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Day-to-day thermosphere parameter variation as deduced from Millstone Hill incoherent scatter radar observations during March 16-22, 1990 magnetic storm period

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Abstract. A self-consistent method for day-time F2-region modelling was applied to the analysis of Millstone Hill incoherent scatter observations during the storm period of March 16-22, 1990. The method allows us to calculate in a self-consistent way neutral composition, temperature and meridional wind as well as the ionized species height distribution. Theoretically calculated N_e(h) profiles fit the observed daytime ones with great accuracy in the whole range of heights above 150 km for both quiet and disturbed days. The overall increase in T_{ex} by 270 K from March 16 to March 22 reflects the increase of solar activity level during the period in question. A 30% decrease in [O] and a two-fold increase in [N_2] are calculated for the disturbed day of March 22 relative to quiet time prestorm conditions. Only a small reaction to the first geomagnetic disturbance on March 18 and the initial phase of the second storm on March 20 was found in [O] and [N_2] variations. The meridional neutral wind inferred from plasma vertical drift clearly demonstrates the dependence on the geomagnetic activity level being more equatorward on disturbed days. Small positive F2-layer storm effects on March 18 and 20 are totally attributed to the decrease in the northward neutral wind but not to changes in neutral composition. A moderate (by a factor of 1.5) O/N_2 ratio decrease relative to the MSIS-83 model prediction is required to describe the observed N_mF2 decrease on the most disturbed day of March 22, but virtually no change of this ratio is needed for March 21.

Introduction

Ionospheric F2-layer storm effects related to geomagnetic disturbances have been studied for some decades because of their great practical importance for HF radio communication. The temporal, as well as spatial, storm effect's appearance is dependent on the intensity of geomagnetic disturbance, local and universal time of SSC, season, latitude and longitude of the observational point. Incoherent scatter observations along with F2-layer theoretical modelling provide an excellent opportunity for an F2-layer storm effect analysis and this is being conducted by scientists in the framework of the CEDAR program. Periods of low (Richards *et al.*, 1989) and high (Buonsanto *et al.*, 1992a; Richards *et al.*, 1994b) solar activity were analyzed using Millstone Hill radar observations.

A 7-day interval of continuous observations in March 16-23, 1990 (high solar activity) comprises quiet (March 16-17) as well as highly disturbed (March 18, 20, 21) periods with $A_p = 76$ on March 21. A comprehensive description of that observational interval and its theoretical interpretation is given in Buonsanto *et al.* (1992a) for the American sector with Millstone Hill data and in Förster *et al.* (1992) for the European sector with EISCAT and satellite data of the 'Active' experiment.

Millstone Hill radar overhead observations provide $N_e(h)$, $T_e(h)$, $T_i(h)$, and $V_z(h)$ values, which can be used for a comparison with theoretical model calculations. Such comparisons were conducted for September 1984 (Richards *et al.*, 1989) and March 1990 (Richards *et al.*, 1994b) disturbed periods. Despite the fact that rather sophisticated theoretical models were used in these analyses they failed to describe the observed negative phase of ionospheric storms. Taking into account vibrationally excited N_2^*, which in some publications (Richards *et al.*, 1989; Pavlov, 1994) is considered as a plausible mechanism for the F2-layer negative storm effect, did not help for the periods in question. The FLIP model (Richards *et al.*, 1994a, c) did not reproduce the observed factor of a 1.7 decrease in the day-time electron density for the September 1984 storm period (Richards *et al.*, 1989) and factor of 4 in the day-time N_mF2 decrease for the March 1990 disturbance (Richards *et al.*, 1994b). Although taking into account N_2^*

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effects gets closer than the calculated N_mF2 to the observed ones for the disturbed days during daytime hours, the difference still remains large for the most disturbed day of March 22 and the inclusion of N_2^* makes the overall agreement between calculated and observed N_mF2 for the quiet days of March 18-20 even worse. So, it was stressed that the inclusion of vibrationally excited N_2^* actually worsens the agreement between modelling and observations (Richards *et al.*, 1994b). The same conclusion concerning the worsening effect of including vibrationally excited N_2^* into model calculations was obtained by Richards *et al.* (1994c) for Millstone Hill data analysis during the period of solar maximum. On the other hand, Pavlov and Buonsanto (1997) put the stress on the importance of taking into account vibrationally excited N_2^* to model the March 16-23 and April 6-12, 1990 disturbed periods.

The main obstacle to obtaining a satisfactory theoretical model description for the F2-layer negative storm effect consists in the proper choice of thermospheric parameters. All mentioned theoretical calculations are based on the empirical (i.e. statistical) MSIS-86 (Hedin, 1987) thermospheric model, which is not designed for the description of specific helio-geophysical conditions for a given day and especially during disturbed periods although first-order geomagnetic activity effects are included in MSIS models. A factor of 3 to 5 decrease in the atomic oxygen density to molecular density ratio at 300 km was needed to explain the observed decrease in electron density for the September 1984 storm period (Richards *et al.*, 1989. The MSIS-86 neutral composition predictions for the severe storm on March 20-21, 1990 turned out to be insufficient to explain a factor of 4 depletion in the observed day-time N_mF2 values. The studies conducted by Richards *et al.* (1994b) and Buonsanto (1995) indicate that successful modelling of F2-layer storms requires a better definition of the storm time inputs, especially of the neutral atmosphere.

On the other hand, neutral composition and temperature as well as vertical plasma drift, i.e. the main aeronomic parameters responsible for $N_e(h)$ distribution in the F-region, may be obtained from radar observations. These observed ionospheric parameters will allow us to describe the observed $N_e(h)$ height profile for the conditions in question with the best accuracy. It is not a new idea to use ionospheric, in particular incoherent scatter data, for the extraction of thermospheric parameters. Incoherent scatter measurements provide an excellent material for such estimates and they have been widely used for this purpose for years (Salah *et al.*, 1974; Alcayde *et al.*, 1974; Evans *et al.*, 1979; Alcayde, 1979; Oliver, 1979, 1980, 1990; Ganguly *et al.*, 1980; Alcayde and Fontanari, 1982; Lathuillere *et al.*, 1983; Hagan and Oliver, 1985; Flå *et al.*, 1986; Alcayde and Fontanari, 1986; Burnside *et al.*, 1988; 1991b Belley *et al.*, 1992; Buonsanto *et al.*, 1992b; Oliver and Glotfelty, 1996).

The general approach is based on the use of the ion energy conservation equation in the F-region. This approach can provide valuable information on neutral temperature, atomic oxygen concentration and thermospheric winds. This method however, is not straightforward. Experimental T_i, T_e and to less extent N_e depend upon the assumed model of ion composition. Usually it is presumed to be unchanged (at Millstone Hill and EISCAT, for instance) for various geophysical conditions and this should result in errors in experimental T_i and T_e values (Waldteufel, 1971; Lathuillere *et al.*, 1983; Kirkwood *et al.*, 1986; Winser *et al.*, 1990; Glatthor and Hernandez, 1990) which are used to produce the energy equation solution. Further, the energy equation usually is considered for O^+ ions in an atmosphere consisting of atomic oxygen only (Alcayde and Fontanari, 1982; Burnside *et al.*, 1988), or the whole neutral composition is taken from an empirical model (Alcayde and Fontanari, 1986; Winser *et al.*, 1988; Glatthor and Hernandez, 1990). However, it is well known that ion composition changes with season and during geomagnetically disturbed periods. Neutral composition may differ from the empirical model predictions for the particular day chosen for the analysis. Nevertheless this approach is widely accepted and, for instance, such popular thermospheric models as the MSIS series are based on neutral temperature derived with the help of this method.

In our self-consistent approach (Mikhailov and Schlegel, 1997) we rely on N_e(h) height distribution as the most reliable parameter measured by the incoherent back-scatter facility to deduce thermospheric data. The traditional approach based on the ion energy conservation equation is used as well as a part of the method to find the area of possible inverse problem solution. Then this solution can be specified with the help of standard multiregressional methods. The method allows us to obtain, in a self-consistent way, such important thermospheric parameters as: concentrations of atomic [O] and molecular [O_2] oxygen, molecular nitrogen [N_2], vertical plasma drift W, exospheric temperature T_{ex} and shape parameter S for the T_n height profile. It provides as well the O^+ ions flux in the topside F2-region as a result of the continuity equation solution. All these aeronomic parameters enable us to understand the physical reason for the observed F2-layer parameter changes in a particular geophysical situation.

The aim of this study is to analyze Millstone Hill daytime $N_e(h)$, $T_e(h)$, $T_i(h)$, $V_z(h)$ observations and to estimate the main aeronomic parameters for the March 16-22, 1990 storm period. We will discover the reason for observed positive and negative F2-layer storm effects in the course of the period in question. As the method of calculation is supposed to deal with a stationary F2-layer, only periods of relative stability in N_mF2 and h_mF2 variations around noon hours are analyzed.

Method

The self-consistent method of Mikhailov and Schlegel (1997) uses a standard set of incoherent scatter radar measured parameters and an F-region theoretical model to calculate the main aeronomic parameters responsible for the formation of $N_e(h)$ profile at F-region heights for daytime conditions. Unlike other similar methods the present one allows us to obtain neutral composition, temperature and vertical plasma drift in a self-consistent way.

The theoretical model of the mid-latitude F-region used in this method is described by Förster *et al.* (1995). It takes into account transport processes for $O^+(^4S)$ and photo-chemical processes only for $O^+(^2D)$, $O^+(^2P)$, $O_2^+(X^2\Pi)$, $N_2{}^+$ and NO^+ ions in the 120-620 km height range. Vibrationally excited N_2 effects are not taken into account explicitly in the model but the McFarland *et al.* (1973) $O^+ + N_2$ reaction rate is presumed to mimic the increase of this reaction rate due to $N_2{}^*$ at high level of solar activity (Ivanov-Kholodny and Mikhailov, 1986). Observed electron concentration at 620 km is used as the upper boundary condition to solve the continuity equation for $O^+(^4S)$. At the lower boundary of 120 km the $O^+(^4S)$ is supposed to be in a photo-chemical equilibrium. Experimental T_e(h) and T_i(h) profiles are used in the calculations.

Line-of-sight plasma velocity, VO is obtained from 80°-90° elevation angles and may be considered as total vertical plasma velocity, $V_z(h)$. It includes the effects of thermospheric winds, electric field and plasma diffusion. These $V_z(h)$ values should be "chirp corrected" before being used in calculations. The "chirp correction" is different for different experiments and equals −11 m/s for the March 16-22 period. Vertical plasma drift W is obtained from $V_z(h)$ with the help of the expression (19.59) from Banks and Kockarts (1973)

$$W = V_z + \frac{k}{m_i \sum v_{ij}} \sin^2 I \left(T_i \frac{\partial \ln N_i}{\partial h} + T_e \frac{\partial \ln N_e}{\partial h} + \frac{g m_i}{k} + \frac{\partial (T_e + T_i)}{\partial h} \right) \quad (1)$$

where I is the magnetic field line inclination, m_i - the O^+ ion mass, T_i and T_e-ion and electron temperatures, N_i and N_e-ion O^+ and electron concentrations, v_i - diffusion collision frequencies for O^+ related to momentum transfer collision frequencies v^* by the expression (see Eq. 19.13 in Banks and Kockarts, 1973) $v_{ij} = m_j/(m_i + m_j) v^*_{ij}$ where i applies to O^+ ions and j applies to other neutral or ionized gas species. Collisions of O^+ ions with neutral O, O_2, N_2 and NO^+, O_2^+, $N_2{}^+$, N^+ ions are taken into account. All O^+ ion collision frequencies have been taken from Banks and Kockarts (1973). After subtraction of $V_{\perp N}$, which is the ion velocity component northward and perpendicular to the magnetic field due to $\mathbf{E} \times \mathbf{B}$ drift, the vertical plasma drift W can be exclusively attributed to the effects of thermospheric wind.

The temperature and concentrations of neutrals as well as the vertical plasma drift W are calculated in a self-consistent way in the N_e(h) fitting procedure. So, T_n, [O], [O_2], [N_2] and W are known at each step in order to solve the continuity equation for O^+ and the chemical balance equations for the other ions.

Likewise any non-linear multi-parametric inverse problem solution, the N_e(h) fitting procedure exhibits many local minima for $\Delta = [\log(N_e(h)_{\text{obs}}/N_e(h)_{\text{cal}})]^2$ corresponding to pseudo-solutions and the problem is to choose one of them using additional physical constraints. The standard multi-regressional methods turn out to be inefficient to minimize Δ for the problem in question and a two-step procedure was developed to localize the minimum. When, after the first step, its approximate position is found then the standard methods may be applied to specify the final values for the parameters.

The first step is based on the use of the ion energy conservation equation in the F-region to find T_{ex}. This is a widely used approach (see references cited in the Introduction). The only difference is that [O], [O_2], and [N_2] used for O^+, NO^+ and O_2^+ collision frequencies calculation are taken in a self-consistent way rather than from empirical models. Taking into account the molecular ions may be important for disturbed periods when their contribution becomes essential even at heights of the F2-region. According to Banks and Kockarts (1973) the ion energy conservation equation may be written as follows:

$$L_{\text{ei}} + Q_{\text{in}} = 0 \quad (2)$$

with

$$L_{\text{ei}} = 3k(T_e - T_i) \sum_{i=1}^{3} N_i v_{\text{ie}}$$

$$Q_{\text{in}} = \sum_{i=1}^{3} \sum_{n=1}^{3} 3k \frac{m_i N_i v_{\text{in}}}{(m_i + m_n)} \left[(T_n - T_i) + \frac{m_n}{3k} (\vec{C_i} - \vec{C_n})^2 \right]$$

where: $\vec{C_i}$ and $\vec{C_n}$ are the ion and neutral velocity vectors, all other symbols are standard. The equation is solved in the 250-400 km height range to find the neutral temperature T_n at each height step. These T_n values are then used to calculate T_{ex} with the help of Bates (1959) expression:

$$T_{\text{ex}} = \frac{T_n - T_{120} \exp[-S(h - h_0)]}{1 - \exp[-S(h - h_0)]} \quad (3)$$

where T_{120} is the neutral temperature at $z_0 = 120$ km taken from the MSIS-83 model (Hedin, 1983). The resultant T_{ex} is the average of all T_{ex} obtained in the 250-400 km height range. The frictional term can be considered as negligible, as long as relative drifts of ions with respect to the neutrals are smaller than about 300 m/s as this gives an error in T_n calculation less than 60 K (Alcayde and Fontanari, 1986). Such an accuracy is, in principle, quite sufficient for the first step of solution finding. On the other hand, daytime electric fields were small for the period in question (Buonsanto *et al.*, 1992a), so the frictional term was ignored in Eq (2). The first step of Δ minimization gives the area of possible T_{ex}, S, [O], [O_2], [N_2] values, which are finally specified at the second step using a standard multi-regressional method with physical constraints on the parameters.

Observations and calculations

The list of periods along with solar and magnetic indices used in the study is given in Table 1.

The regime of observations provides about three overhead height N_e, T_e, T_i and V_z profiles per hour for the

Table 1. List of time intervals of the March 1990 storm period used in the study. The three month average solar 10.7–cm flux was $\overline{F_{10.7}} = 184.1 \times 10^{-22} Wm^{-2}Hz^{-1}$.

Date	Time (UT)	A_p (daily)	$F_{10.7}$ (day/day–1)
1990			
Mar 16	18.0 – 21.0	7	179.9 / 166.0
Mar 17	17.3 – 20.5	3	183.8 / 179.9
Mar 18	16.5 – 19.5	35	198.2 / 183.8
Mar 19	16.5 – 19.5	16	218.2 / 198.2
Mar 20	16.5 – 19.5	30	225.7 / 218.2
Mar 21	17.3 – 18.9	76	229.3 / 225.7
Mar 22	18.4 – 20.0	28	244.7 / 229.3

period in question, so we use at least a two-three hour period of observation (about 8-10 profiles) around the noon hours to calculate median profiles along with the standard deviations at each height. Of course, such a 3 h time interval for averaging is too long keeping in mind the 1.5 h characteristic time for the F2-layer maximum. But the scatter of the observed parameters is large for the disturbed days, so whenever possible we tried not to use shorter time intervals to produce more or less reliable profiles. These median vertical profiles are then smoothed by a polynom up to the 5th degree before being used in the model calculations.

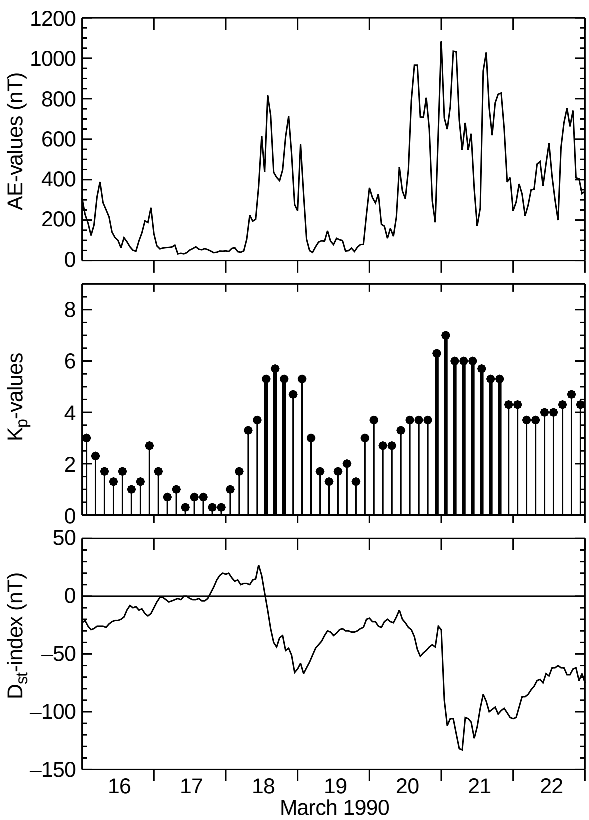

Fig. 1. Observed provisional AE, K_p, and D_{st} indices variation versus universal time for the analyzed period of March 16–22, 1990

Figure 1 gives the variations of AE, K_p and $D_{\rm st}$ indices for the period in question. The first magnetic storm with AE up to 800 nT, K_p up to 5 and $D_{\rm st}$ down to -60 nT on March 18 had its onset during daytime hours in the American sector. Magnetic activity returned to normal during the next day on March 19. The second and more severe magnetic storm with AE up to 1100 nT, K_p up to 7 and $D_{\rm st}$ down to $-130\ nT$ had its SSC near 2245 UT on March 20, but the first splash of auroral activity was registered earlier (Fig. 1) again during daytime hours. This is important for further discussion. The geomagnetic activity decreased to some extent by March 22, but the ionosphere exhibited strong negative F2-layer storm effects on that day. March 17 was chosen as an excellent quiet time reference day.

The results of model calculations in comparison with the Millstone Hill $N_e(h)$ observations for the three most interesting days of March 18, 21 and 22, 1990 are shown in Figs. 2-4. The observed $N_e(h)$ profiles are given along with $\pm$ standard deviations over the chosen period of observations. The quiet time $N_e(h)$ profile of March 17 is given as a reference. The observed median T_e, T_i and V_z profiles used in our calculations are given in Fig. 2 as for March 18 as an example.

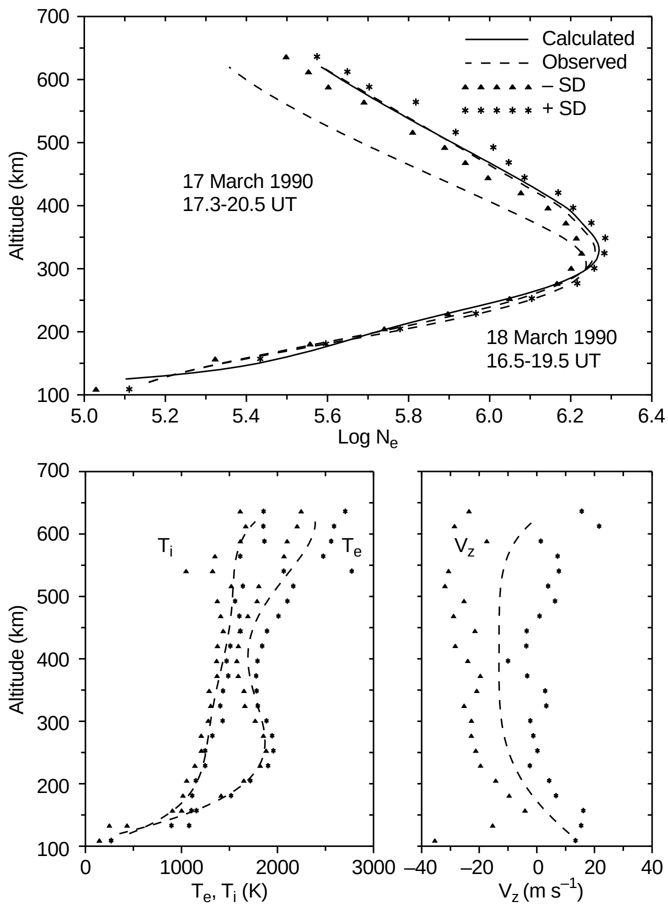

Fig. 2. Observed along with $\pm$ standard deviations and calculated N_e(h) profiles for the disturbed day March 18, 1990 in comparison with the observed quiet time profile of March 17, 1990. Observed T_e, T_i and V_z along with $\pm$ standard deviations median profiles used in our calculations are given in the lower boxes

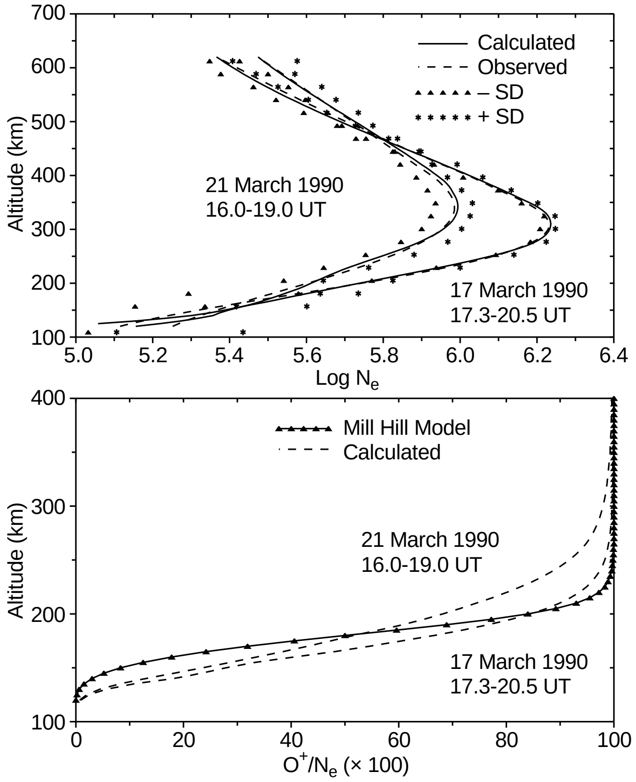

Fig. 3. Observed and calculated N_e(h) profiles for geomagnetically quiet March 17 and disturbed March 21, 1990 days (top panel). The standard deviations of the observed values are indicated. Calculated profiles closely match the observations on both days. Calculated O^+/N_e height variations are shown for the two days (bottom panel) and these are compared to the non–varying Millstone Hill standard ion–composition model

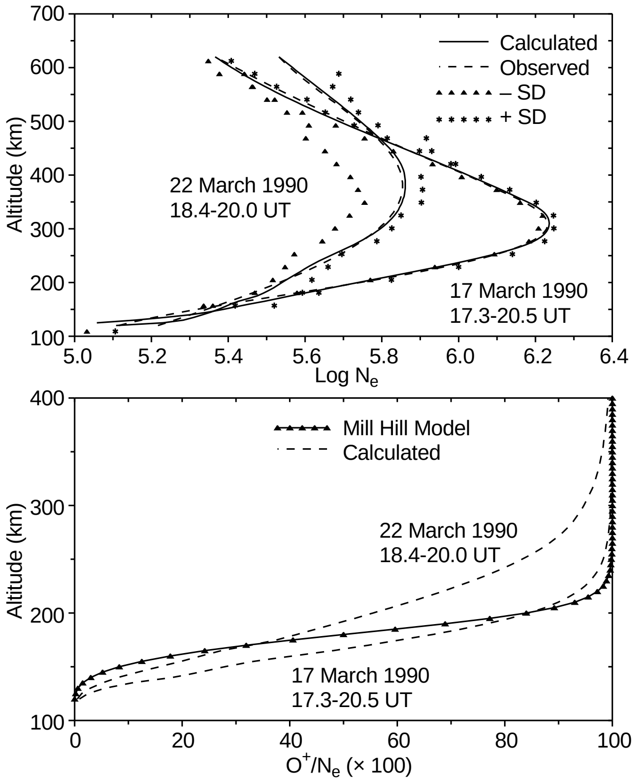

Fig. 4. Same as Figure 3 but for the disturbed day of March 22, 1990

A comparison of the calculated O^+/N_e ratio with the standard Millstone Hill ion composition model is given in Figs. 3-4. The method is seen to provide a good fitting of the calculated to the observed $N_e(h)$ profiles in the whole range of heights above 150 km for both quiet and disturbed days.

Experimental $T_e(h)$, $T_i(h)$ and $N_e(h)$ profiles derived from the incoherent scatter data analysis depend on the ion composition used in the fit of the theoretical to the measured auto-correlation function (ACF). An uncertainty in ion composition may lead to considerable uncertainties in the derived T_e(h) and T_i(h) profiles and to somewhat smaller uncertainties in N_e(h) (Waldteufel, 1971; Lathuillere *et al*., 1983; Kirkwood *et al*., 1986; Winser *et al*., 1990; Glathor and Hernandez, 1990). The most pronounced changes in ion composition take place during disturbed periods and in such conditions some iterations are required to obtain the proper fit to the measured ACF (Mikhailov and Schlegel, 1997). Such a correction applied to the two most disturbed days of March 21 and 22 has shown that the experimental profiles may not be corrected for March 21 as the changes in ion composition are not very strong (Fig. 3). Only one additional iteration was required for the March 22 experimental profiles. In the 200-250 km height range, where the difference in ion composition is the largest (Fig. 4), the corrected values are higher than the initial ones by 140K for T_i, by 450K for T_e and by only 4% for N_e. These corrected profiles for March 22 were used in our further analysis. For more severe disturbances analyzed by Mikhailov and Schlegel (1997); and Mikhailov and Foster (1997) when the ionosphere was molecular-ion dominated up to 250-350 km a similar correction of the experimental profiles was much more important.

The observed day-to-day variations of the F2-layer maximum parameters are shown in Fig. 5. The slight N_mF2 positive storm effect on March 18 resulted from the first geomagnetic disturbance (see Fig. 1) is accompanied by a 20 km h_mF2 increase. Day-time N_mF2 and h_mF2 values on March 19 practically returned to their prestorm values. A slight increase in N_mF2 and a 40 km increase in h_mF2 again take place at the beginning of the second storm on March 20 followed by pronounced negative storm effects on March 21 and 22 when the storm was in progress. The observed changes in N_mF2 and h_mF2 on March 22 relative to the prestorm reference March 17 level are a factor of 2.4 and 76 km, correspondingly.

The four lower boxes in Fig. 5 give the ratio of the calculated O^+ ion production rate q(O^+) to the linear loss coefficient β, the [O]/[N_2] ratio, the O^+ ion outflow at 600 km in comparison with Millstone Hill observations, and the vertical plasma drift W at the height of the F2-layer maximum. These are the most important aeronomic parameters responsible for the F2-layer maximum formation. A comparison of the [O]/[N_2] ratio to the MSIS-83 model prediction is given as well.

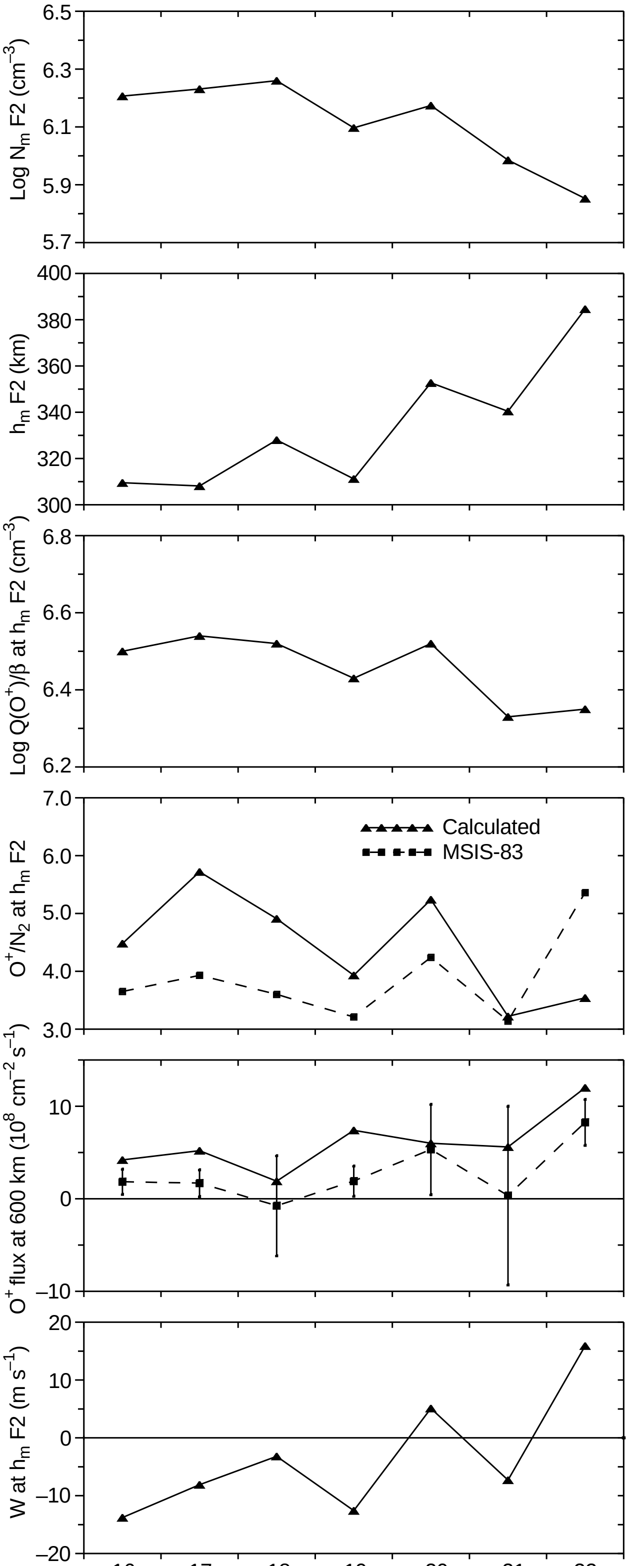

Fig. 5. Observed log N_mF2 and h_mF2 variations for the March 16–22, 1990 period, calculated log q(O^+)/β, O/N_2 ratios and vertical plasma drift at the height of F2–layer maximum as well as O^+ ion outflow at 600 km, compared to the Millstone Hill estimates (dashes) given along with standard deviations. MSIS–83 model O/N_2 prediction is shown for comparison (dashes). Calculated W values are given in the lower box. Figures along the x axis (UT) are dates of March 1990

Figure 6 gives the results of the thermospheric parameter calculations in comparison with the MSIS-83 model predictions and Millstone Hill estimates. The exospheric temperature T_{ex} shows a general increase mostly resulted from the increase of solar activity level during the period in question (see Table 1). The calculated T_{ex} is close to the Millstone Hill T_{ex} estimates and both are higher than the MSIS-83 predictions by 50-130 K (Table 2). The calculated atomic oxygen [O] concentrations are pretty close to the MSIS-83 predictions, but [N_2] and [O_2] are systematically lower at a

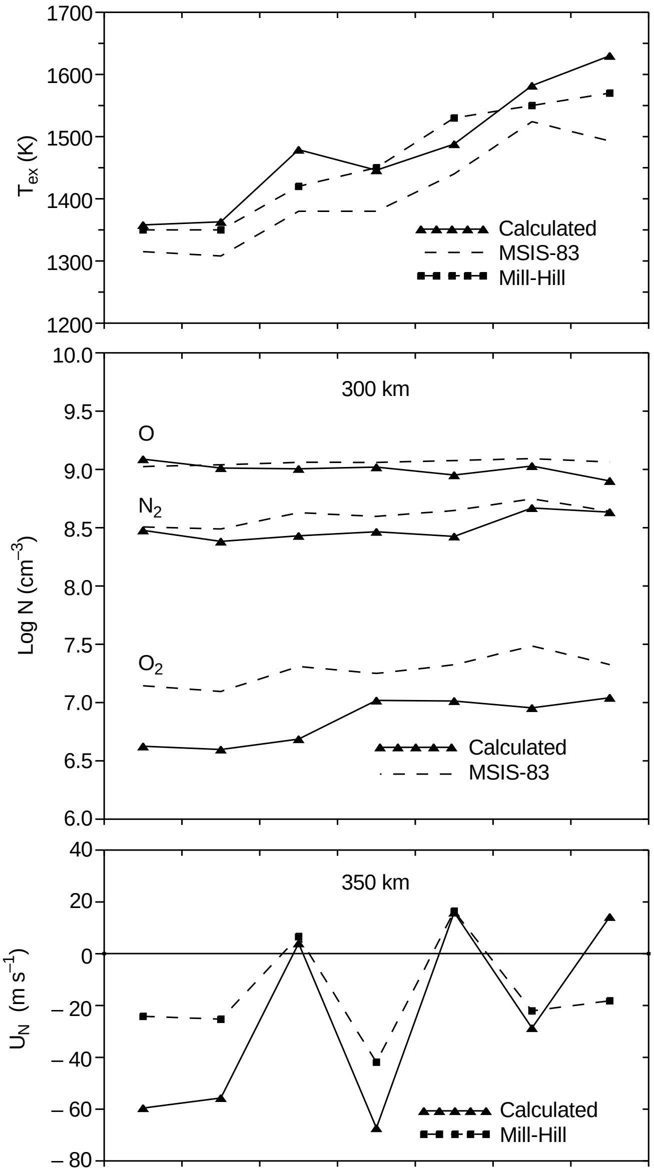

Fig. 6. Calculated (triangles), Millstone Hill estimated (squares) and MSIS–83 predicted (dashes) exospheric temperature T_{ex}. Calculated (triangles) along with the MSIS–83 predicted (dashes) O, N_2 and O_2 variations at 300 km. Calculated values (triangles) in comparison with Millstone Hill estimates (squares) of meridional (along the magnetic meridian) thermospheric wind (positive to the south). Figures along the x axis (UT) are dates of March 1990

Table 2. Calculated thermospheric parameters and MSIS–83 model predictions (second line) at the height of h_mF2

Date	h_mF2 (km)	log[O] (cm^{-3})	log[O_2] (cm^{-3})	log[N_2] (cm^{-3})	S (K)	T_{ex}	W (m/s)
1990							
Mar 16	309	9.028	6.508	8.377	.017	1358	−13.8
		8.964	7.026	8.402	.017	1315	
Mar 17	308	8.954	6.482	8.280	.017	1363	−8.1
		8.979	6.975	8.384	.018	1308	
Mar 18	328	8.842	6.368	8.151	.016	1479	−3.2
		8.889	6.971	8.333	.017	1380	
Mar 19	311	8.962	6.907	8.368	.016	1446	−12.6
		9.002	7.136	8.496	.017	1380	
Mar 20	353	8.680	6.485	7.961	.015	1488	5.1
		8.801	6.784	8.174	.016	1440	
Mar 21	340	8.824	6.551	8.316	.015	1582	−7.3
		8.881	7.072	8.384	.015	1524	
Mar 22	380	8.514	6.280	7.965	.016	1630	15.9
		8.639	6.492	7.910	.015	1493	

fixed height of 300 km. The meridional (along the magnetic meridian) neutral wind U_N is inferred from the vertical plasma drift W after subtraction of the component related to $\mathbf{E} \times \mathbf{B}$ plasma drift ($U_N = (W - V_{\perp N} \cos I)/\sin I \cos I$). This U_N is shown in comparison with the Millstone Hill estimates at the height of 350 km in the bottom box of Fig. 6. The method of U_N derivation at Millstone Hill is described by Buonsanto (1990) and Buonsanto *et al.* (1992a). The calculated U_N repeats Millstone Hill day-to-day U_N, the relative variation being more poleward on March 16, 17 and 19, coincides on March 18 and 20, but differs in sign on March 22.

The results for neutral composition are given in Fig. 6 at a fixed height of 300 km for convenience, but more proper comparison should be made at the height of the F2-layer maximum (Table 2) rather than at a fixed height as this minimizes the effect of different neutral temperatures T_{ex}.

Discussion

The analysis of the calculated T_{ex} (Fig. 6 and Table 2) shows that the T_{ex} elevation by 270 K during the period in question mostly reflects the solar activity level increase from $F_{10.7} = 179.9$ on March 16 to $F_{10.7} = 244.7$ on March 22. A similar T_{ex} increase is seen in the Millstone Hill estimates. The same tendency gives MSIS-83, but it predicts that T_{ex} will decrease from March 21 to March 22 due to an A_p index decrease from $A_p = 76$ to 28 and underestimates T_{ex} by 137 K. On the other hand, average differences for these three curves are less than 10% and within the limits of the experimental T_{ex} determination as well as the accuracy of the model predictions.

A comparison of the MSIS-83 and the calculated absolute [O] concentrations gives a difference of 18% on average. This difference is much less than that which was found at Arecibo by Burnside *et al.* (1991a) and at Millstone Hill by Oliver and Glotfelty (1996). It should be recalled that all collision frequencies used in our calculations are taken from Banks and Kockarts (1973) and $\nu(O^+ - O)$, in particular. But in recent works devoted to the incoherent scatter data analysis (Burnside *et al.*, 1987, 1988; Buonsanto *et al.*, 1989; Burnside *et al.*, 1991b, a; Buonsanto *et al.*, 1992a, b) it is suggested that this value should be increased by a factor of 1.7. The possible effect of such correction is discussed by Belley *et al.* (1992). They point out that the inferred atomic oxygen densities would have to be decreased by the same factor and this would contradict the CIRA-86 model predictions on [O]. A much lower factor of 1.2 - 1.4 for the $\nu(O^+ - O)$ collision frequency was recommended recently by Pesnell (1993); Reddy *et al.* (1994) and Davis *et al.* (1995). This is closer to the Banks and Kockarts (1973) value. In the recent publication by Oliver and Glotfelty (1996) on this problem they found, from an analysis of Millstone Hill observations, that the $(O^+ - O)$ collision cross section is only 75% of the Banks' value. The results of our calculations do not show any necessity to change the Banks and Kockarts (1973) $(O^+ - O)$ value, but simultaneous daytime incoherent scatter and satellite measurements of neutral composition or wind observations are required to clear up this question.

The MSIS-83 model atomic oxygen concentration virtually does not demonstrate any variation with solar and geomagnetic activity at a fixed height of 300 km (Fig. 6) while our calculations show a 30% decrease on March 22 with respect to the quiet reference day of March 17. This [O] decrease takes place despite the 270 K increase in T_{ex} and informs us of the absolute decrease in [O] abundance in the thermosphere on the day of disturbance. A more pronounced difference by a factor of 1.5 in [O] decrease between our calculations and MSIS-83 predictions takes place at the height of h_mF2 (Table 2).

A 30% difference on average between the calculated and MSIS-83 predicted [N_2] concentrations takes place for the period in question (Fig. 6, Table 2), but this may be considered as a normal result. A comparison of [N_2] measured on board the DE-2 satellite with MSIS-83 predictions gives a ratio of 0.5–0.9 for quiet geomagnetic conditions (Hedin and Carignan, 1985). A two-fold increase in [N_2] compared to the prestorm level takes place at 300 km on March 21 and 22 when the second geomagnetic storm was in progress. A very weak reaction to the first geomagnetic disturbance on March 18 is seen in [O] and [N_2] variations. A general increase in [O_2] can be seen throughout the period in question, but the reliability of the calculated [O_2] is not too high as stressed by Mikhailov and Schlegel (1997).

The calculated at 350 km meridional (along the magnetic meridian) neutral wind U_N (Fig. 6) is more positive (more equatorward) for disturbed days in accordance with the present-day understanding of the global circulation pattern. It is similar to Millstone Hill estimates except for the most disturbed day of March 22 when Millstone Hill analysis gives a northward U_N. The reason for this difference is not clear, but it requires a special analysis, outside the scope of this study.

Let us analyze the ionospheric parameter variations given in Fig. 5. Daytime N_mF2 in accordance with Rishbeth and Barron's (1960) concept is mostly controlled by the $q(O^+)/\beta$ variation. The exospheric temperature T_{ex} increase (Fig. 6) provides the general h_mF2 elevation throughout the period in question, but day-to-day h_mF2 relative changes are mostly governed by the vertical drift W variation. The vertical drift, W is seen to reflect the changes in the geomagnetic activity, being more positive for disturbed days, as it is mostly due to the thermospheric wind (Fig. 6) and to a less extent to electric fields. The effect of disturbances on March 18, 20 and 22 is clearly seen in the calculated vertical drift velocity W variations. The onset of the first disturbance on March 18 took place during daytime hours in the American longitudinal sector (Fig. 1). So, we can expect only vertical plasma drift increases due to the thermospheric circulation changes but not changes in [O] and [N_2] concentrations (Mikhailov *et al.*, 1995). This is a well-known concept of forbidden local time for the F2-layer negative storm onset (Prölss and von Zahn, 1978). According to this concept, negative F2-layer storm effects do not appear as a rule at mid-latitudes for geomagnetic storm onsets in the daytime sector, especially for winter and equinox periods. This does take place in our calculations, so a small positive F2-layer storm effect should be totally attributed to the decrease of normal northward thermospheric wind (Fig. 6). A similar situation takes place on March 20, when the first step of the large geomagnetic storm (see Fig. 1) falls again in the daytime hours. Our calculations do not show any noticeable changes in [O] and [N_2] concentrations for this period, but a very pronounced vertical drift increase does occur. This is the effect of the normal background (poleward) thermospheric circulation damped by the increased auroral heating. When the auroral heating is moderate, we have no changes of neutral composition at middle latitudes during winter and equinox periods, but an increase of vertical plasma drift only (Mikhailov and Skoblin, 1990; Mikhailov *et al.*, 1995). Indeed, our calculations as well as Millstone Hill calculations give a small equatorward U_N on these days (Fig. 6). This is in accordance with the Prölss (1980) concept that the daytime positive storm effects are not related to density changes but caused by ionization transport effects due to thermospheric winds (Prölss, 1991, 1993).

The N_mF2 negative storm effect on March 21 and 22 results mostly from neutral composition changes in accordance with the present-day understanding of this phenomenon. The calculated [O] and [N_2] concentrations as well as the exospheric temperature T_{ex} on March 21 are very close to the MSIS-83 predictions (Fig. 6, see also O/N_2 ratio in Fig. 5), so moderate daytime F2-layer storm effects may be explained with the help of empirical models such as MSIS-83.

The situation is different for March 22. The calculated T_{ex} is higher than the model one by 137 K (Table 2), the O/N_2 ratio is less by 1.51 times at the height of h_mF2 (Fig. 5), or by a factor of 1.43 at 300 km. The $q(O^+)/\beta$ ratios at h_mF2 are very close for March 21 and 22 (Fig. 5), but despite the fact that the upward drift of 16 m/s on March 22 helps to increase N_mF2, the N_mF2 decreases instead. This results from a strong $1.2 \times 10^9 cm^{-2}s^{-1}$ outflow of O^+ ions from the F2-region (Fig. 5). It should be mentioned that even larger O^+ fluxes were measured at Millstone Hill for the disturbance on February 8, 1986 (Yeh and Foster, 1990). The overall agreement between calculated and observed O^+ fluxes at 600 km height is seen for the period in question (Fig. 5) and this gives an additional confirmation of the validity of our calculations.

The obtained results have shown that the self-consistent approach to the $N_e(h)$ modelling in the ionospheric F-region can be successfully used for the analysis of both quiet and disturbed conditions. This was shown as well for more severe F2-layer storms by Mikhailov and Schlegel (1997); and Mikhailov and Foster (1997). The method gives reasonable neutral composition, temperature, wind and O^+ flux variations. The observed daytime moderate negative F2-layer storm effects in March 1990 can be totally explained using model MSIS-83 neutral composition for March 21, or slightly changed by a factor of 1.5 O/N_2 ratio for the stronger disturbance on March 22. This differs from the results of other analyses (Richards *et al.*, 1989, 1994b) where much larger O/N_2 ratio changes were suggested. No special consideration of vibrationally excited N_2 effects is made in our method, but the laboratory measured by McFarland *et al.* (1973)($O^+ + N_2$) reaction rate constant efficiently mimics the increase of this reaction rate due to N_2^* at high level of solar activity. This was confirmed by the results of Mikhailov and Schlegel (1997); and Mikhailov and Foster (1997) analyses of disturbed periods during the phase of solar maximum. Recent laboratory measurements of the $O^+ + N_2$ reaction rate constant (Hierl *et al.*, 1997) confirm a steep increase of the reaction rate for temperatures higher than 1300 K due to N_2 vibrational excitation.

Conclusions

The self-consistent method of Mikhailov and Schlegel (1997) for day-time F2-layer modelling was applied to the analysis of Millstone Hill incoherent scatter observations during the storm period of March 16-22, 1990. The method allows us to calculate in a self-consistent way neutral composition and temperature, vertical plasma drift and O^+ ion outflow from the F2-region, i.e. the main aeronomic parameters responsible for the mid-latitude F2-layer formation. Earlier the method was developed and tested using day-time EISCAT observations. Now it is confirmed by the Millstone Hill data that the method can be successfully used for the analysis of other incoherent scatter observations both for quiet and disturbed conditions. The main results of our study may be listed as follows:

1. The F2-layer theoretical model being the core of the method enables us to fit calculated to observed N_e(h)

profiles with great accuracy in the whole range of heights above 150 km for both geomagnetically quiet and disturbed days.
2. The calculated exospheric temperature T_{ex} shows an overall increase by 270 K from March 16 to March 22 resulting from the general increase of the solar activity level during the period in question. The T_{ex} variations are close to Millstone Hill estimates, and both are higher than the MSIS-83 predictions by 50-130 K.
3. The calculated atomic oxygen shows a 30% decrease at 300 km on March 22 relative to the quiet time prestorm period. This [O] decrease takes place despite the 270 K increase in T_{ex} and relates to the absolute decrease in [O] abundance in the thermosphere on the disturbed day in accordance with the present-day understanding of the physical processes in the disturbed thermosphere. The MSIS-83 model, on the contrary, predicts a small increase in [O].
4. A two-fold increase in $[N_2]$ concentration at 300 km compared to the prestorm level takes place on March 21, 22 when the second geomagnetic storm was in progress. Only a small reaction to the first geomagnetic disturbance on March 18 and the initial phase of the second storm on March 20 was found in [O] and $[N_2]$ variations in accordance with the forbidden time for the F2-layer negative storm phase onset concept.
5. The inferred from plasma vertical drift W meridional neutral thermospheric wind clearly demonstrates the dependence on the geomagnetic activity level being more equatorward for disturbed days. This tendency is more pronounced in our calculations than in Millstone Hill estimates of U_N.
6. Small positive F2-layer storm effects with simultaneous N_mF2 and h_mF2 increase observed on March 18 and 20 are totally attributed to the decrease of the northward neutral wind due to the increase of auroral heating but not to changes of neutral composition. This takes place at mid-latitudes when the storm onset falls into day-time hours.
7. The observed daytime negative F2-layer storm effects on March 21 and 22 are produced by neutral composition changes along with increased O^+ ions outflow from the F2-region. They can be totally explained using model MSIS-83 neutral composition for March 21, or slightly decreased by a factor of 1.5 O/N2 ratio for the stronger disturbance on March 22. This is different from the results of other F2-layer negative storm effect considerations where much a larger O/N_2 ratio decrease was required to explain the observed decrease in N_mF2. A plausible explanation to this difference is seen in our self-consistent approach which provides internal consistency for the main aeronomic parameters.

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