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Synchronous *Nm*F2 and *Nm*E daytime variations as a key to the mechanism of quiet-time F2-layer disturbances

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Abstract. The observed *Nm*F2 and *Nm*E variations were analyzed for the periods of positive and negative quiet-time F2-layer disturbances (Q-disturbances) observed in the mid-latitude daytime F2-layer to specify the mechanism of their origin. The noontime δNmF2 and δNmE deviations demonstrate a synchronous type of variation which can be explained by vertical gas motion in the thermosphere. This neutral gas motion should result in atomic abundance variations, the latter being confirmed by the Millstone Hill ISR observations for periods of positive and negative Q-disturbance events. The analysis of the ISR data has shown that atomic oxygen concentration variations are the main cause of the daytime F2-layer Q-disturbances. The auroral heating which controls the poleward thermospheric wind is considered to be the basic mechanism for the Q-disturbances, however, the specific mechanisms of positive and negative Q-disturbances are different. Some morphological features of the Q-disturbances revealed earlier are explained in the scope of the proposed concept.

Keywords. Ionosphere (Ionosphere-atmosphere interactions; Ionospheric disturbances) – Atmospheric composition and structure (Thermosphere – composition and chemistry)

1 Introduction

Our earlier morphological analysis (Mikhailov et al., 2004) of the *Nm*F2 quiet-time disturbances (Q-disturbances) has revealed many interesting features in their occurrence. Positive and negative Q-disturbances exhibit different morphological patterns in diurnal, seasonal, and spatial variations and this implies different mechanisms of their formation. Quiet time F2-layer disturbances are closely related to the problem of the coupling from below: the so-called meteorological control of the Earth's ionosphere (e.g. Danilov, 1986; Danilov et al., 1987; Khachikjan, 1987; Kazimirovsky and Kokourov, 1991; Forbes et al., 2000; Rishbeth and Mendillo, 2001; Kazimirovsky et al., 2003; Laštovička et al., 2003; Vanina and Danilov, 2005). Quasi 2-day oscillations in the ionosphere (Chen, 1992; Apostolov et al., 1995; Forbes and Zhang, 1997; Forbes et al., 2000; Altadill and Apostolov, 2001; Rishbeth and Mendillo, 2001), which are seen in the Q-disturbance occurrence, may also be attributed to the meteorological effects in the F2 region as they are not related to geomagnetic activity. On the other hand, neither one can exclude the high-latitude impact on the global circulation and thermospheric composition. Goncharenko et al. (2006), for instance, revealed a pronounced negative Q-disturbance effect using the Millstone Hill ISR and TIMED observations and attributed it to IMF B_y variations.

Very fruitful WINDII/UARS optical observations (Shepherd et al., 1999, 2002, 2004; Ward et al., 1997; Wang et al., 2002) of the atomic oxygen and wind velocity variations at E-region heights may be useful for studying the mechanism of the F2-region Q-disturbances' formation, because both ionospheric regions are related via thermospheric neutral composition.

We will discuss here the physical interpretation of the Q-disturbance morphology. We start with the daytime conditions when the revealed seasonal variations are well pronounced and the difference in the morphological pattern of the two types of Q-disturbances is obvious (Mikhailov et al., 2004). The formation mechanism of the mid-latitude daytime F2-layer is well established and this should help us find out the pertinent aeronomic parameters and the processes responsible for the observed variations. The possibility to use *Nm*E variations which (along with the *Nm*F2 data) may help in understanding the phenomenon is an additional argument in favor of considering the daytime conditions. So the aim of the paper may be specified in the following way: to analyze the observed *Nm*F2 and *Nm*E changes for the periods

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Table 1. List of stations used in the analysis, geodetic coordinates and invariant latitudes of the stations are given.

Station	Lat	Lon	Inv. Lat	Station	Lat	Lon	Inv. Lat
Kiruna	67.8	20.4	64.4	Slough	51.5	−0.6	49.8
Loparskaya	68.2	33.1	64.0	Ekaterinburg	56.7	61.1	51.4
Sodankyla	67.4	26.6	63.6	Kaliningrad	54.7	20.6	51.2
Lycksele	64.7	18.8	61.5	Moscow	55.5	37.3	50.8
Arkhangelsk	64.6	40.5	60.1	Kiev	50.7	30.3	46.5
Uppsala	59.8	17.6	56.6	Lannion	48.4	−3.3	47.0
St. Petersburg	59.9	30.7	55.9	Poitiers	46.6	0.3	45.1
Gorky	56.1	44.3	51.4	Rostov	47.2	39.7	42.3

Table 2. Average δNmE ±SD value, along with the Student t-parameter, and the correlation coefficient between δNmF2 and δNmE, along with the Fisher F-parameter for negative and positive F2-layer Q-disturbances.

Disturbance	Average ± SD	t-parameter	Corr. coeff	F-parameter
Negative	0.947±0.067	5.95	0.26	3.98
Positive	1.064±0.060	10.66	0.22	2.59

of F2-layer Q-disturbances, to make quantitative estimates of the governing aeronomic parameter variations, and to discuss possible processes which could provide such variations.

2 Data analysis

The analysis was made using the daytime (11:00–14:00 LT) *fo*F2 and *fo*E observations available for the periods of positive and negative F2-layer Q-disturbances. The list of the European ionosonde stations used is given in Table 1. One can find the information on the process of the Q-disturbances extraction from the routine *Nm*F2 observations in Mikhailov et al. (2004). Here we repeat briefly for the sake of convenience the main idea. The $(Nm\mathrm{F2}/Nm\mathrm{F2}_{\mathrm{med}}-1)\times100\%$ hourly deviations exceeding 40% are considered as a Q-disturbance, if all 3-h a_p indices were ≤7 for the preceding 24 h. The 27-day *Nm*F2 running median centered to the day in question rather than the usual monthly median is used for the Q-disturbances' specification. Only long lasting, ≥3-h (4 successive hourly *Nm*F2 values), disturbances are used in our analysis. The same procedure is applied to the *Nm*E hourly variations, but the priority is given to the *Nm*F2 disturbances, that is, we select positive and negative F2-layer Q-disturbances and take the corresponding *Nm*E deviations as they are. The deviations $\delta=\mathrm{Nm}/\mathrm{Nm}_{\mathrm{med}}$ for *Nm*F2 and *Nm*E, averaged over the 11:00–14:00 LT interval, are considered in our analysis.

Mikhailov et al. (2004) showed earlier that the daytime Q-disturbances were relatively rare in occurence, so we had to put together the data for all levels of solar activity to increase the statistics. The negative Q-disturbances are less frequent as compared to the positive ones, but they exhibit a pronounced seasonal variation pattern in the wide latitudinal range, with the maximal occurrence around the winter solstice (December–January). The seasonal variation pattern for positive Q-disturbances depends on latitude, but for the European stations considered in this paper, the occurrence frequency has maxima around equinoxes. So, in the case of positive Q-disturbances, we confine our consideration according to the equinoctial periods only.

3 Synchronous δNmF2 and δNmE variations

The analysis has shown that δNmF2 and δNmE deviations demonstrate, to some extent, a synchronous type of variation during the periods of the F2-layer Q-disturbances. For checking this effect, 58 negative and 101 positive Q-disturbances were analyzed. We checked first whether the type (positive/negative) of δNmF2 and δNmE deviations is the same in a statistical sense. This can be done comparing δNmE with unity (i.e. with a median) for the selected F2-layer disturbances. One can estimate the statistical significance of this difference using the Student t-criterion. The results are presented in Table 2 which shows that the δNmE difference from the unity is significant at any confidence level for both negative and positive Q-disturbances. It means that under negative Q-disturbances in the F2-layer we have negative deviations in the E-layer, whereas positive F2-layer disturbances are accompanied by positive deviations in *Nm*E. So they exhibit in-phase variations in a statistical sense.

It would be interesting to check if there is a point-to-point correlation between δNmF2 and δNmE deviations during such events. Table 2 shows that the correlation is not high but it is significant at least at the 90% confidence level, according to the Fisher F-criterion. On the other hand, the correlation may be much better for individual, strong events. For instance, for the 6–10 April 1973 positive Q-disturbance event (Mikhailov et al., 2004, their Fig. 8), the correlation coefficient between δNmF2 and δNmE is 0.585 and the F-parameter is equal to 21.8, that is, the correlation is significant at the 99% confidence level. This disturbance event is shown in Fig. 1 to illustrate the coherence in the δNmF2 and δNmE day-to-day variations. The δNmF2 and δNmE daily values available at each station for the 6–10 April 1973 period are put together one by one to draw the plot.

It should be emphasized that such point-to-point correlation takes place only for the positive Q-disturbance events, but not for the negative ones. For the latter one can speak about in-phase variations between δNmF2 and δNmE only on average. This confirms the earlier conclusion that positive and negative Q-disturbances are due to different formation mechanisms.

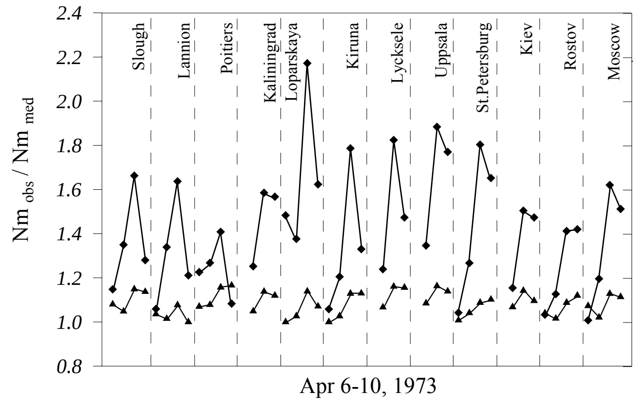

Fig. 1. Observed δNmF2 (squares) and δNmE (triangles) values at 12 ionosonde stations for the 6–10 April 1973 period. The number of days with observations available is different for different stations.

4 Interpretation

We start the interpretation with the δNmE deviations. On the one hand, the formation mechanism of the E-region is relatively simple and allows one to specify the governing parameters unambiguously. On the other hand, this will help us at the second step when we move to a consideration of the δNmF2 deviations. The mid-latitude daytime E-layer is mainly formed via the ionization of neutral O_2 by two close EUV lines λ=977 Å (CIII) and λ=1025.7 Å (HLyβ), providing 80-90% of the total ionization rate. The rest of the ionization rate is provided by the X-ray radiation with $\lambda<$100 Å (Ivanov-Kholodny et al., 1976). Therefore, the classical Chapman theory (Chapman, 1931) may be applied in this case with a sufficient accuracy (Ivanov-Kholodny and Nusinov, 1979).

At E-region heights, the neutral temperature increases upwards, so the scale height of molecular oxygen can be written as H(h)=$H_0+\gamma$h, where γ=0.1–0.3, according to different estimates. The daytime ion composition is presented by two molecular ions, NO^+ and O_2^+, having a close temperature dependence for their dissociative recombination coefficients. Therefore, we may accept that the effective dissociative recombination coefficient is $\alpha'=\alpha_0 T^{-\nu}$, where $\alpha_0=c_0(1/300)^{-\nu}$, $\nu\approx0.8$, and c_0 is a constant. Then we obtain for the maximum electron concentration squared: $(N_mE)^2=q_m/\alpha'_m$

$$q_m/\alpha'_m = \frac{I_\infty \sigma^i n_0}{\alpha_0 T_0^{-\nu}} \left\{ \frac{\cos\chi\,[1+\gamma(1-\nu)]}{n_0 H_0 \sigma^a e} \right\}^{1+\gamma(1-\nu)}, \quad (1)$$

where q_m is the ionization rate at the E-layer maximum, I_∞ is the incident ionizing flux, $H_0=kT_0/mg$ is the scale height, n_0 is the concentration of neutral O_2 at h_0, χ is the solar zenith angle, and σ^i and σ^a are the ionization and absorption cross-sections, respectively.

At the accepted γ and ν values, $1+\gamma(1-\nu)\approx 1$ and so Eq. (1) is reduced to

$$q_m/\alpha'_m = \frac{I_\infty \sigma^i \cos\chi}{\alpha_0 \left(\frac{k}{mg}\right) T_0^{1-\nu} \sigma^a e}. \quad (2)$$

Expression (2) explicitly is independent of γ, therefore, one should not expect any considerable N_mE changes due to the neutral temperature gradient variations. In this case we may consider an isothermal atmosphere at E-region heights and obtain the expression commonly used in the classical theory of the ionospheric E-layer

$$q_m/\alpha'_m = \frac{I_\infty \sigma^i \cos\chi}{\alpha' H \sigma^a e}, \quad (3)$$

where α' now is a constant and H is the molecular oxygen scale height.

It follows from Eq. (3) that there are three possibilities to explain the N_mE variations: (i) day-to-day changes in the solar EUV ionizing flux, (ii) variations in α' due to changes in the ion composition (Eq. 6), or (iii) changes in the molecule oxygen effective scale height $H(O_2)$ due to dynamical processes (vertical gas motion, for instance).

According to our previous morphological analysis (Mikhailov et al., 2004, their Fig. 10), the spatial pattern of Q-disturbances looks like a planetary wave with a steep front, so adjacent stations may have different δNmF2 and δNmE and it is hard to reconcile such morphology with the overall changes in the solar EUV and X-ray radiation.

Now we consider the second possibility: changes in α'. The ion composition in the daytime mid-latitude E-region is presented by two molecular ions, NO^+ and O_2^+, disappearing via the dissociative recombination reactions

$$NO^+ + e \rightarrow N + O \quad (\alpha_1 = 4.5\text{X}10^{-7}(300/T_e)^{0.8}\,\text{cm}^3\,\text{s}^{-1}), \quad (4)$$

$$O_2^+ + e \rightarrow O + O \quad (\alpha_2 = 1.95\text{X}10^{-7}(300/T_e)^{0.7}\,\text{cm}^3\,\text{s}^{-1}). \quad (5)$$

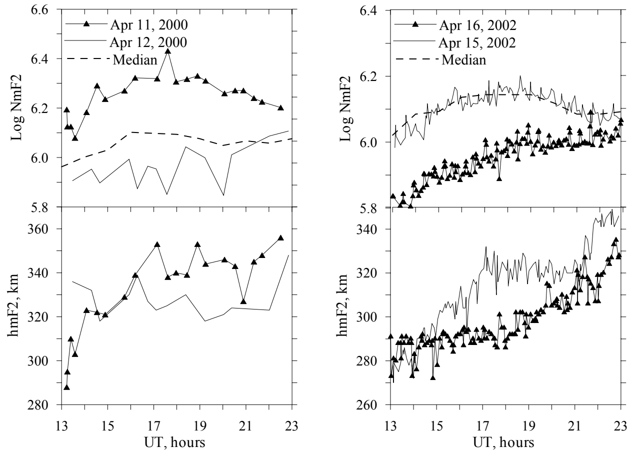

Fig. 2. Positive (11 April 2000) and negative (16 April 2002) Q-disturbances observed at Millstone Hill.

With $n_e=NO^{+}+O_2^{+}$ and $C=NO^{+}/O_2^{+}$, the effective dissociative recombination coefficient may be written as

$$\alpha' = \alpha_1 \frac{NO^+}{n_e} + \alpha_2 \frac{O_2^+}{n_e} = \frac{\alpha_1 C + \alpha_2}{1+C}. \quad (6)$$

The recombination coefficient α' depends only on the $C=NO^{+}/O_2^{+}$ ratio, which is known to be controlled in the E-region by nitric oxide NO (Danilov, 1994).

According to Table 2, the average δ*Nm*E variation during Q-disturbance events is about 5% or 10% in the α' value. Using Eq. (6) this gives an estimate C≈0.13 which looks absolutely unreal for the quiet mid-latitude daytime conditions at E-region heights, according to the ion composition model by Danilov and Smirnova (1995). More accurate numerical estimates using the photochemical model of the E-region (Mikhailov, 2000), taking into account all pertinent processes, confirmed this conclusion. Very strong (up to a factor of 8–10) changes in [NO] are needed to account for the required 5% changes in *Nm*E. Such [NO] variations are unreal for the conditions in question and we have to choose the third possibility (changes in $H(O_2)$) to explain the observed *Nm*E variations.

The effect should have a dynamical origin rather than the temperature one mentioned earlier. Such mechanism of *Nm*E variations was considered earlier by Mikhailov (1983) and Nusinov (1988). In our case a 5% variation in *Nm*E implies a 10% change in $H(O_2)$. Such moderate changes in $H(O_2)$ look plausible and can be caused by vertical motion of the atmospheric gas with a velocity of 1–2 cm/s at E-region heights (Mikhailov, 1983). This mechanism provides in-phase *Nm*F2 and *Nm*E variations taking place during positive Q-disturbance events. The downward gas motion enriches the thermosphere with [O] at F2-layer heights and reduces $H(O_2)$ in the E-region resulting in a synchronous *Nm*F2 and *Nm*E increase. The upwelling of the neutral gas should, in principle, result in the opposite effect (see later).

It follows from the approximate expression for mid-latitude daytime F2 layer (Ivanov-Kholodny and Mikhailov, 1986; Mikhailov et al., 1995) that the thermospheric concentration of atomic oxygen is directly related to *Nm*F2

$$\Delta \lg N_m F2 = \frac{4}{3}\Delta \lg[O] - \frac{2}{3}\Delta \lg \beta + \frac{1}{2}\Delta \lg T_n + \Delta \lg J_o, \quad (7)$$

where [O] is the atomic oxygen concentration, $\beta=\gamma_1[N_2]+\gamma_2[O_2]$ is the linear loss coefficient, Tn is the neutral temperature, and J_o is the ionization efficiency. This expression is invariant relative to height changes in the isothermal thermosphere, so any height in the F2-region may be chosen as the basic level. The ionization efficiency J_o is proportional to the total incident ionizing solar EUV flux and may be considered as unchanged for adjacent days. It will be shown later that the contribution from $\Delta\beta$ and ΔTn to the *Nm*F2 variation is not large. Therefore, the atomic oxygen concentration variations may serve as an indicator of the vertical gas motion during the periods of F2-layer Q-disturbances.

The Millstone Hill ISR observations on 11/12 April 2000 and 15/16 April 2002 were chosen for our analysis. These dates correspond to positive and negative Q-disturbance events (Fig. 2). Formally speaking, the two periods do not correspond exactly to our rules of the Q-disturbances' selection (Mikhailov et al., 2004), but actually they may be considered as such events because both periods were magnetically quiet: the daily values of A_p were 9/7 and 6/7 for 11/12 April 2000 and 15/16 April 2002, respectively. The daytime *Nm*F2 values on 11 April are higher than the monthly median (dashes in Fig. 2) by ≈60%, whereas the day of 12 April which is closer to the median, presents a moderate negative disturbance. For the second period, the *Nm*F2 monthly median coincides with the 15 April 2002 daytime *Nm*F2 values and we have a good case of a negative Q-disturbance on 16 April 2002.

It is worth noting that *hm*F2 (Fig. 2, bottom) also separates according to the type of *Nm*F2 variations. The difference in *hm*F2 is the largest around noontime and decreases towards the morning and evening hours, whereas the difference in *Nm*F2 takes place over the entire daytime. This fact manifests different dependences of *Nm*F2 and *hm*F2 on the main aeronomic parameters and is not discussed here.

The self-consistent approach to the N_e(h) modelling at F2-region heights, proposed by Mikhailov and Schlegel (1997) with the latest modifications by Mikhailov and Lilensten (2004) has been used to find the thermospheric neutral composition ([O], $[O_2]$, and $[N_2]$), temperature Tn(h), vertical plasma drift W related to the neutral thermospheric winds and electric fields, as well as the total solar EUV flux with $\lambda<1050$ Å. The details of the method may be found in the above-indicated references, so only the main idea is sketched here. The standard set of ISR observations (Ne(h), Te(h), Ti(h), and VO(h) vertical profiles) is the initial input

Table 3. Aeronomic parameters at 300 km for the 11/12 April 2000 and 15/16 April 2002 periods. Second line shows the NRLMSISE-00 model values.

Date	T_{ex} (K)	log $[O]_{300}$ (cm^{-3})	log $[O_2]_{300}$ (cm^{-3})	log $[N_2]_{300}$ (cm^{-3})	logβ_{300} (s^{-1})	W (m/s)
11 April	1457	9.019	7.150	8.602	-3.309	≈0
	1312	9.095	6.884	8.588		
12 April	1427	8.751	7.102	8.519	−3.381	7.6
	1303	9.094	6.848	8.568		
15 April	1447	8.889	6.866	8.404	−3.511	1.0
	1344	9.078	6.921	8.588		
16 April	1439	8.667	6.824	8.311	−3.624	−7.1
	1326	9.073	6.891	8.570		

information. All these observed parameters enter the continuity equations for the main ionospheric ions in the F2-region. By fitting the calculated Ne(h) profile to the experimental one, a self-consistent set of the main aeronomic parameters responsible for the observed Ne(h) distribution can be found. The experimental profiles observed over some period are specially processed before being used in the calculations. Usually this time interval is 1–2 h (17:30–18:30 UT for 15/16 April 2002), but it was increased up to 5 h (15:45–20:30 UT) because of sparse observations (Fig. 2, left) during the 11/12 April 2000 experiment. The results of the calculations are presented in Table 3.

Table 3 along with (Eq. 7) show that almost the entire *Nm*F2 difference between adjacent dates is due to atomic oxygen variations for both periods, as the contributions of the linear loss coefficient β and Tn are small. In principle, the vertical plasma drift W may be converted into the meridional thermospheric wind Vnx as

$$W = Vnx \mathrm{Sin} I \mathrm{Cos} I \mathrm{Cos} D + V_{\perp N} \mathrm{Cos} I, \quad (8)$$

providing that $V_{\perp N}$ is available and resulted from the zonal electric field. Such $V_{\perp N}$ observations are available for the 15/16 April 2002 experiment (Goncharenko et al., 2005, their Fig. 13), but zonal electric fields were small around 18:00 UT for both dates. Therefore, we may conclude that Vnx was around zero on 15 April and it was northward (about 30 m/s) on 16 April, additionally reducing the daytime *Nm*F2. Our Vnx estimates are close to the Millstone Hill meridional winds determination for 18:00 UT (Goncharenko et al., 2006, their Fig. 17).

The exospheric temperatures Tex estimated at Millstone Hill and the observations of the column O/N_2 ratio by the GUVI instrument aboard the TIMED satellite may serve as an additional check for the derived thermospheric parameters. The calculated Tex are close to the Millstone Hill estimates for both periods, being larger than the NRLMSISE-00 (Picone et al., 2002) model predictions by about 100 K. A similar underestimation of the NRLMSISE-00 model Tex was noted by Lei et al. (2004). The O/N_2 column ratio observed with the GUVI instrument for the 15/16 April 2002 period shows a 30–50% reduction from 15 April to 16 April in the Atlantic longitudinal sector (Goncharenko et al., 2006). A direct comparison of our [O] and $[N_2]$ with the GUVI column observations is problematic due to many technical reasons (Goncharenko et al., 2006), however, our O/N_2 ratio at 300 km reduced to 07:30 LT (the local time of the GUVI observations) also exhibits a 40% reduction on 16 April with respect to 15 April. Of course, the NRLMSISE-00 model does not reproduce the strong O/N_2 day-to-day variations, obtained in our both calculations and observed by the GUVI instrument. Therefore, the obtained results on the derived thermospheric parameters' variation may be considered as reliable and used for the interpretation.

Days with larger *Nm*F2 are distinguished by higher atomic oxygen concentration, the difference being 67% for the 15/16 April case and 85% for 11/12 April. However there is a difference between the two cases. The *Nm*F2 value for 15 April coincides exactly with the *Nm*F2 monthly median (Fig. 2, right-hand panel) and we have a pure case of a negative Q-disturbance counted from this median. In the case of 11/12 April, the median is located between the two *Nm*F2 curves (Fig. 2, left-hand panel), therefore, the absolute difference in [O] is larger. Being counted with respect to the median (as in the case of 15/16 April), the difference in [O] would also be about 60%. This confirms our earlier estimates of the day-to-day variations of [O] obtained for similar equinoctial transition conditions (Mikhailov and Schlegel, 2001).

An important conclusion of our analysis is that both positive and negative Q-disturbances in the F2-region are mainly due to the atomic oxygen concentration variations presumably resulted from the vertical gas motion in the thermosphere, including the heights of the ionospheric E-region. The relationship between the vertical gas motion and atomic oxygen abundance in the thermosphere is well established (e.g. Rishbeth and Müller-Wodarg, 1999; Ward et al., 1997; Liu and Roble, 2004). In the E-region, as was emphasized earlier, the vertical gas motion is the only mechanism capable of explaining the observed *Nm*E variations. The comparison of *Nm*E available for 11 April 2000 and 16 April 2002 with the monthly median values of *Nm*E obtained from the Millstone Hill digisonde observations is not very impressive, but it is in line with our statistical results. The *Nm*E value averaged over 3 noon LT hours exceeds the monthly median by 3.7% for 11 April, but this difference is less than 1% for 16 April.

Therefore, there is an obvious problem mentioned earlier. If both positive and negative F2-layer Q-disturbances are due to the vertical gas motion resulting in [O] (F2-region) and $H(O_2)$ (E-region) changes, why is there no point-to-point correlation between δNmF2 and δNmE for negative Q-disturbance events and can we detect synchronous δNmF2 and δNmE changes only on average?

According to the results of our calculations, the negative daytime Q-disturbances are accompanied by low atomic oxygen concentration and enhanced poleward thermospheric wind (see also Goncharenko et al., 2006). Our analysis of 35 negative and 105 positive daytime Q-disturbances observed at European ionosondes shows the difference between the two types of events with regard to their formation. The A_p indices averaged over 27 days preceding each event were calculated for all positive and negative disturbances in question. In the case of the negative Q-disturbances, the averaged A_p=9.87±3.88, whereas this value equals 16.96±6.78 for the positive Q-disturbance events. The difference between the two classes of events is significant at any confidence level, according to the Student t-criterion. This result indicates that the positive Q-disturbances were counted from a relatively low median level, because the preceding 27-day periods included many disturbed days (average A_p=16.96). In the case of the negative Q-disturbances, the reference (median) level was higher, corresponding to an average A_p=9.87.

Therefore, one may propose the following mechanism. Under very low geomagnetic activity when the auroral heating is minimal, we have an unconstrained solar-driven thermospheric circulation with a relatively strong daytime poleward wind, in accordance with our calculations for 16 April 2002. This poleward wind is seasonally dependent, being the strongest in winter (Buonsanto and Witasse, 1999, their Fig. 5). This is partly due to the fact that Joule heating is the minimal in winter when the ionization and conductivity levels are low, reinforcing the prevailing solar-driven circulation (Forbes et al., 1996; Fuller-Rowell et al., 1996). The poleward thermospheric wind produces in the F2-region a downward plasma drift decreasing *Nm*F2. This is one of the causes for the daytime negative Q-disturbances to cluster around the winter solstice, according to our morphological analysis (Mikhailov et al., 2004). Very quiet geomagnetic conditions correspond to a ground state of the thermosphere with relatively low atomic oxygen concentration at middle and subauroral latitudes. According to the model calculations by Rishbeth and Müller-Wodarg (1999, their Fig. 3), there is a moderate upwelling (about 0.5 m/s) in a wide range of latitudes around noontime under quiet (K_p=2+) conditions, with the upwelling being able to support the low background level of the atomic oxygen concentration. This relatively low [O] abundance (Table 3) is the second and the main cause of low *Nm*F2.

The high-latitude heating increases with geomagnetic activity and this damps the solar-driven poleward thermospheric wind. This damping produces a downwelling of the neutral gas and a corresponding enrichment of the thermosphere with atomic oxygen. This results in *Nm*F2 and *Nm*E increases, as has been discussed earlier.

According to Kutiev and Muhtarov (2001), the most probable (i.e. median) state of the ionosphere corresponds to $K_p \approx 3_o$ (A_p=15) and, on average, the usual negative disturbances correspond to a geomagnetic activity level higher than A_p=15. Therefore, both the *Nm*F2 and *Nm*E median values bear the effect of gas downwelling, that is, the medians are slightly higher as compared to the basic (background) state of the ionosphere, corresponding to a very low level of geomagnetic activity when negative Q-disturbances occur. So, their appearance, both in the F2 and E regions, just manifests the monthly median level from where they are counted. Therefore, in the case of negative Q-disturbances, we have synchronous δNmF2 and δNmE changes only on average, as no physical mechanism relating δNmF2 and δNmE is involved in this case. On the contrary, in the case of positive Q-disturbances, the downward gas motion in the thermosphere produces in-phase δNmF2 and δNmE changes not only on average, but at the point-to-point level, as well (Fig. 1). The proposed explanation can help understand different morphology of the positive and negative F2-layer Q-disturbances (see Discussion).

In the framework of this explanation, the sketch in Fig. 3 may help specify the location of Q-disturbances and the usual F2-layer disturbances on the scale of the A_p indices. The negative Q-disturbances appear under very low geomagnetic activity and their occurrence depends on the *Nm*F2 median level. If a month was geomagnetically disturbed with usual negative F2-layer storm events, the *Nm*F2 median level would be lower and this would prevent an occurrence of negative Q-disturbances. On the contrary, one may expect the negative Q-disturbances to appear if a month was quiet and the *Nm*F2 median level was relatively high. In addition to our earlier analysis, this was checked for some years around solar minimum and for three months (November, December, January) when the negative Q-disturbances were the most numerous. The monthly A_p indices and the data of the Slough station for negative Q-disturbances were used to obtain the results presented in Table 4. One can see a tendency of the Q-disturbances to appear under less disturbed conditions for each of the three months.

The area of the long-duration positive F2-layer disturbances in Fig. 3 corresponds to moderately disturbed ($5 \le A_p \le 15$) conditions and the positive Q-disturbances just

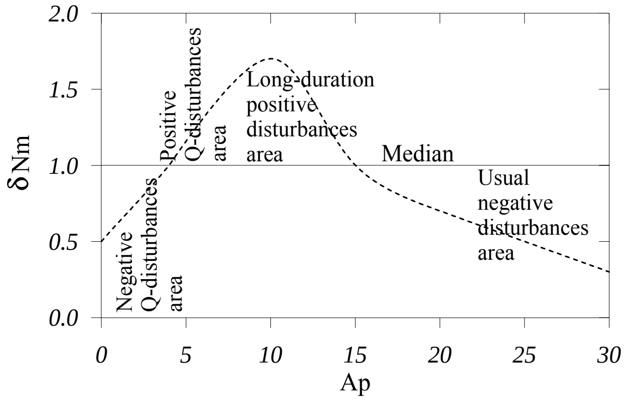

Fig. 3. A sketch to illustrate the place of Q-disturbances on the A_p index scale.

occupy the left-hand wing of this area. Their formation mechanism is the same: the damping of the poleward solar-driven thermospheric wind due to the increase in the auroral heating, the downwelling of the neutral gas and the related increase in the atomic oxygen abundance. A further increase in the auroral activity inverses the solar-driven circulation and this corresponds to the area where the usual negative F2-layer disturbances occur, their mechanism being well established (e.g. Prölss, 1995). According to Zevakina and Kiseleva (1978), there are two types of positive disturbances in the F2-region. Short and strong positive disturbances of type II (unlike long-duration positive disturbances of type I) are followed by negative storm effects. They just present the first (positive) phase of a two-phase disturbance, so they may take place in this area, as well.

5 Discussion

In their morphological analysis, Mikhailov et al. (2004) emphasized the difference between negative and positive Q-disturbances with regard to spatial variations, in particular. They also noted the principle difference in the latitudinal variations between Q and the usual negative F2-layer disturbances, but a similarity in these variations in the case of positive perturbations. The occurrence frequency and the amplitude of the positive Q-disturbances increase with latitude, whereas both characteristics exhibit no pronounced variation in the case of the negative Q-disturbances. All this implies different formation mechanisms for the two types of Q-disturbances.

The simultaneous consideration of the *Nm*F2 and *Nm*E variations during Q-disturbance events was expected to show the path to an explanation via the vertical gas motion. Moreover, the WINDII/UARS observations (Shepherd et al., 1999, 2004; Ward et al., 1997; Wang et al., 2002) relate directly the atomic oxygen abundance with the vertical gas motion in the lower thermosphere. But the absence of the point-to-point

Table 4. Monthly A_p indices and number (in parenthesis) of negative Q-disturbances observed at Slough for three months and years around solar minimum. Months with low A_p are marked bold.

Month	1962	1963	1964	1965	1966
Nov	12.8 (1)	12.3 (1)	7.3 (1)	**6.0 (3)**	9.5 (1)
Dec	12.8 (0)	10.9 (2)	**5.3 (5)**	7.1 (1)	11.6 (1)
Jan	**7.0 (4)**	11.3 (1)	11.8 (0)	6.2 (1)	**7.5 (4)**

correlation between δNmF2 and δNmE and the weak latitudinal dependence of the occurrence frequency and the amplitude of negative Q-disturbances has forced us to look for some other solution. The fact that negative Q-disturbances occur under very quiet geomagnetic activity allowed us to propose an idea of the ground state of the thermosphere with an unconstrained solar-driven circulation (due to the minimal auroral heating level) and relatively low atomic oxygen abundance in the thermosphere. This made it possible to explain both the morphological features of the negative Q-disturbances. It was shown earlier that the atomic oxygen variations provide the main contribution to the *Nm*F2 changes (Table 3). According to the NRLMSISE-00 model, the latitudinal variations of atomic oxygen at F2-region heights are very small (5–10%), within the (35–65°) latitudinal interval under low geomagnetic activity in December (winter solstice). These small latitudinal variations are in line with the results of the model calculations by Rishbeth and Müller-Wodarg (1999, their Fig. 3), showing almost constant moderate upwelling in a wide range of latitudes under daytime quiet conditions in December. The other parameter, the downward vertical plasma drift W=VnxSinICosI, also does not change much with latitude. Although the SinICosI product decreases by a factor of 2 within the considered latitudinal range, according to the UARS observations, the northward wind Vnx increases with latitude during the December solstice under daytime quiet conditions (Fejer et al., 2000, their Fig. 1). Therefore, one should not expect pronounced latitudinal variations of *Nm*F2 for the conditions in question. The small changes in $\delta Nm = Nm/Nm_{\text{med}}$ also imply small latitudinal variations in the *Nm*F2 median values. The analysis of the monthly medians for the chain of stations from the low-latitude one Alma-Ata (Φ=33.4) to the sub-auroral station St.Petersburg (Φ=56.2) shows small (<6% under solar maximum and <20% under solar minimum) $Nm\text{F2}_{\text{med}}$ variations for the noon hours in December.

As was noted earlier, the appearance of negative Q-disturbances does not imply any physical process but just manifests the difference between the *Nm*F2 values corresponding to the ground state of the ionosphere and to its median level. The latter is always higher, as it bears the effect of downwelling under moderate ($A_p \le 15$) geomagnetic activity. Therefore, we have synchronous δNmF2 and δNmE variations only on average, that is, both deviations are less than the unity, on average.

Considering the mechanism of the F2-layer negative Q-disturbances, it is worth mentioning an attempt to relate the large *Nm*F2 reduction on 16 April 2002 (Fig. 2) with the strong positive B_y component of IMF (Goncharenko et al., 2006). Based on the GUVI/TIMED data on the O/N_2 column density, the authors tried to interpret the observed negative perturbation in terms of an usual negative F2-layer storm effect. Indeed, the GUVI observations show a 30–50% reduction of this ratio on 16 April as compared to the preceding geomagnetically quiet days. During the usual F2-layer negative storms, the O/N_2 ratio also decreases (e.g. Prölss, 1995), but the F2-layer perturbation on 16 April belongs to a different class of events. The F2-layer maximum height *hm*F2 always increases during usual F2-layer negative daytime storms due to the enhanced neutral temperature Tex and linear loss coefficient β. However, during the 16 April event the daytime *hm*F2 values were much lower as compared to the 15 April values (Fig. 2, also their Fig. 2), while both Tex and β were only slightly decreased (Table 2), that is, they changed in the opposite way as compared to the normal variations of these parameters during F2-layer negative storms. The main contribution to the *Nm*F2 reduction in that case belonged to the atomic oxygen variations, but the O/N_2 column density bears no indications of that. The electron concentration in the F2-layer depends on various aeronomic parameters and the dependence is different for each of them (Ivanov-Kholodny and Mikhailov, 1986), so one parameter (the O/N_2 column density) is not sufficient for any physical interpretation.

The positive, long-duration F2-layer disturbances (positive Q-disturbances belong to the same class of the F2-layer perturbations) are related to low or moderate auroral activity, when the solar-driven thermospheric circulation is damped and the neutral gas downwelling increases the atomic oxygen concentration in the thermosphere. This was shown, for instance, by Rishbeth (1998, his Fig. 3). The downwelling increases towards the auroral oval and this explains the increase with latitude of the amplitude and the occurrence frequency of the positive Q-disturbances. By analogy with the negative Q-disturbances, we have the same two factors (the atomic oxygen amount and meridional thermospheric wind), but now they work in opposite direction, thereby increasing *Nm*F2. Another morphological feature of high-and middle-latitude positive Q-disturbances is clustering around equinoxes (Mikhailov et al., 2004). The feature can be related to the maximal occurrence of geomagnetic disturbances during equinoxes (e.g. Roosen, 1966). According to the proposed concept, the enhanced auroral activity damps the meridional wind and stimulates the downwelling, thereby increasing the atomic oxygen abundance at sub-auroral and middle latitudes.

It has been mentioned earlier that the WINDII/UARS data on atomic oxygen variations in the lower thermosphere are directly related to the problem of the Q-disturbances, as these variations are due to the vertical gas motion during the transition periods (Shepherd et al., 2004). Moreover, the spatial and seasonal variations of the O(^{1}S) emission demonstrate the features similar to those revealed for the F2-layer Q-disturbances. Unfortunately, the March–April 1992 period, which is the most thoroughly covered in publications (Shepherd et al., 1999, 2004), was not geomagnetically quiet, and the corresponding variations of ionospheric parameters cannot be considered as Q-disturbances. The other problem is that the authors relate the observed transitions with downwelling and upwelling in the lower thermosphere, whereas in the scope of the proposed concept only the positive Q-disturbances are related to the downwelling, but the upwelling is only supposed to form the ground state of the thermosphere. The coupling from below does exist and some types of the Q-disturbances undoubtedly are related to this coupling, therefore future analyses are needed to check the relationship between such transitions in the lower thermosphere and the Q-disturbances in the F2-region.

6 Conclusions

The results of our analysis may be summarized as follows:

1. The analysis of the daytime (11:00–14:00 LT) observations of *Nm*F2 and *Nm*E at sub-auroral and mid-latitude stations for the periods of positive and negative F2-layer Q-disturbances has shown a synchronous type of the δ*Nm*F2 and δ*Nm*E variations. The δ*Nm*E difference from the unity (i.e. the median) is significant at any confidence level for both negative and positive Q-disturbances. Therefore, under the negative Q-disturbances in the F2-layer we have negative deviations in the E-layer and the positive F2-layer disturbances are accompanied by positive deviations in *Nm*E. Thus, δ*Nm*F2 and δ*Nm*E exhibit in-phase variations in a statistical sense. In the case of the positive Q-disturbances, the in-phase variations take place not only on average, but also at the point-to-point level. This confirms the morphological conclusion obtained earlier that the positive and negative F2-layer Q-disturbances are due to different formation mechanisms.

2. The only mechanism capable of explaining the observed δ*Nm*E variations is the vertical gas motion, which changes the effective scale height H(O_2) of the molecule oxygen distribution at E-region heights. The neutral gas downwelling enriches the thermosphere with atomic oxygen at F2-layer heights and decreases H(O_2) in the E-region, to result in synchronous *Nm*F2 and *Nm*E increases. The upwelling of the neutral gas should result in the opposite effect.

3. The expected variations of atomic oxygen during F2-layer Q-disturbance events were confirmed by the Millstone Hill ISR observations for the periods of positive

and negative Q-disturbances. The self-consistent approach to the N_e(h) modelling at F2-region heights developed earlier has been used to find the thermospheric neutral composition ([O], [O_2], and [N_2]), temperature Tn(h), and vertical plasma drift W related to the thermospheric winds and electric fields. It was shown that both the positive and negative Q-disturbances in the F2-region are mainly due to the atomic oxygen concentration variations. The negative disturbances correspond to low concentration of atomic oxygen and strong poleward neutral wind. The opposite situation takes place for the positive Q-disturbances. However, some morphological features of the negative Q-disturbances cannot be explained by the neutral gas upwelling. Therefore, an idea of the ground state of the thermosphere is proposed.

4. The ground state of the thermosphere corresponds to very low geomagnetic activity, with an unconstrained solar-driven thermospheric circulation characterized by relatively strong daytime poleward wind and relatively low atomic oxygen concentrations at middle and sub-auroral latitudes. It follows from the model calculations by Rishbeth and Müller-Wodarg (1999) that the low concentrations may be related to a moderate upwelling (about 0.5 m/s).

5. The negative Q-disturbances occur under the ground state of the thermosphere, with low atomic oxygen concentration and strong poleward thermospheric wind, which produces the downward plasma drift decreasing *Nm*F2. A weak latitudinal variation of both aeronomic parameters explains the small latitudinal variations in the occurrence frequency and amplitude of the negative Q-disturbances revealed earlier in the morphological analysis. The clustering of the negative Q-disturbances around winter solstice is related to the poleward wind, which is the strongest under such conditions. Actually, the occurrence of negative Q-disturbances is not related to any physical process, but depends on the *Nm*F2 median level from where they are counted. If the month was geomagnetically disturbed with usual negative F2-layer storm events, the *Nm*F2 median level is lower and this does prevent the appearance of the negative Q-disturbances. On the contrary, the negative Q-disturbances should appear if a month was quiet and the *Nm*F2 median level was relatively high.

6. The positive Q-disturbances appear under slightly enhanced auroral activity when the high-latitude heating increases and damps the solar-driven poleward thermospheric circulation. This damping produces a downwelling of the neutral gas with the corresponding enrichment of the thermosphere with atomic oxygen at F2-region heights and a decrease in H(O_2) in the E-region. This results in a synchronous *Nm*F2 and *Nm*E increase. The downwelling is expected to increase towards the auroral oval and this explains the increase with latitude of the amplitude and occurrence frequency of the positive Q-disturbances revealed in our previous morphological analysis. The tendency of the high- and middle-latitude positive Q-disturbances to cluster around equinoxes can be related to the maximal occurrence of geomagnetic disturbances during equinoxes. According to the proposed concept, enhanced auroral activity damps the meridional wind and stimulates neutral gas downwelling, thereby increasing the atomic oxygen abundance at sub-auroral and middle latitudes. The damped poleward neutral wind also reduces the downward plasma drift in the F2-region, thereby increasing *Nm*F2. The positive Q-disturbances just present the left-hand wing of the positive, long-duration F2-layer disturbances area on the A_p-index scale. The mechanism of both disturbances is the same: the damped poleward circulation and neutral gas downwelling resulting in the [O] abundance increase.

7. Different formation mechanisms of the daytime positive and negative Q-disturbances explain the different level of the synchronism in the δ*Nm*F2 and δ*Nm*E variations. For the negative Q-disturbances, we have in-phase δ*Nm*F2 and δ*Nm*E changes only on average (i.e. in a statistical sense), as no physical processes relating δ*Nm*F2 and δ*Nm*E are involved in this case. On the contrary, in the case of the positive Q-disturbances, the downward gas motion in the thermosphere produces the in-phase δ*Nm*F2 and δ*Nm*E changes not only on average, but at the point-to-point level, as well.

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