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Long-term trends of *fo*E and geomagnetic activity variations

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Abstract. A relationship between *fo*E trends and geomagnetic activity long-term variations has been revealed for the first time. By analogy with earlier obtained results on the *fo*F2 trends it is possible to speak about the geomagnetic control of the *fo*E long-term trends as well. Periods of increasing geomagnetic activity correspond to negative *fo*E trends, while these trends are positive for the decreasing phase of geomagnetic activity. This "natural" relationship breaks down around 1970 (on some stations later) when pronounced positive *fo*E trends have appeared on most of the stations considered. The dependence of *fo*E trends on geomagnetic activity can be related with nitric oxide variations at the E-layer heights. The positive *fo*E trends that appeared after the "break down" effect may also be explained by the [NO] decrease which is not related to geomagnetic activity variations. But negative trends or irregular *fo*E variations on some stations for the same time period require some different mechanism. Chemical pollution of the lower thermosphere due to the anthropogenic activity may be responsible for such abnormal *fo*E behavior after the end of the 1960s.

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

1 Introduction

Ionospheric parameter long-term trends have been widely discussed during the last decade. This interest is due to possible anthropogenic impact on the Earth's atmosphere, and the ionospheric trends may serve as an indicator of such changes in the upper atmosphere. The interest was greatly stimulated by model calculations by Roble and Dickinson (1989), Rishbeth (1990) and Rishbeth and Roble (1992), who predicted changes in the neutral atmosphere and related ionospheric effects under the increase in the atmosphere greenhouse gas concentrations. Since then, researchers have been trying to reveal and confirm the predicted ionospheric effects related to the thermosphere cooling (Bremer, 1992, 1998, 2001; Givishvili and Leshchenko, 1994; Ulich and Turunen, 1997; Jarvis et al., 1998; Upadhyay and Mahajan, 1998; Sharma et al., 1999). But the greenhouse hypothesis encounters serious problems at least with the F2-region parameter long-term trends (Mikhailov and Marin, 2000, 2001; Mikhailov et al., 2002; Mikhailov, 2002).

The main efforts have been directed towards the F2-region parameter long-term trends analysis, since these observations are the most abundant and consistent, while trends in the E-region were considered only by some researchers (Givishvili and Leshchenko, 1993, 1995, 1996, 1998; Bremer, 1998, 2001; Sharma et al., 1999). The result of these analyses is that positive *fo*E trends are the most probable and are presumably due to a decrease in the neutral NO concentration at the E-region heights (Danilov and Smirnova, 1997; Bremer, 1998; Danilov, 2001). The "NO mechanism" is strongly supported by $[NO^+]/[O_2^+]$ rocket mass-spectrometer observations analyzed by Danilov (1997), Danilov and Smirnova (1997). Since the late 1950s, this ratio demonstrates a pronounced decrease which can be related only to a [NO] decrease at the E-region heights.

The nitric oxide concentration in the E-region is known to be strongly dependent on the geomagnetic activity level (e.g. Titheridge, 1997; Solomon and Barth, 1999; Ridley et al., 1999). Therefore, in the framework of the NO mechanism, in principle, one may expect *fo*E trends of different signs for the periods of rising and falling geomagnetic activity, and this would be a good test for the proposed explanation. Besides this mechanism of natural origin, an anthropogenic impact on the neutral atmosphere cannot be excluded as well. Among such artificial factors are the earlier mentioned greenhouse effect and the atmosphere pollution due to the increasing rate of rocket and satellite launchings (Kozlov and Smirnova, 1999; Adushkin et al., 2000). Unfortunately, earlier proposed methods for the E-region trend analysis cannot be used for such investigations, and a new, more accurate approach should be developed to reveal and separate natural and anthropogenic (if it exists) parts in the

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*fo*E long-term variations.

The aim of the paper is to develop a method which would be able to remove solar and geomagnetic activity effects from the observed *fo*E long-term variations, to analyze the dependence of *fo*E trends on the phase of geomagnetic activity and to check for any unnatural effects present in the *fo*E trends revealed.

2 Method description

A general method for the $F2$-layer trends analysis was described by Mikhailov et al. (2002), which, with some modifications, is used in the present study. As earlier we proceed from an assumption that natural *fo*E long-term variations are due to solar and long-term geomagnetic activity variations which may be presented by R_{12} and 11-year running mean A_p indices. The method includes the following steps:

1. Observed mid-latitude monthly median *fo*E values for 10:00, 11:00, 12:00, 13:00, 14:00 LT are reduced to a 12:00 LT moment, to give average noon *fo*E values. The dependence *fo*E $\propto$ $(\cos\chi_o)^p$, where χ_o – solar zenith angle and $p = 0.6$ (Muggletone, 1972), is used for this reduction. The use of an average over 5 values increases the reliability of the analyzed noon *fo*E values.

2. A regression of this noon *fo*E with R_{12}

   $$foE_{reg} = a_0 + a_1 R_{12}^{\alpha} \quad (1)$$

   is used to define monthly relative deviations

   $$\delta foE = \left(foE_{obs} - foE_{reg}\right)/foE_{obs}. \quad (2)$$

   We, as initially it was proposed by Danilov and Mikhailov (1998, 1999), we analyze relative rather than absolute δ*fo*E deviations normally considered in the ionospheric trend analyses by most of the authors. As far as we know, relative deviations were considered only by Deminov et al. (2000), to analyze *fo*F2 trends. Relative deviations allows us to combine different months and obtain annual mean δ*fo*E which are used in the analysis, with the final method being based on the 11-year running mean δ*fo*E values. A simple arithmetic running mean smoothing with an 11-year gate is applied everywhere .

   The optimal 12 different values of α (for each month of the year) are specified to provide the least standard deviation (*SD*) after a regression (see later) of 11-year smoothed δ*fo*E values with Ap_{132} (11-year running mean A_p indices). The 11-year δ*fo*E smoothing requires all 12 values of α to be available simultaneously at each step of the *SD* minimization. This implies an application of special multi-regressional methods (Press et al., 1992) to solve the problem considered.

   The expression (1) is of a general type and depending on α, it can describe both the linear and nonlinear relationship of *fo*E with R_{12}. The regression coefficients a_i are specified by the least-squares method for each month and a given α value. It should be stressed that the expression (1) does not provide the best approximation of the observed *fo*E versus R_{12} dependence (other dependencies may give less sum of residuals), but it should be considered in terms of the following δfoE_{132} regression with Ap_{132} to find the minimal *SD* (see later). Therefore, the regression (1) is not a "model" in the usual sense of this word, as it is accepted in other approaches. This regression is used to remove the solar activity part from the observed *fo*E variations, since a "pure" *fo*E dependence on solar activity (presented by the R_{12} index) a priori is not known for each month. The application of this general approach has shown that all 12 values of α turned out to be close to unity, and this strongly simplifies the calculation. It should be noted that monthly α vary in a wide range in the case of the *fo*F2 trends analysis (Mikhailov et al., 2002). The reason for α to be close to unity is considered in the Discussion.

3. One-hour gaps in *fo*E within the 10:00–14:00 LT interval are filled by spline interpolation, but large gaps in observations are not filled. If the number of months with available *fo*E values for a given year is less than 6, then the year is marked as "zero". During the 11-year δ*fo*E smoothing, the arithmetic mean is calculated over the non-zero years only. Due to this smoothing, even one-year gaps do not introduce any visible deviation in the foE_{132} variation. But large gaps result in noticeable perturbations in the δfoE_{132}, variations and an additional analysis is needed for each station to select the period for analysis. Therefore, only clear enough periods were left for further analysis on each station.

4. The geomagnetic activity effect is removed from the 11-year running mean δ*fo*E variation using a regression with Ap_{132}

   $$\delta foE_{132} = b_0 + b_1 Ap_{132}^{\beta}(t+n), \quad (3)$$

   where δfoE_{132} and Ap_{132} are 11-year running mean values, β is a fitting parameter, $\boldsymbol{n} = 0 \div -5$ is a time shift in years of Ap_{132} with respect to δfoE_{132} variations, both parameters being specified to give the least *SD* for the residuals after Eq. (3). The regression coefficients b_i are found by the least squares-method.

5. Our previous analysis (Mikhailov et al., 2002) has shown that the best results (the least *SD*) can be obtained if an additional smoothing is applied to δfoE_{132} and Ap_{132} variations. Such smoothing is made by a 5-order polynomial approximation of these parameter variations.

6. The residual linear trend with the slope K_r (in 10^{-4} per year) may be estimated over the residuals after the regression (3).

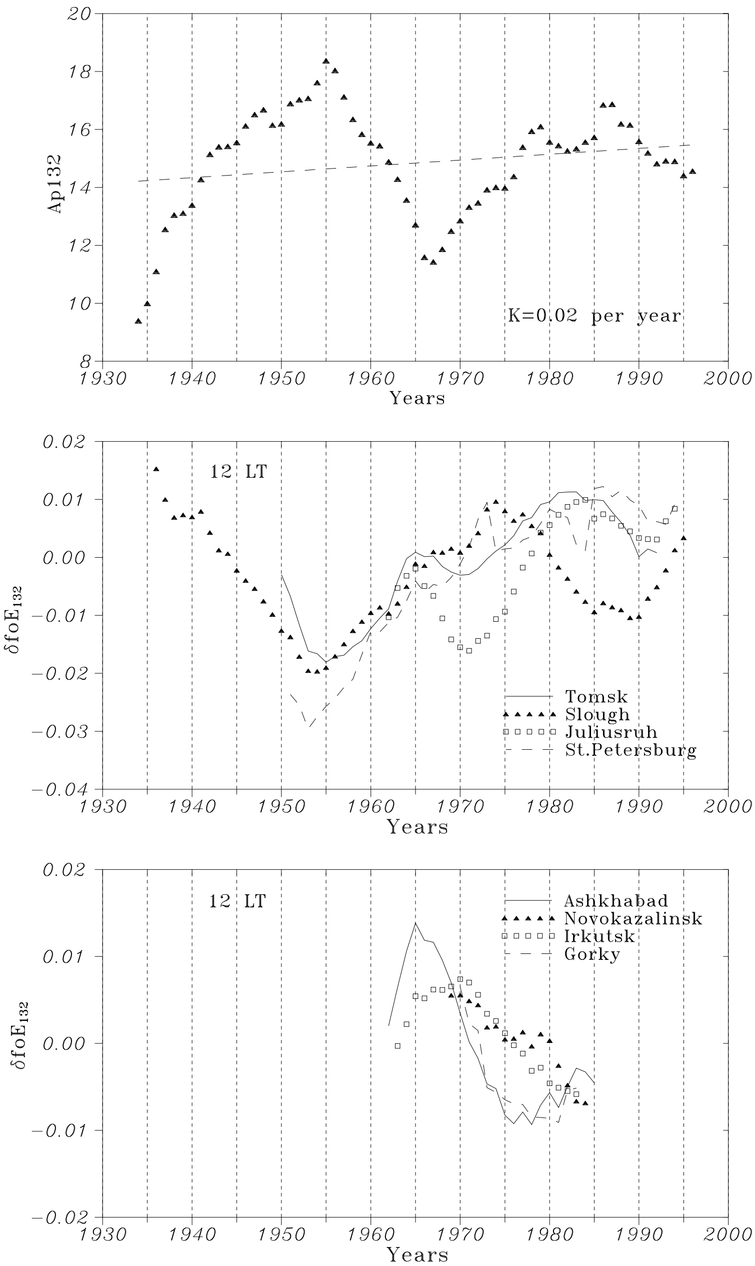

Fig. 1. Long-term variations of geomagnetic activity (top panel) and corresponding $\delta fo\mathrm{E}_{132}$ changes for the stations with different types of $\delta fo\mathrm{E}_{132}$ variations after the end of the 1960s. Note the unsystematic $\delta fo\mathrm{E}_{132}$ variations after the end of the 1960s (middle panel). Dashed line in the top panel is a linear, very long-term trend with the slope $K = 0.02$ per year in geomagnetic activity obtained over the observed Ap_{132} variations.

7. The test of significance for the linear trend parameter K_r (the slope) is made with Fisher's F criterion (Pollard, 1977)

   $$F = r^2(N-2)/1-r^2),$$

   where r is the correlation coefficient and N is the number of pairs considered. Keeping in mind that we work with smoothed variations, we put the number of degrees of freedom $(N-2) = 4$ (the 5th order polynomial is defined by 6 coefficients).

3 Dependence on geomagnetic activity

Figure 1 demonstrates $\delta fo\mathrm{E}_{132}$ and Ap_{132} long-term variations. Four stations with available periods of observations (in brackets): Slough (1931–2000), Tomsk (1945–1997), St. Petersburg (1946–1999), and Juliusruh (1957–1999) were used in these calculations (Fig. 1, middle panel). The 11-year smoothing applied to δfoE reduces the available periods by 10 years as shown in Fig. 1. Negative *fo*E trends are seen to take place before 1953–1955 for the period of increasing ge-

Table 1. The sign of the $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence ("+" – direct, "-" – inverse) and years during which it persists. Symbol "0" means the absence of any pronounced dependence

Station	Coordinates Lat	Coordinates Lon	Period and sign of dependence	Station	Coordinates Lat	Coordinates Lon	Period and sign of dependence
Tomsk	56.5	84.9	+ 1971-1983	Uppsala	59.8	17.6	+ 1970–1979
Rome	41.9	12.5	+ 1972–1987	Karaganda	49.8	73.1	+ 1970–1977
Tashkent	41.3	69.6	+ 1969–1979	Slough	51.5	359.4	+ 1955–1974
Ekaterunburg	56.7	61.1	+ 1972–1984	Moscow	55.5	37.3	+ 1954–1977
Poitires	46.6	0.3	+ since 1970	Kiev	50.7	30.3	0 1969–1977
Alma-Ata	43.2	76.9	+ since 1964	Boulder	40.0	254.7	0 since 1968
Tbilisi	41.7	44.8	+ since 1971	Gorky	56.1	44.3	- 1970–1981
Khabarovsk	48.5	135.1	+ since 1969	Novokazalinsk	45.8	62.1	- 1969–1984
St.Petersburg	59.9	30.7	+ since 1953	Lannion	48.5	356.7	- 1976–1981
Yakutsk	62.0	129.6	+ 1971–1983	Ottawa	45.4	284.1	- 1962–1977
Dourbes	50.1	4.6	+ 1964–1992	Irkutsk	52.5	104.0	- 1970–1983
Kaliningrad	54.7	20.6	+ 1969–1979	Ashkhabad	37.9	58.3	- 1966–1977

omagnetic activity (Fig. 1, top), while they are positive until 1965, in accordance with the decrease in geomagnetic activity. Close $\delta fo\mathrm{E}_{132}$ variations are seen to take place for the stations until 1965, while this coherence breaks down after the end of the 1960s. A tendency to switch to a negative *fo*E trend is clearly seen for Tomsk and Juliusruh after 1965, in accordance with a positive phase in the Ap_{132} variation, but something overpowers this tendency, making the trends positive. The $\delta fo\mathrm{E}_{132}$ variations are seen to be different at different stations after 1970. Therefore, the "natural" type of $fo\mathrm{E}_{132}$ dependence on geomagnetic activity seems to break down after the end of the 1960s.

Figure 2 shows the $fo\mathrm{E}_{132}$ versus Ap_{132} dependence in a explicit way for Tomsk, Rome, and Khabarovsk. The inverse relationship takes place between these parameters before 1970 (Rome–1972), but it switches abruptly to a direct one around 1970. The selected stations demonstrate the most pronounced cases of such a changeover in the type of dependence. The results of such analysis for 24 mid-latitude ionosonde stations are given in Table 1. Unfortunately, observations on many stations start only after 1964–65 (1969–70 after 11-year smoothing); therefore, it is only possible to check the sign of this dependence for the years available. For the long observing stations only the discussed period is considered in Table 1.

Table 1 shows that most of the stations demonstrate a direct $\delta fo\mathrm{E}_{132}$ relationship with Ap_{132} after 1968–1972, but there are stations (the end of Table 1) which exhibit the inverse type of this dependence for the same period. Variations of $\delta fo\mathrm{E}_{132}$ for these stations are given in Fig. 1 (bottom). Although *fo*E observations are absent for earlier years on these stations, they clearly show the "natural" type of behavior, that is the inverse $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence. Ashkhabad and Irkutsk present the best cases with positive *fo*E trends before 1965 and negative ones afterwards, in accordance with the Ap_{132} long-term variation (Fig. 1, top). At Ashkhabad this "natural" dependence breaks down after 1976. This analysis shows that not all stations were subjected to that breakdown of the "natural" *fo*E behavior after the end of the 1960s. The reason(s) for this is not clear now, and further analysis is needed to explain this interesting result. An important conclusion of this analysis is that *fo*E trends similar to *fo*F2 trends are subjected to geomagnetic control (Mikhailov and Marin, 2000; Mikhailov, 2002), that is the sign of the *fo*E trend depends on the phase of geomagnetic activity long-term variations (Fig. 1, top).

4 Complementary and residual *fo*E trends

The observed $\delta fo\mathrm{E}_{132}$ long-term variations show a clear dependence on geomagnetic activity at least for the period before 1970–1972, while some stations demonstrate this dependence for later years as well (Fig. 1). Therefore, we may try to remove this "natural" dependence on geomagnetic activity and analyze the residual *fo*E trend. Figure 3 shows the $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence for Slough and Ashkhabad, where the "natural" type of *fo*E behavior takes place for different years. Two branches are seen in this dependence: on Slough – before and after 1955, on Ashkhabad – before 1965 and after 1967 (Fig. 3, left-hand panels). The inverse type of $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence takes place for both branches, but the curves are shifted. It seems as if the "efficiency" of geomagnetic activity has been increasing with time as the same $\delta fo\mathrm{E}_{132}$ values correspond to lower Ap_{132} after the end of the 1950s on Slough and after 1967 on Ashkhabad. The same effect takes place at Tomsk (Fig. 2 for early ages), Moscow, and St. Petersburg, not shown in the plot. It should be stressed that Ashkhabad, which was

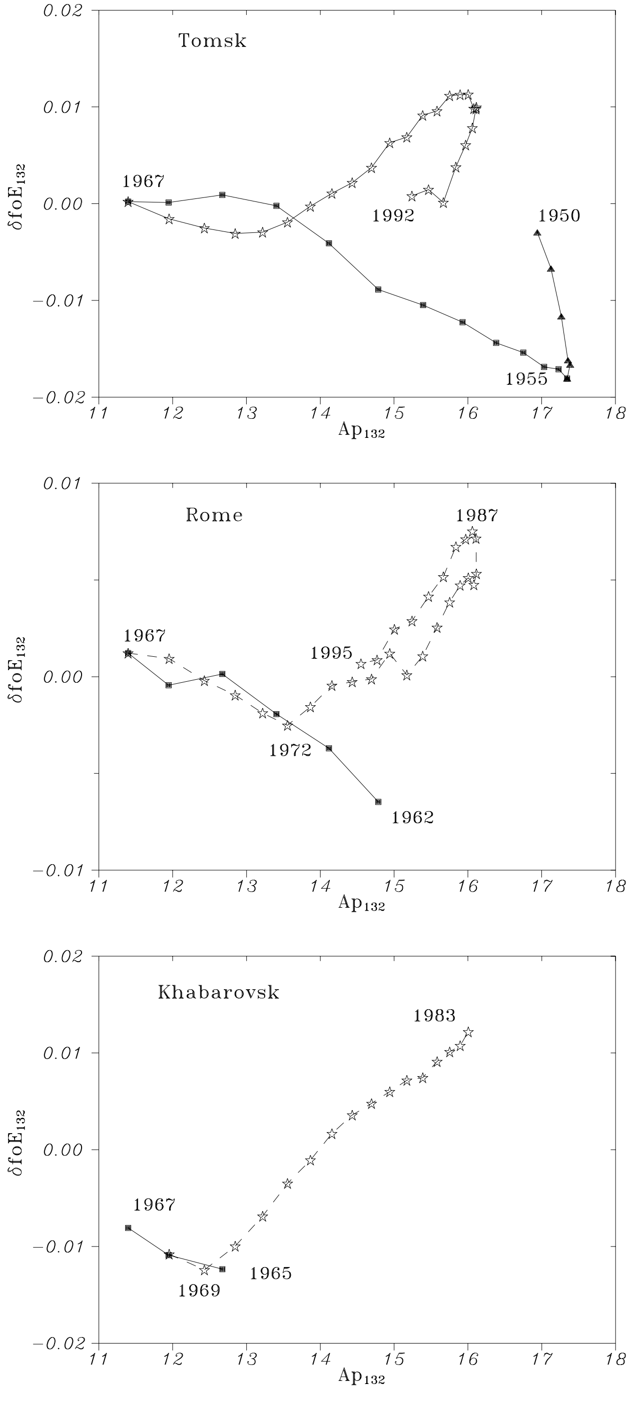

Fig. 2. Relationship between $\delta fo\mathrm{E}_{132}$ and Ap_{132} for three stations with a pronounced "break down" effect in this dependence after the end of the 1960s.

not subjected to the 1970–1972 "break down" effect, demonstrates the same type of $\delta fo\mathrm{F2}_{132}$ versus Ap_{132} dependence and for later years as well. (Fig. 3, left-hand bottom panel).

The ambiguity in this dependence can be removed to a great extent by adding a complementary positive linear trend K_c to the $\delta fo\mathrm{E}_{132}$ variations. This approach was used earlier for the *fo*F2 long-term trend analysis (Mikhailov et al., 2002) where the same situation takes place. By a complete analogy with the *fo*F2 trend results, the least *SD* (the best fitting) is obtained if the complementary trend is applied for the whole analyzed period, starting from the first year. The optimum complementary trends $K_\mathrm{c} = +5.13 \times 10^{-4}$ per year for Slough and $K_\mathrm{c} = +11.8 \times 10^{-4}$ per year for Ashkhabad, being added to $\delta fo\mathrm{E}_{132}$ variations squeeze the loops in the $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence practically to one curve (Fig. 3, right-hand panels), while the curves after 1967 for Slough and after 1975 for Ashkhabad exhibit quite different types of variation.

Figure 4 shows observed (smoothed) and calculated $\delta fo\mathrm{E}_{132}$ variations, as well as their difference for Slough and Ashkhadad. A good quality of model fitting practically results in zero residual trends on Slough ($K_\mathrm{r} = -0.22\times^{-4}$ per year for the period 1936–1967) and on Ashkhadad ($K_\mathrm{r} = 0.04 \times 10^{-4}$ per year over 1962–1975), the trends being insignificant in both cases. This means that the "natural" $\delta fo\mathrm{E}_{132}$ dependence on geomagnetic activity can be efficiently removed and there is no residual *fo*E trend left. On the other hand, strong positive *fo*E trends are seen for the two stations after the years mentioned.

5 Discussion

The proposed approach to the *fo*E trend analysis has shown a close relationship between $\delta fo\mathrm{E}_{132}$ and Ap_{132} long-term variations. The "natural" type of this dependence is the inverse one, that is positive *fo*E trends correspond to decreasing geomagnetic activity and vice verse. This is a new result which was not mentioned in earlier publications on the *fo*E trends. However, it should be mentioned that Givishvili and Leshchenko (1996), using quite different methods were the first to reveal the *fo*E trends of different signs before and after the end of the 1950s without any explanation of this effect. Due to this dependence on the phase of geomagnetic activity, one should be careful with the selection of the periods for trend analysis and not put together years belonging to different (rising/falling) periods of geomagnetic activity. Unfortunately, this is not taken into account in other publications devoted to the ionospheric trends and this (as one of the reasons) results in a chaos of various signs and magnitudes of the trends at various stations.

Our approach allows us to remove to a great extent solar and geomagnetic activity effects from *fo*E long-term variations and to show that the residual *fo*E trends are close to zero for the years before the "break down" effect occurs in the $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence (see earlier). From a physical point of view, the obtained result is interesting, telling us that practically all observed *fo*E long-term variations may be attributed to the variations in solar and geomagnetic activity – that is they are of a natural origin. An additional (presumably of a manmade origin) effect is also clearly seen in the $\delta fo\mathrm{E}_{132}$ variations after the end of the 1960s on most of the stations and for later years on some other stations.

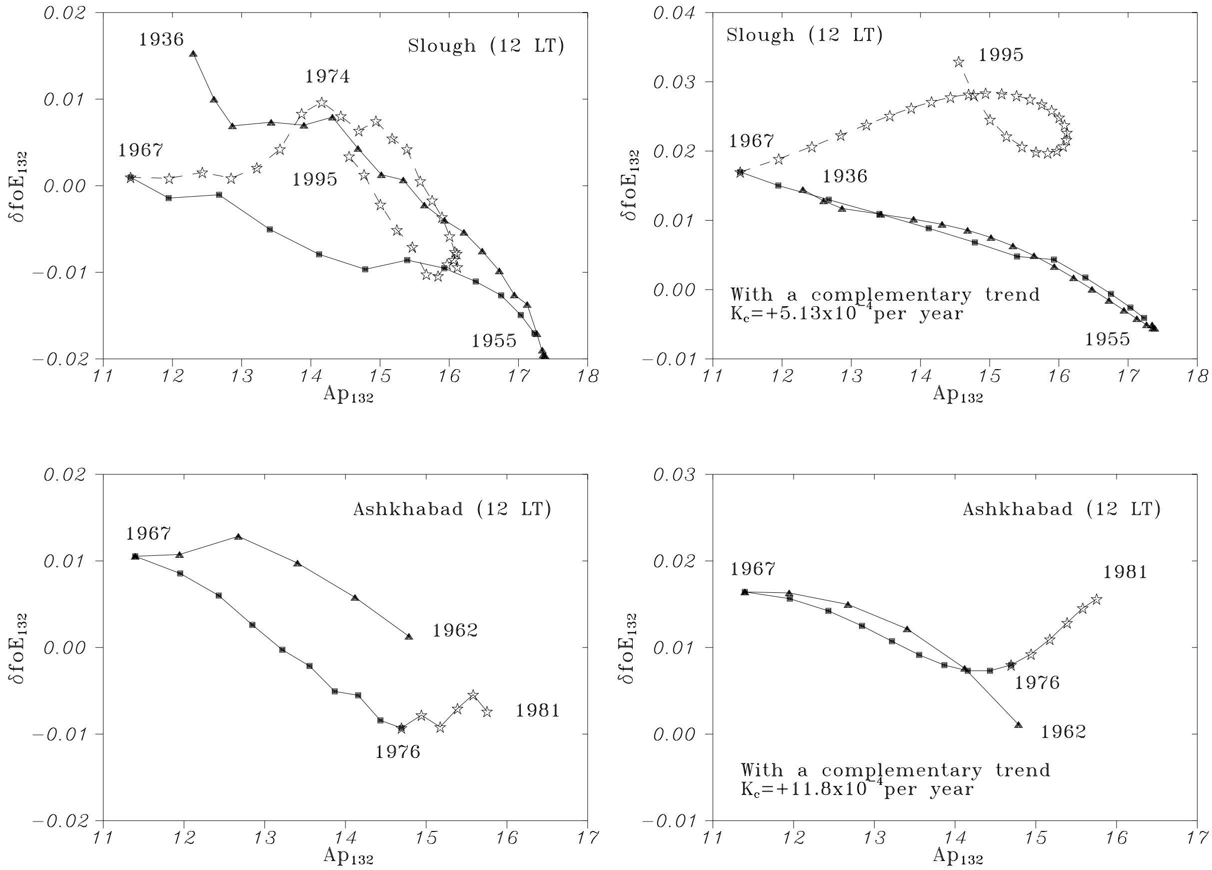

Fig. 3. Two stations illustrating the "natural" inverse type of $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence during 1936–1967 on Slough and 1962–1975 on Ashkhabad (left-hand panel). Right-hand panels show the same dependencies after applying the complementary trends. Note the tightening of the two branches in the $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence before the "break down" effect occurs.

The obtained results are mainly due to the efficiency of the method applied and some comments are required in this relation. The first one concerns the procedure of the solar activity effect removal. According to our general approach to the trend analysis (Mikhailov et al., 2002), first, we used a general type of *fo*E relationship with R_{12} (see Eq. 1), to remove the solar activity part from *fo*E long-term variations. But unlike our previous results on the *fo*F2 trend analysis (Mikhailov et al., 2002), where monthly α values varied in a wide range $1.8 < \alpha < 3$, in the case of *fo*E, the α parameter turned out to be close to unity and this strongly simplified the calculations. This result may be explained as follows. As the mid-latitude daytime E-layer is produced via the ionization of neutral O_2 by two close *EUV* lines $\lambda = 977$Å (CIII) and $\lambda = 1025.7$Å (HLyβ), the classical Chapman theory (Chapman, 1931) may be applied in this case with a sufficient accuracy (Ivanov-Kholodny and Nusinov, 1979). The ionization rate in the E-layer maximum may be written as

$$q_m = \frac{I_\infty \sigma^i \cos\chi_\Theta}{H\sigma^a e}, \tag{4}$$

where I_∞ – the incident ionizing flux, H – scale height of neutral O_2, χ_o – solar zenith angle, $\sigma^{i,a}$ – ionization and absorption cross sections. Critical frequency, *fo*E is proportional to

$$fo\mathrm{E} \propto \sqrt[4]{q_m/\alpha_{\mathrm{eff}}}, \tag{5}$$

where α_{eff} is the effective dissociative recombination coefficient for the molecular ions NO^+ and O_2^+. The intensity of solar *EUV* emission is proportional to $F_{10.7}^p$, where $p = 1 \div 0.67$ (Nusinov, 1984, 1992; Tobiska et al., 2000, and references therein). Our method gave a linear *fo*E relationship with R_{12}. This is also valid for $F_{10.7}$, as annual mean $F_{10.7}$ and R_{12} indices are known to be highly correlated (the correlation coefficient is 0.991 being significant at the 99% confidence level). This means that under the root sign we have to have an expression depending on solar activity as $F_{10.7}^4$, or the $H\alpha_{\mathrm{eff}}$ product should be proportional to $F_{10.7}^{-3}$, at least. The only possibility of obtaining such a strong dependence on solar activity is to take into account a strong dependence of T_e/T_n on $F_{10.7}$, revealed by rocket probe measurements in the E-region at the 110 km height (Duhau and Azpiazu, 1985; also Oyama et al., 2000). We used this idea earlier to explain seasonal variations in the E-region (Mikhailov et al., 1999). The dependence T_e/T_n versus $F_{10.7}$ (Fig. 2 in Duhau and Azpiazu, 1985) is well approximated by cubic polynomial on $F_{10.7}$. Keeping in mind

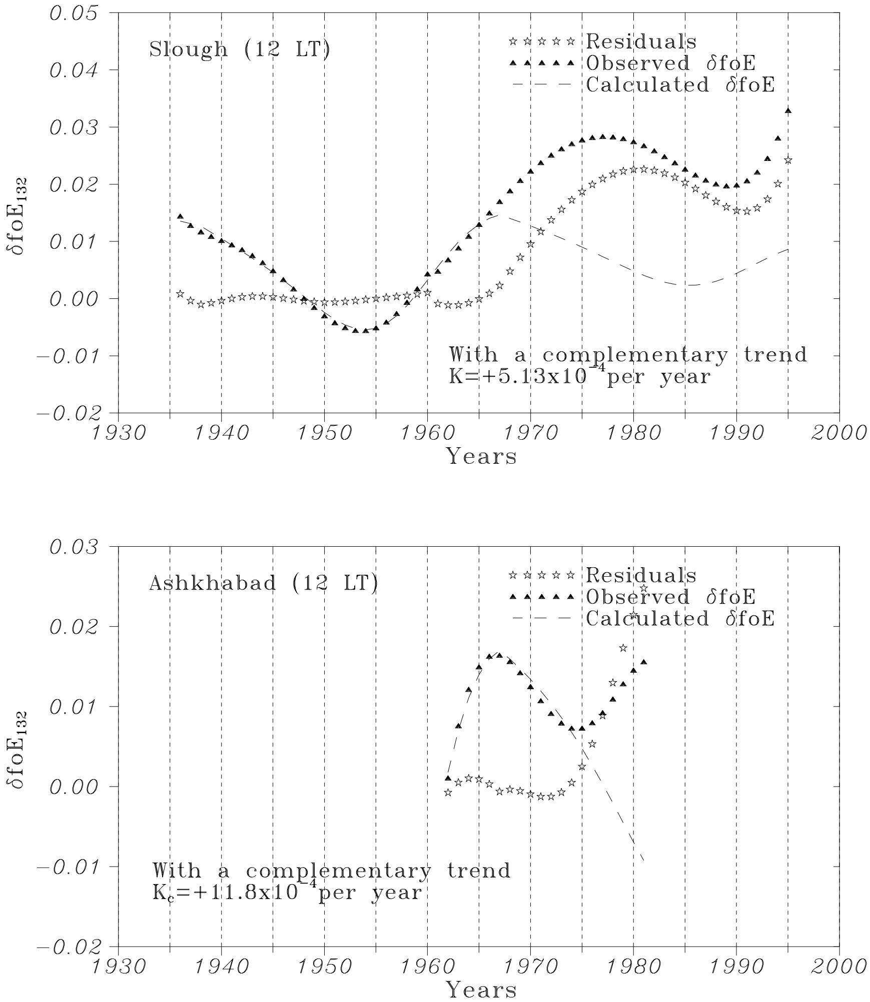

Fig. 4. Polynomial approximated observed, calculated $\delta fo\mathrm{E}_{132}$ and their difference, resulting in practically zero residual *fo*E trends on Slough and Ashkhabad for the period before the "break down" effect occurs. Calculations were performed with the complementary trends given on the plots.

that α_{eff} is proportional to $T_{\mathrm{e}}^{-0.8}$, this practically gives the required dependence on $F_{10.7}$ under the root sign in (5), while T_{n} is highly compensated in the $H\alpha_{\mathrm{eff}}$ product as $H \propto T_{\mathrm{n}}$.

The other problem concerns the removal of geomagnetic activity effects from the *fo*E long-term variations. This problem was discussed by Mikhailov et al. (2002) with respect to *fo*F2 trends. Here we used the same approach with the only difference – the dependence on β in the regression (3) is of a general type as a priori we do not have any information on this dependence. Similar to F2-layer trends, a time shift n (in years) of Ap_{132} with respect to $\delta fo\mathrm{E}_{132}$ variations is required to obtain the least *SD* for the residuals after the regression (3). In our case the average time shift is 1 year. As in the F2-layer case, no physical explanation can be proposed now for this delayed thermosphere reaction to the geomagnetic activity variations, and a special consideration is required to understand this result. Such time delay implies the whole Earth's atmosphere to be involved with the processes provoked by geomagnetic activity. Changes in the global atmospheric circulation and/or in eddy diffusion and related variations in the thermospheric neutral composition and temperature is the most probable mechanism. On the other hand, one should keep in mind that Ap_{132} maybe is not the most adequate proxy for solar wind influence on long-term trend studies. Unfortunately, A_p, as well as R_{12}, are the only indices which have been observed long enough to be used for the long-term trend analyses.

The revealed relationship between *fo*E trends and geomagnetic activity may be explained by the variations of nitric oxide, NO, whose concentration in the E-region is strongly dependent on the geomagnetic activity level (e.g. Titheridge, 1997; Solomon and Barth, 1999; Ridley et al., 1999). The variation of [NO] alters the $[\mathrm{NO}^+]/[\mathrm{O}_2^+]$ ratio by transforming primary O_2^+ ions to NO^+ via the fast charge transfer reaction

$$\mathrm{O}_2^+ + \mathrm{NO} \rightarrow \mathrm{NO}^+ + \mathrm{O}_2 \quad \left(\gamma = 4.4 \times 10^{-10}\right) . \tag{6}$$

After this, the standard scheme (e.g. Danilov, 1994) of chemical processes may be used. The total ion concentration ($\mathrm{n_e} = \Sigma \mathrm{n_i}$) in the E-region is presented by molecular ions O_2^+ and NO^+ which disappear via the reactions of dissociative recombination

$$\mathrm{NO}^+ + \mathrm{e} \rightarrow \mathrm{N} + \mathrm{O} \left(\alpha = 4.5 \times 10^{-7}\,(300/\mathrm{T_e})^{0.83}\right) \tag{7}$$

$$\mathrm{O}_2^+ + \mathrm{e} \rightarrow \mathrm{O} + \mathrm{O} \left(\alpha = 1.95 \times 10^{-7}\,(300/\mathrm{T_e})^{0.7}\right). \tag{8}$$

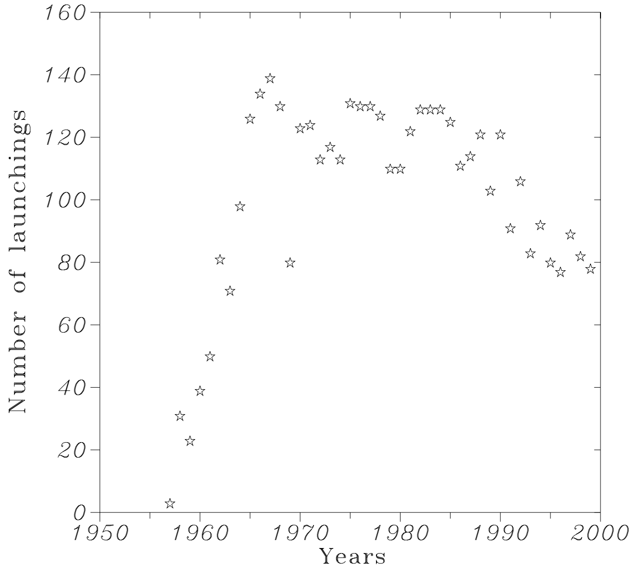

Fig. 5. Total number of rocket launchings during the 1957–1999 period.

The key point of the "NO mechanism" is the difference in the reaction rate constants of these two reactions. Under increasing geomagnetic activity (before 1955 and after 1967, Fig. 1, top), resulting in the neutral [NO] increase, the share of NO^+ ions increases via the reaction (6). Since the recombination rate for NO^+ ions is higher (Eqs. 7 and 8), the electron concentration decreases and we have negative trends in *fo*E (Fig. 1, middle and bottom panels). During the decreasing phase of geomagnetic activity (1955–1967), the situation inverses and we have positive trends in *fo*E (Fig. 1). This mechanism explains the "natural" relationship of *fo*E trends with geomagnetic activity.

An inclusion of a complementary linear trend to our analysis restores the unambiguity in the $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence (Fig. 3) and practically results in zero residual trends (Fig. 4) at least for the years when a "natural" relationship between $\delta fo\mathrm{E}_{132}$ and Ap_{132} is valid. By a complete analogy with the results of the *fo*F2 trend analysis (Mikhailov et al., 2002), the only plausible explanation (as it is seen from now) of the complementary trend is a compensation of a negative *fo*E trend, which is due to a very long-term increase in geomagnetic activity during the 20th century. This increase is seen even for the analyzed period (Fig. 1, top) where a positive trend with $K = 0.02$ per year exists in the observed Ap_{132} variation. Figure 1 (top) is only a fragment of the general picture showing the increase in geomagnetic activity in the course of the 20th century (e.g. Clilverd et al., 1998). This long-term effect in geomagnetic activity cannot be removed using conventional indices and smoother Ap_{132} indices are required for its description. But this is a very delicate question which requires a special consideration and is not discussed here. The same NO mechanism can be used to explain the negative background *fo*E trend related to this very long-term increase in geomagnetic activity.

But around 1970±2 (on some stations later), this "natural" inverse relationship of *fo*E trends with geomagnetic activity has broken down. A well-pronounced positive *fo*E trend not related to geomagnetic activity variations has appeared on most of the stations analyzed (Fig. 2 and Table 1). In some cases this hardly can be considered as a trend – just a positive $\delta fo\mathrm{E}_{132}$ upsurge lasting for some years followed by a drop in the $\delta fo\mathrm{E}_{132}$ variation (Table 1, Fig. 1). But in many cases, this is a prolonged positive effect. The only plausible possibility is to relate this effect with the anthropogenic impact on the upper atmosphere. Among such mechanisms may be considered the increasing rate of rocket and satellite launchings which leads to the thermosphere chemical pollution (Kozlov and Smirnova, 1999; Adushkin et al., 2000) and the greenhouse effect mentioned in the Introduction.

Since the E-region formation mechanism is relatively simple, some explanations may be proposed for this positive effect in the $\delta fo\mathrm{E}_{132}$ variations. A decrease in the molecular oxygen neutral scale height H will increase the production rate and *fo*E, correspondingly (see Eqs. 4 and 5). The scale height H may be decreased by an intensified downward air motion at the E-region heights, as model calculations show (Mikhailov, 1983). Another possible channel of the *fo*E increase is via a decrease in the effective dissociative recombination coefficient α_{eff} (Eq. 5) due to a decrease in [NO] at the E-region heights. The decrease in α_{eff} in this case is due to the $[NO^+]/[O_2^+]$ ratio decrease, as explained earlier. This mechanism of positive *fo*E trends was considered by Danilov (2001), who has found a strong confirmation of it in both the $[NO^+]/[O_2^+]$ ratio trend at 120 km and in the positive trend of electron concentration in the D-region, where the ionization of NO plays the dominate role in the total ionization rate. Both results may be explained by the vertical transfer of NO from the E- to D-region due to intensified downward air motion or eddy diffusion. The latter was obtained by Kalgin (1998), analyzing rocket mass-spectrometer data on the $[Ar]/[N_2]$ ratio at the E-region heights for the 1966–1991 period. But vertical air motion seems to be more preferable, since it decreases the neutral scale height H and transfers NO downward, thus, increasing the positive effect in *fo*E.

Such explanations come from normal processes taking place in the lower thermosphere. But chemical pollution due to rocket launching may result in quite a different scheme of chemical processes, since the rocket fuel comprises exotic for the upper atmosphere components. Long-living "holes" in the electron concentration is a well-known effect accompanying heavy rocket launchings (Adushkin et al., 2000). Such chemical pollution looks as a very probable mechanism to explain the break down effect in the natural $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence around 1970–1972. Figure 5 gives the number of rocket launchings for the 1957–1999 period. Data may be found in Aviation Week and Space Technology for 1957–1991, Rocket-Space Technique GONTI-1 for 1975–2000 (in Russian), (Adushkin et al., 2000). Maximum occurrence of rocket launchings is seen to take place in the second half of the 1960s. Keeping in mind that some time is necessary for the accumulation of the effect, we obtain the discussed "break down" time around 1970.

With regard to the greenhouse hypothesis widely used in attempts to explain the ionospheric trends, the following may be noted. There are serious problems with this hypothesis in the F2-region (Mikhailov and Marin, 2001; Mikhailov 2002), since it cannot be reconciled with the observed F2-layer parameter trends. Positive *fo*E trends in the E-region observed for some periods seem to be in qualitative agreement with this hypothesis, but the observed trends already are much larger than predicted (Bremer, 2001), although we are still very far from the doubling of greenhouse gases in the atmosphere (Keeling et al., 1995; Houghton et al., 1996). On the other hand, positive *fo*E trends, usually related with the worldwide greenhouse effect, in fact does not take place at all stations – the sign of trends may be different (Fig. 1 and Table 1). One can say about the spotty global pattern with an unsystematic *fo*E behavior at different stations after 1970 (cf. Slough and Juliusruh in Fig. 1, middle panel). It is only possible to conclude that since the beginning of the 1970s, there has appeared an additional factor in the lower thermosphere which has broken down the normal *fo*E dependence on geomagnetic activity on a long-term time scale. Chemical pollution of the upper atmosphere due to the rocket launchings and perhaps the greenhouse effect look like the most probable reasons.

6 Conclusions

The main results of our analysis may be summarized as follows:

1. Using a newly proposed approach to the *fo*E trend analysis, it was shown for the first time the relationship between *fo*E trends and geomagnetic activity long-term variations. By a complete analogy with the earlier obtained results on the *fo*F2 trends, the periods of increasing geomagnetic activity correspond to negative *fo*E trends, while these trends are positive for the decreasing phase in geomagnetic activity. Therefore, it is possible to speak about the geomagnetic control of the *fo*E long-term trends as well.

2. Similar to the *fo*F2 trends, there exists a background negative *fo*E trend which may be considered as a manifestation of a very long-term geomagnetic activity increase which took place during the 20th century (e.g. Clilverd et al., 1998). This effect is seen in the $\delta fo\mathrm{E}_{132}$ versus Ap_{132} dependence before the breaking down of "natural" dependence around 1970 (on some stations later). After removal of this background effect the residual *fo*E trends are close to zero and insignificant. This means that observed "natural" *fo*E long-term variations (trends) have a natural origin and may be attributed to solar and geomagnetic activity long-term variations.

3. The dependence of *fo*E trends on geomagnetic activity can be related with [NO] variations at the E-layer heights, where the [NO] is known to be dependent on the geomagnetic activity level. The key point of this NO mechanism is the $[\mathrm{NO}^+]/[\mathrm{O}_2^+]$ ratio change, resulting in the effective dissociative recombination coefficient alteration.

4. Positive *fo*E trends (or more or less prolonged positive upsurges) appearing after the "break down" effect around 1970 may be related with the [NO] decrease at the E-region heights due to the intensification of the downward air motion (Danilov, 2001). But negative trends or irregular *fo*E variations also take place on some stations for the same time period, and this tells us about some other additional mechanism. Chemical pollution of the lower thermosphere due to the increasing rate of the rocket launchings and/or the greenhouse effect may be responsible for such abnormal *fo*E behavior since the beginning of the 1970s.

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