the nighttime positive storm effect. Additional processes such as an increased plasmaspheric influx due to plasma compression (Mikhailov and F(rster, 1999) may turn out to be important. According to this mechanism very strong night-to night NmF2 variations are observed even in quiet geomagnetic conditions. Future investigations should also include the F2-region perturbations related to meteorological phenomena (thunderstorms, strong cloudiness, atmospheric fronts etc.).

Equatorial F2-region mainly is controlled by ExB plasma drifts (Ey component of the electric field) related to IMF and high-latitude electric field variations. Therefor, strong NmF2 variations are not necessary related to geomagnetic disturbances. Negative NmF2 perturbations may be caused both by upward ExB drift increase due to plasma outflow from the F2-region and by strong downward drifts resulting in the recombination rate increase at lower heights. The effects of neutral composition changes are not very strong, but an increase in [O] may contribute to the positive storm effect when ExB drifts are small. On the other hand, negative NmF2 perturbations are not related to neutral composition changes.

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