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A revised approach to the *fo*F2 long-term trends analysis

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Abstract. A new approach to extract *fo*F2 long-term trends, which are free to a great extent from solar and geomagnetic activity effects, has been proposed. These trends are insensitive to the phase (increasing/decreasing) of geomagnetic activity, with long-term variations being small and insignificant for such relatively short time periods. A small but significant residual *fo*F2 trend, with the slope $K_r = -2.2 \times 10^{-4}$ per year, was obtained over a 55-year period (the longest available) of observations at Slough. Such small trends have no practical importance. On the other hand, negative (although insignificant) residual trends obtained at 10 ionosonde stations for shorter periods (31 years) may be considered as a manifestation of a very long-term geomagnetic activity increase which did take place during the 20th century. All of the revealed *fo*F2 long-term variations (trends) are shown to have a natural origin related to long-term variations in solar and geomagnetic activity. There is no indication of any manmade *fo*F2 trends.

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

1 Introduction

Due to an increasing interest in the anthropogenic impact on the Earth's atmosphere the ionospheric parameter long-term trends are widely discussed in recent publications (Bremer, 1992, 1998; Givishvili and Leshchenko, 1994, 1995; Givishvili et al., 1995; Danilov, 1997, 1998; Ulich and Turunen, 1997; Rishbeth, 1997; Jarvis et al., 1998; Upadhyay and Mahajan, 1998; Sharma et al., 1999; Foppiano et al., 1999; Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000; Deminov et al., 2000; Danilov and Mikhailov, 2001). The interest in the ionospheric trend analysis was greatly stimulated by the model calculations of Rishbeth (1990) and Rishbeth and Roble (1992), who predicted the ionospheric effects of the atmosphere greenhouse gas concentration increase. Since then, researchers have been trying to reveal the predicted ionospheric effects related to the thermosphere cooling (Bremer, 1992; Givishvili and Leshchenko, 1994; Ulich and Turunen, 1997, Jarvis et al., 1998; Upadhyay and Mahajan, 1998). The atmosphere cooling effect should have been noticeable in the *hm*F2 rather than in the *fo*F2 trends, due to a weak dependence of *Nm*F2 on neutral temperature. Moreover, the expected neutral temperature decrease due to the greenhouse effect should result in a positive *fo*F2 trend in contrast to the observations (Mikhailov and Marin, 2000). The analyzes have shown that there are well-pronounced and significant *hm*F2 as well as *fo*F2 trends. The worldwide pattern of the F2-layer parameter trends turned out to be very complicated and this cannot be reconciled with the greenhouse hypothesis. On the other hand, one cannot exclude the anthropogenic effects in the upper atmosphere related to the increasing rate of rocket and satellite launching during the last few decades, which has led to the thermosphere pollution (Kozlov and Smirnova, 1999; Adushkin et al., 2000). Therefore, further efforts are required in this direction to find out the physical mechanism of the F2-layer trends.

Despite many publications devoted to the F2-layer parameter long-term trends, the results of different authors are still contradictory to a great extent. This is due to both the accuracy of the experimental material and the methods used to extract long-term trends from the observations. The most suitable for the trend analysis parameter is the F2-layer critical frequency. It has been observed routinely over the worldwide ionosonde network for 3–5 solar cycles using one and the same method of ionospheric sounding. The critical frequency, *fo*F2, is registered directly (unlike *hm*F2) and with an acceptable accuracy of ≈ 0.1 MHz. Unlike *fo*E or *fo*F1, the F2-layer critical frequency is observed all day long and this allows one to follow diurnal variations in the *fo*F2 long-term trends. But even in case of *fo*F2, the useful "signal" is very small and the "background" is very noisy, therefore, the success of analysis depends strongly on the method used. An approach being developed by Danilov and Mikhailov (1999) and Mikhailov and Marin (2000, 2001) has allowed us to

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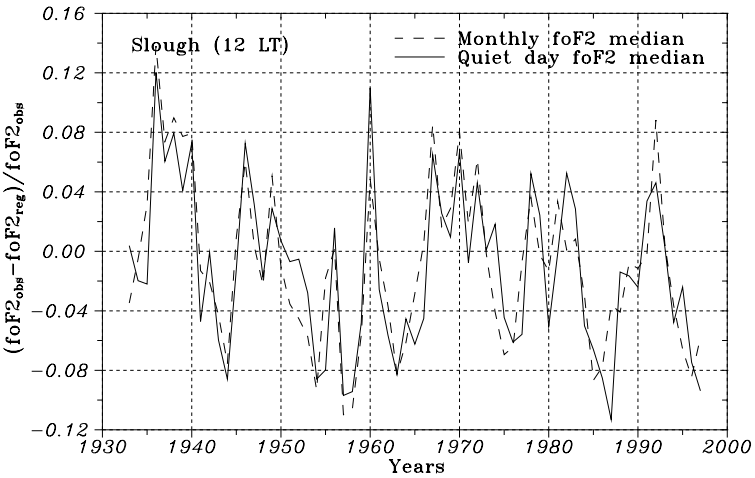

Fig. 1. A comparison of annual mean δ*fo*F2 variations at Slough (12:00 LT) when the usual monthly median and *Q*-median *fo*F2 values are used in the calculations.

find systematic variations in *fo*F2 and *hm*F2 trends, unlike other approaches (e.g. Bremer, 1998; Upadhyay and Mahajan, 1998), resulting in various signs and magnitudes of the trends at various stations. An application of this approach to the *fo*F2 trend analysis resulted in a geomagnetic control concept (Mikhailov and Marin, 2000, 2001) to explain the revealed latitudinal and diurnal variations of the F2-layer parameter long-term trends. It was shown that an interpretation of the F2-layer parameter trends should consider the geomagnetic effects as an inalienable part of the trends revealed and this can be done based on the contemporary understanding of the F2-layer storm mechanisms (Mikhailov and Marin, 2000, 2001).

Although the geomagnetic control concept allowed us to explain the main morphological features of the *fo*F2 long-term trends revealed, there are still some questions remaining. The most important one is whether it is possible to remove the geomagnetic effect from the *fo*F2 long-term variations, in order to analyze the residual trends. What is the origin (anthropogenic or natural) of such residual trends if they exist? Earlier developed approaches cannot be used for such analysis as they give *fo*F2 trends that are strongly contaminated with geomagnetic activity effects, despite the attempts to delete them (Mikhailov and Marin, 2000, 2001). Therefore, a revised method has been developed in this paper which allows us to delete to a great extent solar and geomagnetic activity effects from the observed *fo*F2 long-term variations and reveal the residual *fo*F2 trends.

2 Method description

A revised method described here is based on the analysis given in Sect. 3 of the paper. The final version of the method comprises the following.

1. We proceed from an assumption that observed *fo*F2 variations are mainly due to solar and long-term geomagnetic activity variations that (with some reservations) may be described with R_{12} and 11-year running mean Ap indices. The results of our analysis (see later) have shown that such a combination provides the best description accuracy and the most consistent results. Therefore, the method includes the following steps. A regression of monthly *fo*F2 with R_{12}

$$foF2_{reg} = a_0 + a_1\, R_{12}^{\alpha} \tag{1}$$

is used to find monthly relative deviations

$$\delta foF2 = (foF2_{obs} - foF2_{reg})/foF2_{obs}\ . \tag{2}$$

We analyze (for each LT moment) relative rather than absolute δ*fo*F2 deviations considered in the *fo*F2 and *hm*F2 trend analyzes by Bremer (1998); Ulich and Turunen (1997); Jarvis et al. (1998); Upadhyay and Mahajan (1998); Sharma et al. (1999); Foppiano et al. (1999). As far as we know relative deviations were considered only by Deminov et al. (2000) in their *fo*F2 long-term trend analysis. Relative deviations allow us to combine different months and obtain an annual mean δ*fo*F2 that is used in the analysis, with the final method being based on the 11-year running mean δ*fo*F2 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 an 11-year smoothed δ*fo*F2 with Ap_{132} (11-year running mean Ap indices). The 11-year δ*fo*F2 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) matched 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*F2 with R_{12}. The regression coefficients a_i are specified by the least-squares method for each

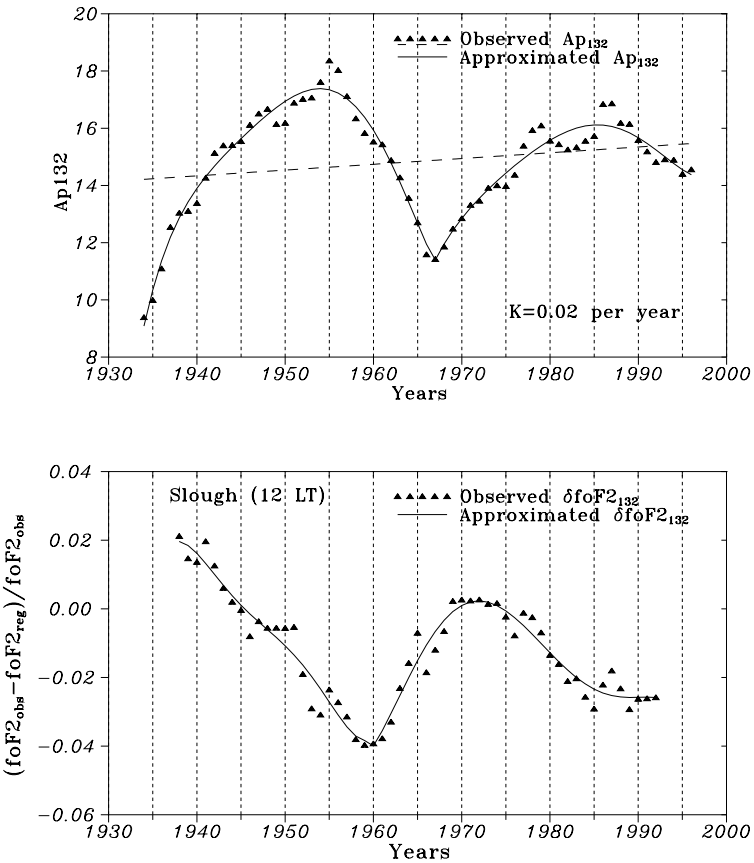

Fig. 2. Observed and polynomial approximated Ap_{132} and $\delta foF2_{132}$ variations used in the trend analysis. Dashed line is a linear, very long-term trend with the slope K = 0.02 per year in geomagnetic activity obtained over the observed Ap_{132} variations. Note also a 4-year shift between the Ap_{132} and $\delta foF2_{132}$ variations.

month and a given α value. It should be stressed that the expression (1) does not provide the best approximation of the observed *fo*F2 versus R_{12} dependence (other dependencies may yield a smaller sum of the residuals), but it should be considered in terms of the following regression with Ap_{132} to find the minimal SD (see later). Therefore, the regression (1) is not a "model" in the usual sense of the word, since it is accepted in all earlier approaches. This regression is used to remove the solar activity part from the observed *fo*F2 variations as a "pure" *fo*F2 dependence on solar activity (presented by the R_{12} index) a priori is not known for each month (see Sect. 6: Discussion).

2. Q-medians proposed by Deminov et al. (2000) are used in the method instead of the usual monthly *fo*F2 ones. Such Q-medians are obtained over quiet days of each month. In our approach, unlike that of Deminov et al. (2000), a day is considered to be quiet if daily $Ap \leq 10$ for this and the two previous days. The Q-median value is set to zero if there are no such days in a month. A threshold was set to 1 and 3 quiet days a month. Testing has shown that generally 3-quiet day medians provide better results for some stations, but too many gaps in the observations, due to such severe selection, led to peculiar results on other stations. Therefore, the 1-quiet day threshold has been accepted. An example of annual mean $\delta foF2$ (after Eq. 2) variations obtained with the usual monthly and Q-medians is shown in Fig. 1. The difference is seen for the two cases, both during the periods of solar maximum and minimum. It may seem not to be very large, but one should keep in mind that during the trend analysis, we work at the level of noise and even small differences in the initial material may affect the final result. Despite the removal of short-term (monthly) geomagnetic effects by using Q-medians, strong year-to-year $\delta foF2$ fluctuations take place (Fig. 1). These oscillations may be related to the variations in solar activity (Ivanov-Kholodny and Chertoprud, 1992; Ivanov-Kholodny, 2000), but they are not removed by any regression with R_{12} or Ap, and an 11-year running mean smoothing is applied to conquer them (see later).

3. Unlike our earlier method, where only years around solar cycle maxima and minima were analyzed to avoid the hysteresis effect at the rising and falling parts of solar cycles, the proposed method uses all years available. A comparison has shown close results for different year selections using the proposed method. This takes away the problem of using different year selections for *fo*F2 and *hm*F2 trend analysis (Marin et al., 2001; Mikhailov and Marin, 2001).

Gaps in observations are not filled in. If the number

Table 1. Correlation coefficients, r, between $\delta foF2_{132}$ and Ap_{132} found over one and the same period 1957–97 (1962–92 after 11-year smoothing). The "appr." refers to the polynomial approximated $\delta foF2_{132}$ and Ap_{132} variations. The first line refers to Q-medians, the second to the usual monthly *fo*F2 medians used in the calculations. Bold face figures show significant r with a confidence level 99%, normal face figures correspond to 95% confidence level, italic figures are not significant r. The optimal time shift Δt (in years) between $\delta foF2_{132}$ and Ap_{132} variations is given as well

Station	00:00 LT				12:00 LT			
	$\delta foF2_{132}$ appr. vs. Ap_{132}	Δt	$\delta foF2_{132}$ appr. vs. Ap_{132} appr.	Δt	$\delta foF2_{132}$ appr. vs. Ap_{132}	Δt	$\delta foF2_{132}$ appr. vs. Ap_{132} appr.	Δt
Lycksele	*−0.773*	0	*−0.778*	0	−0.906	-2	**−0.932**	-2
	−0.863	-5	−0.859	-5	**−0.959**	0	**−0.984**	0
Uppsala	−0.911	-2	**−0.943**	-2	**−0.919**	-2	**−0.946**	-2
	−0.758	-2	*−0.757*	-2	**−0.938**	0	**−0.977**	0
St. Petersburg	*−0.504*	-2	*−0.493*	-2	**−0.927**	-3	**−0.957**	-3
	−0.734	0	*−0.771*	0	−0.887	-1	−0.913	-1
Juliusruh	−0.843	-2	−0.857	-2	−0.881	-3	−0.898	-3
	−0.881	0	−0.916	0	−0.882	-2	−0.908	-2
Moscow	−0.828	-2	−0.842	-2	**−0.928**	-3	**−0.974**	-3
	−0.922	0	**−0.948**	0	−0.908	-2	**−0.942**	-2
Tomsk	*−0.684*	-3	*−0.671*	-3	*−0.629*	-3	*−0.608*	-3
	−0.795	0	−0.828	0	*−0.809*	0	−0.833	0
Slough	−0.902	-3	**−0.921**	-2	**−0.941**	-3	**−0.971**	-3
	−0.791	0	−0.817	0	**−0.935**	-2	**−0.977**	-2
Dourbes	**−0.918**	-4	**−0.960**	-4	−0.861	-4	**−0.918**	-4
	−0.845	-1	−0.856	-1	*−0.725*	-2	*−0.756*	-3
Poitiers	**−0.916**	-4	**−0.931**	-4	−0.859	-4	−0.894	-4
	−0.924	-2	**−0.957**	-2	*−0.770*	-5	*−0.817*	-4
Rome	**−0.933**	-2	**−0.967**	-2	**+0.919**	-3	**+0.951**	-3
	−0.853	-4	−0.865	-4	*−0.594*	-3	*−0.625*	-3

of months with available *fo*F2 values for a given year is less than 6, then the year is marked as "zero". During the 11-year $\delta foF2$ smoothing, the arithmetic mean is calculated over the non-zero years only.

4. The geomagnetic activity effect is deleted from the 11-year running mean $\delta foF2$ variation using a regression with Ap_{132}

$$\delta foF2_{132} = b_0 + b_1\, Ap_{132}(t+n) + b_2\, Ap^2_{132}(t+n)\ , \qquad (3)$$

where n is a time shift in years of Ap_{132} with respect to $\delta foF2_{132}$ variations, which is selected to give the least SD for the residuals after Eq. (3). The regression coefficients b_i are specified by the least-squares method. A nonlinear dependence of $\delta foF2$ on the geomagnetic activity is expected in accordance with Zevakina and Kiseleva (1978) and Muhtarov and Kutiev (1998).

5. An analysis has shown that the best results (the least SD) can be obtained if an additional smoothing is applied to $\delta foF2_{132}$ and Ap_{132} variations. Such smoothing is made by a 5-order polynomial approximation of these parameter variations. The initial and approximated Ap_{132} and $\delta foF2_{132}$ variations are shown in Fig. 2 for Slough (12:00 LT) as an example. A 4-year shift is clearly seen between the two variations.

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

7. The test of significance for the linear trend parameter K_r (the slope), as well as for the correlation between the parameters analyzed, 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 set the number of degrees of freedom to be $(N-2) = 4$ (the 5th order polynomial is defined by 6 coefficients). Such tough requirements on the $(N-2)$ value formally results in insignificant trends, in many cases, despite the existence of obvious and pronounced trends calculated over some dozens of points. Sometimes the number of degrees of freedom is higher than 4 and this is mentioned separately in each case. Student's T-criterion (Pollard,1977) was used to test whether the difference between values is significant.

3 Choosing a combination of parameters

In developing the method we have considered monthly, the annual mean and the 11-year running mean $\delta foF2$, to find the

Table 2. Correlation coefficients, r, between $\delta fo\mathrm{F2}_{132}$ and R_{132} found over one and the same period 1957–97 (1962–92 after 11-year smoothing). The "appr." refers to the polynomial approximated $\delta fo\mathrm{F2}_{132}$ and R_{132} variations. The first line refers to Q-medians, the second to the usual monthly *fo*F2 medians used in the calculations. Bold face figures show significant r with a confidence level 99%, normal face figures correspond to 95% confidence level, italic figures are not significant r. The optimal time shift Δt (in years) between $\delta fo\mathrm{F2}_{132}$ and R_{132} variations is given as well

Station	00:00 LT				12:00 LT			
	$\delta fo\mathrm{F2}_{132}$ appr. vs. R_{132}	Δt	$\delta fo\mathrm{F2}_{132}$ appr. vs. R_{132} appr.	Δt	$\delta fo\mathrm{F2}_{132}$ appr. vs. R_{132}	Δt	$\delta fo\mathrm{F2}_{132}$ appr. vs. R_{132} appr.	Δt
Lycksele	*−0.631*	0	*−0.768*	0	*−0.791*	-1	**−0.924**	-1
	−0.888	-5	−0.885	-4	−0.845	0	**−0.921**	0
Uppsala	−0.849	-1	**−0.952**	-1	*−0.891*	0	**−0.947**	-1
	−0.548	-3	*−0.728*	-2	*−0.789*	0	−0.910	0
St. Petersburg	*−0.400*	-5	*−0.425*	-4	−0.905	-3	**−0.973**	-3
	−0.450	0	*−0.575*	0	*−0.720*	0	−0.852	-1
Juliusruh	*−0.683*	-1	−0.849	-1	*−0.795*	-3	−0.911	-2
	−0.699	0	−0.843	0	*−0.775*	-2	−0.887	-2
Moscow	*−0.718*	-3	−0.851	-2	**−0.948**	-2	**−0.994**	-2
	−0.774	0	−0.890	0	−0.843	-1	**−0.924**	-2
Tomsk	*−0.608*	-5	*−0.659*	-3	*−0.596*	-5	*−0.614*	-4
	−0.545	0	*−0.674*	0	*−0.613*	0	*−0.682*	0
Slough	*−0.768*	-2	**−0.919**	-2	**−0.942**	-4	**−0.996**	-3
	−0.555	0	*−0.672*	0	**−0.949**	-2	**−0.991**	-1
Dourbes	**−0.939**	-4	**−0.997**	-4	−0.896	-3	**−0.960**	-4
	−0.737	-1	*−0.762*	-1	*−0.662*	-2	*−0.730*	-3
Poitiers	**−0.922**	-5	**−0.957**	-3	−0.852	-4	−0.947	-5
	−0.837	-1	**−0.951**	-1	*−0.767*	-2	−0.830	-4
Rome	−0.867	-1	**−0.981**	-1	+0.869	-1	**+0.957**	-2
	−0.869	-5	−0.898	-4	*−0.509*	-1	*−0.558*	-3

combination which would provide the least SD after deleting the geomagnetic activity effect. The latter was supposed to be presented by smoothed or non-smoothed Ap or R_{12} indices. Usual monthly and Q-median, smoothed and non-smoothed *fo*F2 values were considered. The R_{12} index was considered (along with Ap) as an indicator of long-term solar/geomagnetic activity variations (Deminov et al., 2000). In the beginning we examined the correlation coefficients between δfoF2 and Ap (or R_{12}) indices. Only the results which led us to the final method (Sect. 2) are presented here.

All correlation coefficients for monthly, as well as for annual mean δfoF2, are found to be low (0.2–0.5), both for non-smoothed and smoothed Ap (or R_{12}) indices and, therefore, cannot be considered as candidates for the method. An essential increase in the correlation coefficient takes place only after moving to 11-year running mean values. An additional increase in the correlation is possible if one applies a smoothing approximation to $\delta fo\mathrm{F2}_{132}$ and Ap_{132} (or R_{132}) variations (Fig. 2). Such approximated values provide the largest correlation coefficients and the least SD; therefore, this approach was used in the final method.

The testing results over 10 stations are given in Tables 1 and 2, where Q- and the usual monthly *fo*F2 medians are compared. Ap_{132} and Ap_{132} approximated indices were used in Table 1, while R_{132} and R_{132} approximated – in Table 2. One and the same period 1957–1997 (1962–1992 after the 11-year smoothing) for all stations was considered. Maximal correlation coefficients corresponding to the optimal time shift of Ap_{132} (or R_{132}), with respect to $\delta fo\mathrm{F2}_{132}$ variations, are given in Tables 1 and 2 for 00:00 and 12:00 LT.

The results of Tables 1 and 2 show that the correlation coefficients are larger when both approximated $\delta fo\mathrm{F2}_{132}$ and Ap_{132} (or R_{132}) variations are considered. The difference when approximated and non-approximated indices are used is significant at the 99.9% confidence level according to the T-criterion. The use of Q-medians compared to the usual monthly ones provides a larger number of significant cases. The percentage of significant cases (Q-medians/usual medians) is 80% / 67% when Ap_{132} is used, and 67% / 45% when R_{132} is considered. Therefore, Q-medians seem to be preferable for the method. On the other hand, the difference between significant correlation coefficients from Tables 1 and 2 is not significant according to the T-criterion when Ap_{132} is used, and the difference between the two medians is significant at the 98% confidence level (Q-medians are better) when R_{132} is considered. Thus, some additional characteristics should be compared. A comparison of the time shift between δfoF2 and Ap_{132} (or R_{132}) variations can help select the best combination. The average optimal time shifts along with SD calculated for the significant cases from Tables 1 and 2 are given in Table 3. The Q-medians/Ap_{132} approximated combination provides the least SD for the time shift, which is around −3 years. This combination has been chosen for the final method.

Table 3. Average optimal time shift with $\pm SD$ between δ*fo*F2 and Ap_{132} (or R_{132}) approximated variations calculated from the results of Tables 1 and 2

Q-medians		Usual monthly medians	
Ap_{132} appr.	R_{132} appr.	Ap_{132} appr.	R_{132} appr.
−2.8±0.83	−2.3±1.25	−1.4±1.59	−1.6±1.62

Table 4. Ionosonde stations and calculated slope K_r (in 10^{-4} per year) for the period of increasing geomagnetic activity 1965–1991. K_{M+m} values from Mikhailov and Marin (2000) are given for a comparison. Bold face figures for K_{M+m} show significant trends with a confidence level ≥ 90%, italic face figures are trends which are not significant at the 90% confidence level

Station	Φ	Φ_{inv}	Geographic		00:00 LT		12:00 LT	
	Deg	Deg	Lat	Lon	K_r	K_{M+m}	K_r	K_{M+m}
Lycksele	62.70	61.42	64.70	18.80	*−6.21*	**+1.9**	*−0.96*	**−26.0**
Uppsala	58.44	56.61	59.80	17.60	*−0.56*	**−42.2**	*−0.40*	**−27.6**
St. Petersburg	56.17	55.91	60.00	30.70	*−1.04*	*−19.2*	*−0.09*	**−16.1**
Juliusruh	54.40	51.61	54.60	13.40	*−1.80*	**−33.7**	*−0.82*	**−12.2**
Ekateringburg	48.42	51.45	56.70	61.10	*−5.20*	**−30.2**	*−0.31*	**−12.0**
Moscow	50.82	51.06	55.50	37.30	*−1.10*	**−25.6**	*+0.31*	*−12.0*
Tomsk	45.92	50.58	56.50	84.90	*−0.95*	*−16.9*	*−1.10*	**+5.0**
Slough	54.25	49.80	51.50	359.43	*−0.27*	*−13.1*	*−0.52*	*−5.9*
Dourbes	51.89	47.80	50.10	4.60	*−0.30*	**−3.9**	*−0.25*	*+1.7*
Poitiers	49.40	45.05	46.60	0.30	*−0.83*	*−9.4*	*−0.67*	**−0.3**
Rome	42.46	37.48	41.90	12.52	*0.00*	**−2.3**	*−2.57*	**+6.2**
Ashkhabad	30.39	30.55	37.90	58.30	*−0.40*	**−4.4**	*−0.88*	**−1.4**

Table 5. Same as Table 4, but for the period of decreasing geomagnetic activity 1955–1970

Station	00:00 LT		12:00 LT	
	K_r	K_{M+m}	K_r	K_{M+m}
Slough	*+0.66*	**+38.9**	*−1.29*	**+20.3**
Moscow	*+0.25*	**+32.2**	*−0.03*	**+16.2**
Tomsk	*+0.46*	*+12.4*	*+0.06*	*+15.2*

The obtained significant correlation coefficients (Tables 1 and 2) are seen to be large and negative both for 00:00 and 12:00 LT. The only case of positive correlation of δ*fo*F2 with geomagnetic activity is demonstrated at the lower latitude station of Rome at 12:00 LT, and this may be explained in the framework of contemporary F2-layer storm mechanisms (Mikhailov and Marin, 2001).

4 Rising and falling periods in geomagnetic activity

The basic points of the geomagnetic control concept by Mikhailov and Marin (2000) is the dependence of *fo*F2 trends on geomagnetic (invariant) latitude and the existence of negative/positive *fo*F2 trends for the periods of long-term increasing/decreasing geomagnetic activity. Both features were explained using the F2-layer storm mechanisms (Mikhailov and Marin, 2001). Therefore, if the revised approach is free of the geomagnetic control, then both features should be absent in the *fo*F2 trends revealed. The same period 1965–1991, as in Mikhailov and Marin (2000) of increasing geomagnetic activity (Fig. 2, top), was chosen for the analysis (Table 4). Keeping in mind the 11-year smoothing, only stations with available observations for the period 1960–1996 could be analyzed. Slopes K for (M+m) year selection from Mikhailov and Marin (2000) are given for a comparison. Table 4 shows that unlike our previous results the calculated trends do not demonstrate any latitudinal dependence being small and insignificant. Relatively large and insignificant K_r for Lycksele (00:00 LT) and Rome (12:00 LT) are random and due to the scatter of data for the conditions in question.

Similar analysis was made for the 1955–1970 period (Table 5) of decreasing geomagnetic activity (Fig. 2, top) for the 3 stations from Mikhailov and Marin (2000) where observations are available at least since 1950. The calculated trends are seen to be small and insignificant, while K_{M+m}

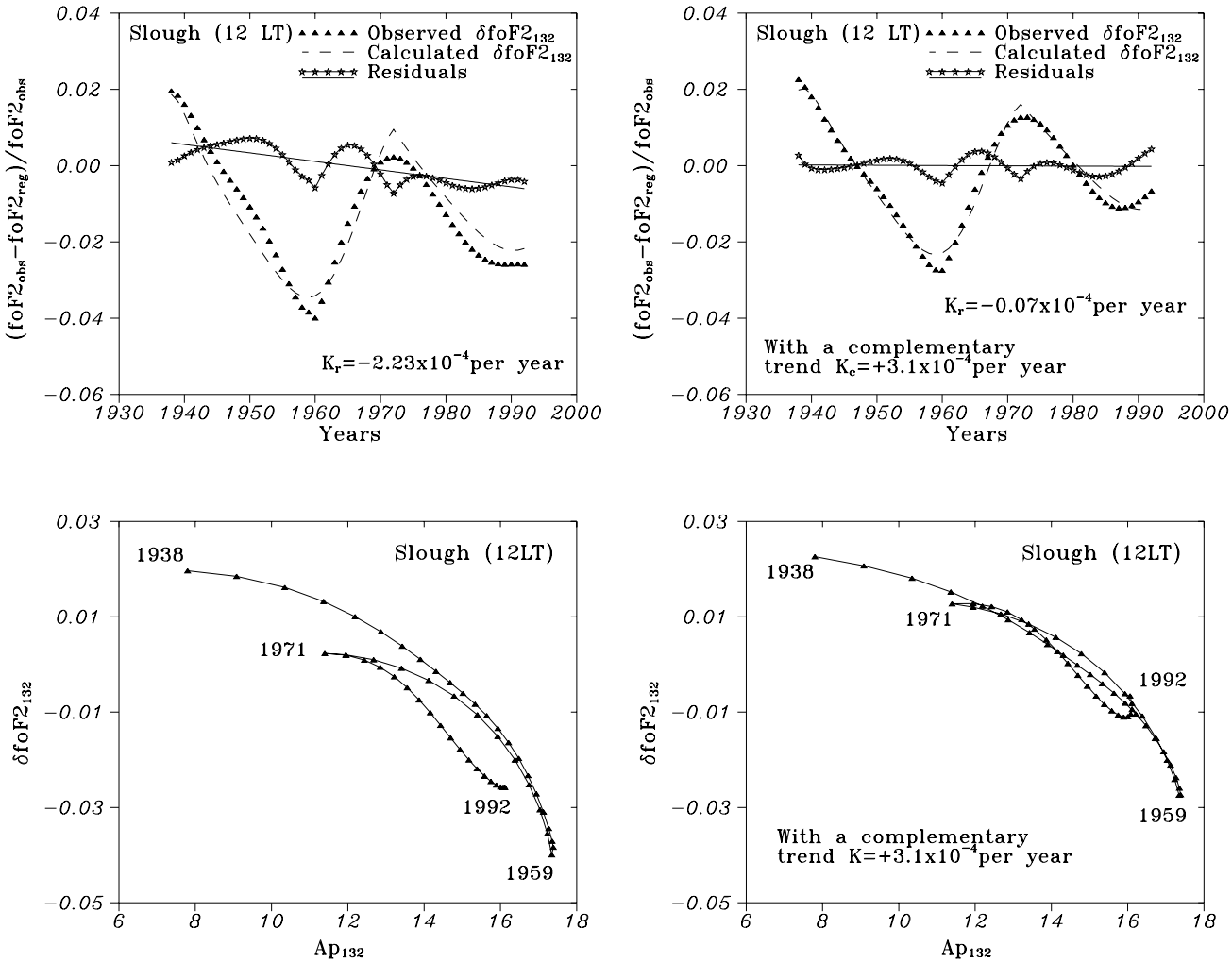

Fig. 3. Observed, calculated $\delta fo\mathrm{F2}_{132}$ and their difference resulting in a residual *fo*F2 trend with the slope K_r for Slough 12:00 LT (top panels), along with the relationship between polynomial approximated $\delta fo\mathrm{F2}_{132}$ and Ap_{132} (bottom panels). Right-hand panels show the results with a complementary trend ($K_c = +3.1 \times 10^{-4}$ per year). Note the tightening of two branches in the $\delta fo\mathrm{F2}_{132}$ versus Ap_{132} dependence (left-hand, bottom) after applying a complementary trend (right-hand, bottom).

are large and positive, in accordance with the geomagnetic control concept.

The results obtained show that the proposed method provides *fo*F2 trends which are small, insignificant and latitudinal independent, regardless of the phase of the geomagnetic activity long-term variation. This means that trends are free of geomagnetic effects in terms of the geomagnetic control concept. On the other hand, most of the trends are seen to be negative (Table 4) and this may tell us about an additional mechanism affecting the trends (see later).

5 Residual *fo*F2 trends

The obtained *fo*F2 trends were shown to be insignificant for relatively short time intervals (rising or falling periods of geomagnetic activity). Obviously, high correlation coefficients, resulting in good fitting and small K_r, can be easier obtained for short time intervals, including only one branch of the geomagnetic activity variation, but this may not be the case for longer periods. Therefore, the method was applied to Slough where *fo*F2 observations for 12:00 LT are available for the 1933–1997 period. After 11-year smoothing, the available period for analysis reduces to 1938–1992. Calculated and observed $\delta fo\mathrm{F2}_{132}$ variations, as well as their differences, are shown in Fig. 3 (left-hand, top). The proposed method is seen to describe the main features of the observed $\delta fo\mathrm{F2}_{132}$ variation. The residuals demonstrate a long-term linear trend with a slope $K_r = -2.23 \times 10^{-4}$ per year, which is significant at the 95% confidence level. Instead of pronounced negative *fo*F2 trends for the 1940–1960 and 1970–1992 periods and a positive trend for the 1960–1970 period, which we would have under the geomagnetic control concept, the residuals (Fig. 3) do not reflect these long-term variations in geomagnetic activity. Some fluctuations of the residuals around the regression line reflect the imperfection of the model fitting

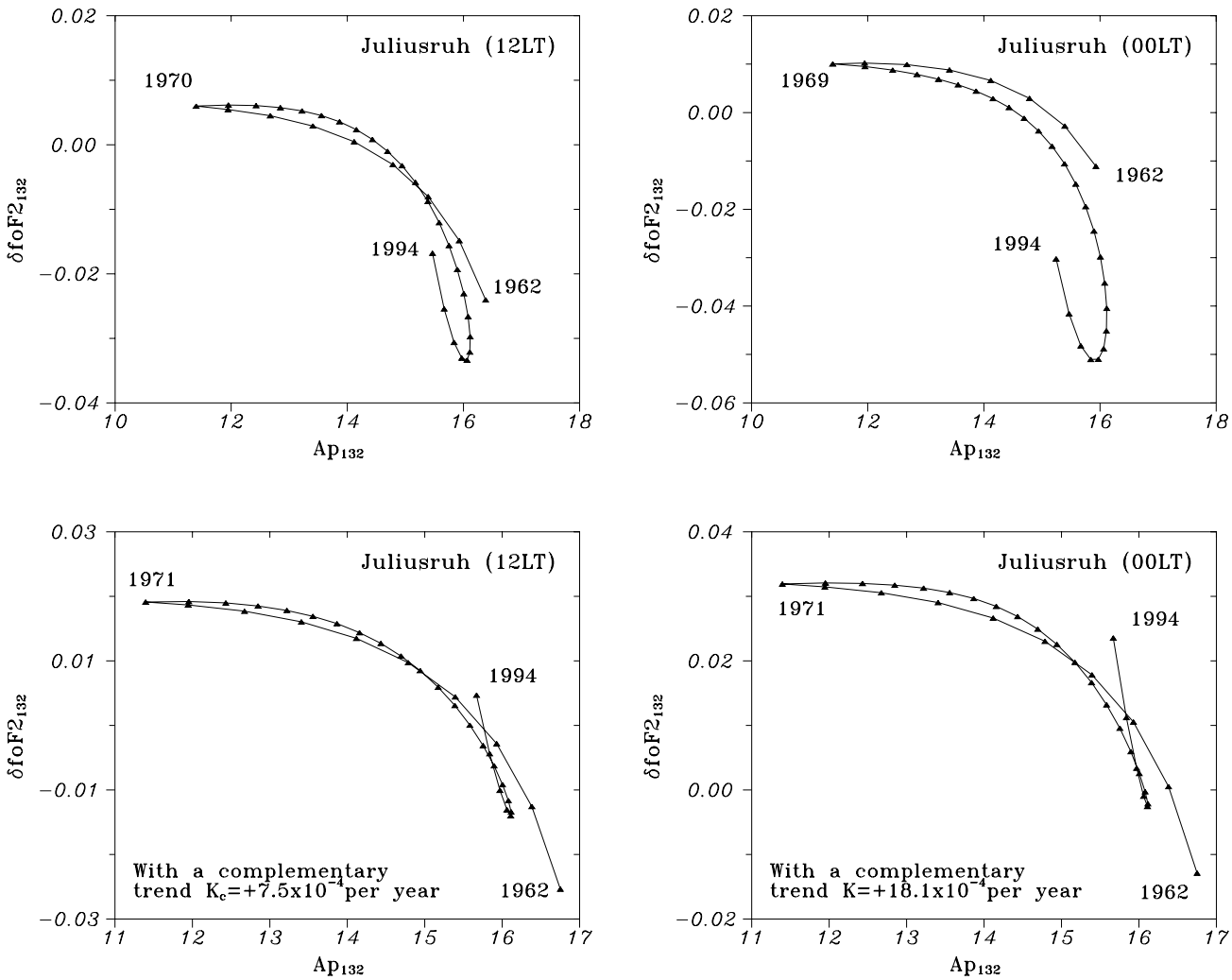

Fig. 4. Relationship between polynomial approximated $\delta fo\mathrm{F2}_{132}$ and Ap_{132} for Juliusruh (12:00 and 00:00 LT) (top panels) and the same dependencies after applying a complementary trend (bottom). Note the tightening of the loops in the second case.

the observed $\delta fo\mathrm{F2}_{132}$ variations.

Strong diurnal variation of the *fo*F2 trend magnitude was another feature revealed and explained in the framework of the geomagnetic control concept (Mikhailov and Marin, 2000, 2001). This was also checked for Slough where *fo*F2 observations for all LT moments are available for the 1944–1997 period. The results of the calculations are given in Table 6. Unlike our previous results, the calculated K_r are small and most of them are insignificant all day long. Only trends around noon and in the evening turn out to be significant. Despite this insignificance in the trends (which were calculated absolutely independently for 24 LT moments), they clearly demonstrate a consistent pattern of some diurnal variation (Table 6). This means that the calculated trends are not random and may need physical interpretation in future. The important result for further discussion is that most of the trends in Table 6 are negative similar to the conclusion made in Table 4. The optimal time shift between Ap_{132} and $\delta fo\mathrm{F2}_{132}$ variations averaged over 24 LT moments is -3.4 ± 0.88 years. This is comparable with the estimate obtained over 10 stations for 12 LT (Table 3, the Q-medians/Ap_{132} approximated combination).

The residual trend is seen to result from incomplete fitting of the calculated $\delta fo\mathrm{F2}_{132}$ variation to the observed one (Fig. 3, left-hand, top). This is due to the $\delta fo\mathrm{F2}_{132}$ versus Ap_{132} regression used in the calculations. The left-hand bottom panel of Fig. 3 gives a dependence between approximated $\delta fo\mathrm{F2}_{132}$ and Ap_{132} values used in the calculations. Two branches are seen in this dependence: one – before the end of the 1950s, the other – after 1971. The type of dependence is about the same, but the curves are seen to be shifted. An additional analysis has shown that the difference between the two branches remains, regardless of the shift ($-5 \div 0$ years) applied to the Ap_{132} variation with respect to the $\delta fo\mathrm{F2}_{132}$ one. It seems as if the "efficiency" of geomagnetic disturbances has increased since the middle of the 1960s as the same $\delta fo\mathrm{F2}_{132}$ values correspond to lower Ap_{132} after 1971.

Table 6. Diurnal variation of the slope K_r (in 10^{-4} per year) of the residual trend for Slough. The optimal time shift Δt (in years) between $\delta fo\mathrm{F2}_{132}$ and Ap_{132} variations is given as well. Bold face figures show significant trends with a confidence level 95%, normal face figures are trends with a confidence level 90%, italic face figures are trends which are not significant at the 90% confidence level

LT	K_r	Δt	LT	K_r	Δt
00	*−1.84*	-3	12	−2.76	-5
01	*−1.68*	-3	13	*−2.48*	-4
02	*−1.54*	-3	14	*−3.96*	-3
03	*−0.53*	-2	15	−4.27	-4
04	*+0.12*	-2	16	**−5.75**	-4
05	*+0.45*	-2	17	**−7.90**	-4
06	*+0.04*	-2	18	**−10.50**	-4
07	*−0.91*	-3	19	**−8.76**	-4
08	*−2.51*	-3	20	−5.53	-3
09	*−1.90*	-4	21	*−4.75*	-5
10	−3.39	-4	22	*−2.59*	-4
11	**−3.71**	-4	23	*−1.74*	-3

Table 7. The minimal SD (in 10^{-3}) and corresponding slopes (in 10^{-4} per year) of a complementary K_c and residual K_r trends for Slough (12:00 LT). The start years for the complementary trend to start are shown

Start years	SD	K_c	K_r
1980	4.19	+2.98	−1.79
1975	3.85	+3.22	−1.48
1970	3.38	+3.41	−1.18
1965	3.18	+3.04	−1.04
1960	2.88	+3.20	−0.73
1955	2.46	+3.19	−0.44
1950	2.14	+3.17	−0.18
1945	2.09	+3.27	−0.33
1940	1.99	+3.23	−0.23
1938	2.01	+3.11	−0.07

The ambiguity in this dependence can be removed to a great extent by applying a "complementary" linear trend to the $\delta fo\mathrm{F2}_{132}$ variation. Table 7 shows the results of such calculations for Slough (12:00 LT) when a complementary trend with the slope Kc was switched on for different start years.

The results of Table 7 show that SD and the slope K_r of the residual trend decrease as the start year for the complementary trend shifts towards the beginning of the period in question, with the complementary trend being about the same with the slope K_c, close to $+3\times10^{-4}$ per year. The least SD (the best fitting) is obtained if the complementary trend is applied for the whole period analyzed, starting from the first year, with the latter being important for further discussion. The final variations are shown in Fig. 3 (right-hand boxes). A complementary positive trend with $K_c = 3.1\times10^{-4}$ per year tightens the loops in the $\delta fo\mathrm{F2}_{132}$ versus Ap_{132} dependence to practically one curve (Fig. 3, right-hand, bottom). The resultant residual trend is close to zero ($K_r = -0.07\times10^{-4}$ per year) in this case. Similar results were obtained for some other stations with the complementary trends depending on station and LT. An example of tightening the loops in the $\delta fo\mathrm{F2}_{132}$ versus Ap_{132} dependence demonstrates Juliusruh for the 1962–1994 period (Fig. 4).

6 Discussion

The proposed approach to the *fo*F2 trend analysis allows us to remove to a great extent solar and geomagnetic activity effects from *fo*F2 long-term variations and to show that the residual *fo*F2 trends are small both for rising and falling periods of geomagnetic activity (Tables 4 and 5). The residual significant *fo*F2 trend for Slough (12:00 LT), with the longest available period of *fo*F2 observations, was found to be small with the slope $K_r = -2.23\times10^{-4}$ per year. Such a small trend gives around 0.1 MHz in the *fo*F2 change over a 55-year period for any reasonable mean *fo*F2 value accepted. Therefore, such trends have no practical importance. But from a physical point of view, the obtained result is interesting, telling us that practically all observed *fo*F2 long-term variations may be attributed to the variations in solar and geomagnetic activity, i.e. they are of a natural origin. Although this result was obtained using conventional indices, R_{12} and Ap, they should be converted to R_{12}^{α} and Ap_{132}, to be used in the trend analysis. This is due to the fact that initial R_{12} and monthly Ap cannot properly present solar and geomagnetic activity effects in the *fo*F2 long-term variations and more efficient indices are required. There are some related problems. The first one concerns the procedure of the solar activity effect removal. The commonly accepted approach is based on the *fo*F2 regression (linear dependence) with sunspot number R_{12}. This came from empirical modelling (for instance, IRI-90), where quite a different problem was solved. The goal of monthly median ionosphere empirical modelling is to find the best approximation for the observed monthly median *fo*F2, M(3000)F2, *fo*F1, or *fo*E solar cycle variations using any index of solar activity. A linear or nonlinear relationship with direct solar indices (R_{12}, $F_{10.7}$) or ionospheric indices (T, IG, $MF2$) is used to solve this problem (e.g. Mikhailov and Mikhailov, 1999 and references therein). Monthly *fo*F2 medians include both solar and geomagnetic activity effects and the empirical relationship with R_{12} is no more than a successful approximation, having practically nothing to do with the F2-layer formation mechanisms. Therefore, using the regression of *fo*F2 with R_{12} we attribute to R_{12} both effects in the observed *fo*F2 variations. Whether it is possible to describe "pure" *fo*F2 solar activity variations using the R_{12} index and how such a dependence looks like is a question of special consideration. Anyway, it is clear that such a "pure" dependence cannot just be a linear regression of *fo*F2 with R_{12}, which only presents the first term of an expansion in a power series of R_{12}.

As an example, this can be shown for the mid-latitude summer daytime F2-layer, when vertical plasma drift is close to zero due to small thermospheric winds. For such geophysical conditions we can use the well-known expressions by Rishbeth and Barron (1960)

$$N_m\,F2 = 0.75 \times q_m/\beta_m, \quad \beta_m \times H^2/D_m = 0.6\,, \tag{4}$$

where ion production rate, q_m, linear loss coefficient, β_m, and ambipolar diffusion coefficient, D_m, are given at the F2-layer maximum, with H being the atomic oxygen neutral scale height. These two expressions may be combined and re-written for a fixed height h_1, say 300 km (Mikhailov et al., 1995), to give

$$N_m\,F2 \propto \frac{I_o\,[\mathrm{O}]_1^{4/3}}{T_n^{5/6}\,[\mathrm{N}_2]_1^{2/3}}\,, \tag{5}$$

where I_o – solar EUV flux, [O] and [N_2] – atomic oxygen and molecular nitrogen concentration, T_n – neutral temperature. According to the Nusinov (1984, 1992) model total solar EUV flux is $I_0 \propto F_{10.7}^{2/3}$. The ratio of thermospheric parameters in Eq. (5) may be estimated using the MSIS-86 thermospheric model (Hedin, 1987). This ratio may be shown to be proportional to $F_{10.7}^4$ at 300 km height. Therefore,

$$foF2 \propto \sqrt{N_m F2} \propto F_{10.7}^{7/3}\,.$$

Annual mean $F_{10.7}$ and R_{12} indices are known to be highly correlated (the correlation coefficient is 0.991, and is significant at the 99% confidence level). Then we obtain *fo*F2$\propto R_{12}^{2.33}$. According to our calculations for Slough (as an example), the summer daytime (12:00 LT) α values are the following: May (2.43), Jun (2.61), Jul (2.78), Aug (1.85), which are close to the above made estimate. Therefore, the "pure" *fo*F2 dependence on R_{12} may differ essentially from just the linear law usually used in the *fo*F2 long-term trend analysis. It should be stressed once again that the regression (1) is not a "model" in the usual sense of the word, since it is accepted in all earlier approaches. This regression removes the solar activity part from the observed *fo*F2 variations, rather than drawing the best curve over the observed points.

The other problem concerns the removal of geomagnetic activity effects from the *fo*F2 variations. The use of monthly or even annual mean Ap indices is not efficient as our analysis has shown. Indeed, an inclusion of the monthly Ap index to the regression does not remove the geomagnetic activity effects, but only contaminates (due to low correlation with monthly *fo*F2) the analyzed material without changing, in principle, the results obtained (Mikhailov and Marin, 2000). As it was mentioned earlier, the usual monthly *fo*F2 medians bear F2-layer storm effects (geomagnetic activity effects) which, however, cannot be removed using conventional monthly Ap indices. This is not surprising, since the global Ap index cannot, in principle, take into account the whole complexity of the F2-layer storm effects with positive and negative phases depending on season, UT and LT of storm onset, storm magnitude, etc. Therefore, an interpretation of the F2-layer parameter long-term trends (based on previous methods) should consider the geomagnetic effects as an inalienable part of the trends revealed, and this can be done based on the contemporary understanding of the F2-layer storm mechanisms (Mikhailov and Marin, 2000, 2001).

A fruitful idea has been proposed by Deminov et al. (2000), who used quiet time *fo*F2 median (Q-median) values to analyze the *fo*F2 long-term trend for Slough. Specially selected quiet time periods were used to produce such monthly Q-medians, which are free from short-term (monthly) variations of geomagnetic activity. We have used a simpler approach to obtain *fo*F2 Q-medians, which are also free from short-term geomagnetic activity effects (as our analysis has shown), but long-term geomagnetic activity variations are still present in such *fo*F2 Q-medians. This is clearly seen in Fig. 2, where the δ*fo*F2 variation closely follows the long-term Ap_{132} changes with a ≈4–year time shift.

An essential point of the proposed method is the 11-year running mean smoothing of δ*fo*F2 and Ap values. The use of 11-year smoothing conquers quasi-biannual δ*fo*F2 oscillations (Fig. 1), which are not removed by any regression with monthly or annual mean Ap, due to low correlation coefficients. This is a principle point which usually is not taken into account during the trend analysis. As far as we know, only Ulich and Turunen (1997) and Deminov et al. (2000) used correspondingly 11-year and 5-year smoothing in their analyzes. Our consideration has shown that only the use of 11-year running mean δ*fo*F2 and Ap smoothing, along with a polynomial approximation of these variations (which works as an additional smoothing), allows one to bring up to the 0.90–0.95 correlation coefficient level (Table 1). Only with such high correlation coefficients (which are significant at the 95–99% confidence level) it is possible to draw a conclusion that observed *fo*F2 long-term variations can be presented mainly by solar and geomagnetic activity variations.

The 11-year smoothing of δ*fo*F2 values enable us to use all years with observations, rather than only years around solar minimum (m) or solar minima and maxima (m+M). The latter was the crucial point of our previous method (Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000), which allowed us to avoid the hysteresis effect in *fo*F2 solar cycle variations. The effect is known to take place at the rising and falling parts of a solar cycle and is due to peculiarities in solar EUV flux and geomagnetic activity variations in the course of a solar cycle (Mikhailov and Mikhailov, 1995).

An interesting result is a -3 ± 1-year time shift between Ap_{132} and δ*fo*F2$_{132}$ variations (Table 3), which provides the maximal correlation coefficient (Table 1). The results of the calculations show that this time shift varies slightly from station to station (for one and the same LT) and depends on LT at a given station (Table 6). An analysis of this problem is out of scope for this paper and now it is not clear what the mechanism of such a 3–4 year delay is in the thermosphere reaction to the long-term changes in geomagnetic activity. Such a large time delay implies that the whole Earth's atmosphere is involved with the processes provoked by geomagnetic activity. Changes in the global atmospheric circulation

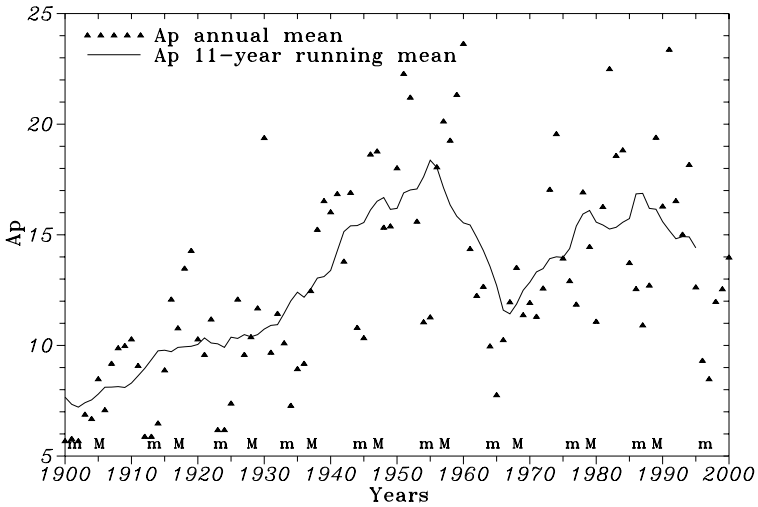

Fig. 5. Annual mean and 11-year running mean Ap index variations during the 20th century. Annual mean Ap indices prior to 1932 were reconstructed from aa indices available since 1868. Symbols (m) and (M) refer to years of solar cycle minimum and maximum.

and related variations in the thermospheric neutral composition and temperature are the most probable mechanisms.

Although the proposed approach essentially deletes solar and geomagnetic activity effects and gives small and insignificant residual *fo*F2 trend for the rising period of geomagnetic activity (Table 4), most of these trends are negative. Slough (12:00 LT) also demonstrates negative and significant residual trend calculated over the 55-year period which include both rising and falling periods in geomagnetic activity (Fig. 3, left-hand box).The same result was obtained on diurnal variations for Slough (Table 6). Therefore, this result can hardly be coincidental. Negative *fo*F2 trends may be considered as a manifestation of the geomagnetic control which is not completely removed by the proposed method. Indeed, there is a very long-term increase in geomagnetic activity (e.g. Clilverd et al., 1998) which requires more smoother than Ap_{132} indices for its description. This long-term increase takes place even for the analyzed period (Fig. 2, top), where a positive ($K = 0.02$ per year) trend is seen in the observed Ap_{132} variation. Figure 2 (top) is only a fragment of the general picture showing the increase in geomagnetic activity in the course of the 20th century (Fig. 5). This is a very delicate question which requires special consideration and is not discussed here.

An inclusion of a complementary linear δ*fo*F2 trend to our analysis restores the unambiguity in the $\delta foF2_{132}$ versus Ap_{132} dependence (Figs. 3 and 4) and practically results in a zero residual trend. Let us consider the sense of this complementary trend. The loop in the $\delta foF2_{132}$ versus Ap_{132} dependence (Figs. 3 and 4), in principle, may be related to some changes in the Ap index determination after the middle of the 1960s (new stations, a modified method, etc.). The difference between the two branches is not large (10–15%), but it is clearly seen in Figs. 3 and 4. On the other hand, Fig. 4 (top) shows that we have a new branch after 1990, shifted in the same direction and this can hardly be related to any changes in the method of the Ap index determination. Therefore, we should accept that observed $\delta foF2_{132}$ values include an additional negative long-term trend which is not described by R^{α}_{12} and Ap_{132} variations and the complementary trend just compensates it. An intriguing explanation of the complementary trend could be related to the anthropogenic activity, such as, for instance, the increasing rate of rocket and satellite launching, which leads to the thermosphere pollution (Kozlov and Smirnova, 1999; Adushkin et al., 2000). Indeed, switching on a complementary trend since 1960 (as the beginning of the cosmic era) improves to some extent the picture with the loops in Figs. 3 and 4, but the best results (the least SD) are obtained if the trend is switched on from the first year (1938) of the period analyzed (Table 7). It is impossible to link this result with the anthropogenic space pollution. Therefore, the only plausible explanation (as it is seen from now) of the complementary trend is a compensation of a negative trend initially presented in the observed $\delta foF2_{132}$ values. This negative trend presumably has the same F2-layer storm nature as discussed by Mikhailov and Marin (2001) and is due to the earlier discussed very long-term increase in geomagnetic activity in the 20th century.

7 Conclusions

1. A new method to extract *fo*F2 long-term trends, which are free to a great extent from solar and geomagnetic activity effects, has been proposed. This is achieved by using:

   (a) a *fo*F2 regression with R^{α}_{132} (where α is a fitting parameter) to remove the solar activity part from the *fo*F2 long-term variations;

   (b) relative rather than absolute δ*fo*F2 deviations to find $\delta foF2_{132}$ (11-year running mean values);

   (c) a regression with Ap_{132} (11-year running mean Ap values) to remove the geomagnetic activity effects from the *fo*F2 long-term variations. Both $\delta foF2_{132}$ and Ap_{132} variations are to be further smoothed,

to provide the best correlation coefficients. Neither monthly nor annual mean δfoF2 values provide a high enough correlation with Ap indices and cannot be recommended for the *fo*F2 trend analysis;

(d) *fo*F2 quiet time (Q-medians) rather than usual monthly medians;

(e) all available δfoF2 observations rather than (m) or (m+M) year selections used in the previous version of our method;

(f) a -3 ± 1-year time shift between Ap_{132} and $\delta fo\mathrm{F2}_{132}$ variations, to obtain the best correlation (the least SD). This time shift may be due to a large delay in the thermosphere reaction to the long-term changes in geomagnetic activity, with the physical mechanism of such an influence being unclear now.

2. The *fo*F2 trends calculated for rising and falling phases of the long-term geomagnetic activity variation show neither latitudinal dependence nor any dependence on the phase being small and insignificant. The existence of such dependencies for the trend magnitude was the basic point of the geomagnetic control concept by Mikhailov and Marin (2000, 2001).

3. The residual trend for Slough, calculated over the 55-year period, is small ($K_r = -2.2 \times 10^{-4}$ per year) and significant. Such small *fo*F2 trends have no practical importance. On the other hand, negative (although primarily insignificant), residual trends that are calculated over 10 ionosonde stations for a shorter period (31 years) may be considered as a manifestation of a very long-term geomagnetic activity increase, which did take place in the 20th century (Clilverd et al., 1998). But this effect cannot be removed even by using very smoothed indices, such as Ap_{132}.

4. The main conclusion is that all revealed *fo*F2 long-term variations (trends) may be attributed to the long-term solar and geomagnetic activity variations, i.e. they are of a natural origin. There is no indication of any manmade *fo*F2 trends.

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