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Letter to the editor

Spatial and seasonal variations of the *fo*F2 long-term trends

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Abstract. Using a method suggested by the authors earlier, the long-term trends of the F2-layer critical frequency, *fo*F2 are derived for a set of ionospheric stations with a wide latitudinal and longitudinal coverage. All the trends are found to be negative. A pronounced dependence on geomagnetic latitude is found, the trend magnitude increasing with the latter. No globe scale longitudinal effect in trends is detected. For the majority of the stations there is also a pronounced seasonal effect, the trend magnitude being higher in summer than in winter.

Key words. Ionosphere (ionospheric disturbances; mid-latitude ionosphere)

1 Introduction

There is an interest in the problem of long-term variations (trends) in the upper atmosphere parameters (see reviews by Danilov (1997, 1998). Trends of the ionospheric F2-region parameters were considered in several papers, e.g. by Givishvili and Leshchenko (1994, 1995), Bremer (1996), Ulich and Turunen (1997), Danilov and Mikhailov (1998), Bencze *et al.* (1998), Jarvis *et al.* (1998). Recently a detailed consideration of the trends in the ionospheric E, F1 and F2 regions was presented by Bremer (1998).

Danilov and Mikhailov (1998) proposed a new approach to revealing the *fo*F2 trends. With this new approach, the authors obtained negative trends for all four ionospheric stations considered and some indications to the existence of a latitudinal effect, the magnitude to the negative trend increasing with latitude. Contrary to that Bremer (1998), analyzing *fo*F2 trends for European ionospheric stations, obtained different signs of the trend for different groups of stations (some sort of a longitudinal effect) and detected no latitudinal variation. This contradiction is discussed below.

In this paper, further analysis of the *fo*F2 data in the scope of the new approach proposed by the authors is performed with an accent on spatial and seasonal variations of the trends.

2 Method and data

The method proposed by Danilov and Mikhailov (1998) is based on the following:

1. Relative deviations of the observed *fo*F2 values from some model

$$\delta fo\mathrm{F2} = (fo\mathrm{F2}_{\mathrm{obs}} - fo\mathrm{F2}_{\mathrm{mod}})/fo\mathrm{F2}_{\mathrm{mod}} \qquad (1)$$

are analyzed instead of absolute values considered by Givishvili and Leshchenko (1994, 1995) and Bremer (1996, 1998). The advantage of using relative values instead of absolute ones are discussed by Danilov and Mikhailov (1998). A third-degree polynomial in respect to the sunspot number R_{12} is used as a model:

$$fo\mathrm{F2} = a_0 + a_1X + a_2X^2 + a_3X^3 \qquad (2)$$

where $X = R_{12}$ and coefficients a_i are found by the least squares method.

2. A 12-month running mean *fo*F2 rather than monthly values are used for the analysis.

3. Only three years around solar maxima and minima [M(3) + m(3)] are considered to reveal *fo*F2 trends. This is done to get rid of the hysteresis effect which may be strong during the rising and falling phases of solar cycle and distorts the long-term variations sought for. In fact [see Danilov and Mikhailov (1998) for details] using only the M(3) + m(3) years it is possible to obtain stable negative trends, whereas for all years (including rising and falling phases) there is a chaos with various signs of the trends obtained on various stations.

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4. Trends at different stations may be compared only if one and the same time period is taken for the analysis. A period 1965–1990 is the most rich with observations over the worldwide ionosonde network. Moreover it was shown by Danilov and Mikhailov (1998) that the most stable picture of the trends for all months and all the stations considered is observed if only the data since 1965 are analyzed. This seems quite reasonable if the trends in question are by this or that way related to anthropogenic effects. That is why in the present study we used the M(3) + m(3) data for 1965–1990 for all the stations considered. On the other hand, it should be stressed that the model (*fo*F2 versus R_{12} regression) is derived over all *fo*F2 observations available on a particular ionosonde station.

5. Gaps in the initial observational data are filled in using the monthly median MQMF2 model by Mikhailov *et al.* (1996) based on a new ionospheric index MF2 (Mikhailov and Mikhailov, 1995). This index may be applied for monthly median *fo*F2 modelling over the whole northern hemisphere, so this approach was used for all the stations in question. All *fo*F2 observations (given in zonal or UT time) were converted to solar local time using spline-interpolation. Only the data for 1200 SLT were used in the present analysis.

3 Spatial variations

Ground-based ionosonde observations over Europe, North America and Asia were used in this study. The

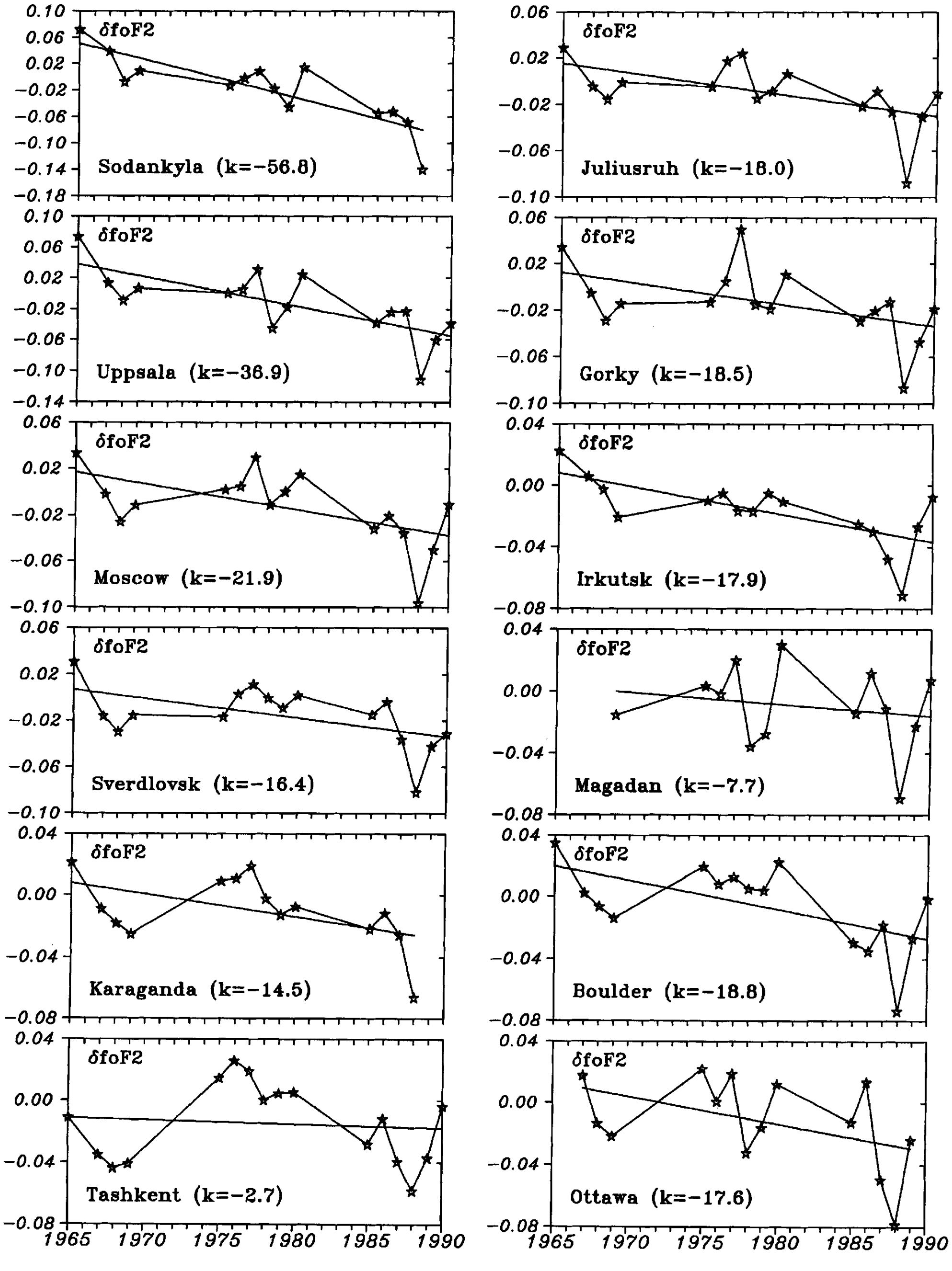

Fig. 1. The δ*fo*F2 values versus a year for different latitudes (*left-hand panel*) and longitudes (*right-hand panel*) for April. The slope *k* of the regression line is shown in 10^{-4} units/per year

Table 1. Ionosonde stations and calculated annual mean slope *k* (in 10^{-4} units/per year)

Station	Geographic		Geomag Lat	Annual mean *k*
	Lat	Lon		
Sodankyla	67.4 N	26.6 E	63.7	−53.9
Uppsala	59.8 N	17.6 E	58.4	−31.1
Salekhard	66.5 N	66.7 E	57.3	−27.9
Ottawa	45.4 N	284.1 E	56.8	−13.7
Leningrad	60.0 N	30.7 E	56.2	−18.8
Julinsruh	54.6 N	13.4 E	54.4	−16.1
Yakutsk	62.0 N	129.6 E	51.0	−31.0
Moscow	55.5 N	37.3 E	50.8	−19.1
Magadan	60.1 N	151.0 E	50.7	−7.94
Gorky	56.1 N	44.3 E	50.3	−15.9
Boulder	40.0 N	254.7 E	48.9	−15.5
Svedlovsk	56.7 N	61.1 E	48.4	−14.2
Tomsk	56.5 N	84.9 E	45.9	−3.39
Rome	41.9 N	12.5 E	42.5	−2.58
Irkutsk	52.5 N	104.0 E	41.1	−15.3
Sofia	42.6 N	23.4 E	41.0	−16.9
Karaganda	49.8 N	73.1 E	40.3	−11.6
Khabarovsk	48.5 N	135.1 E	37.9	−5.39
Novokazalinsk	45.8 N	62.1 E	37.6	−14.1
Alma-Ata	43.2 N	77.0 E	33.4	−0.82
Tashkent	41.3 N	69.6 E	32.3	−2.29
Ashkhabad	37.9 N	58.3 E	30.4	−9.14

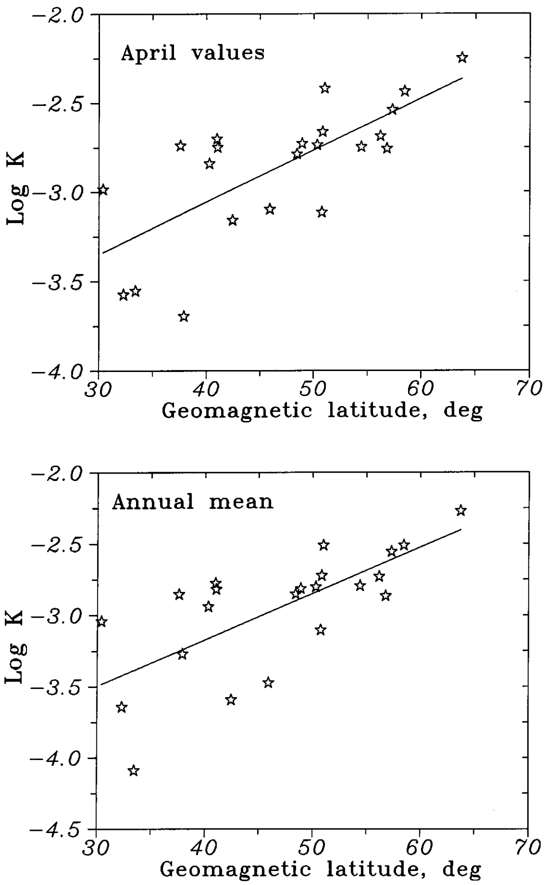

Fig. 2. The April (*top box*) and annual mean (*bottom*) log *k* values versus geomagnetic latitude

station list is given in Table 1. The stations are named as they were called in the period of observations. Table 1 shows that there is a broad coverage of the latitudes (both geographic and geomagnetic) and longitudes which provides the possibility of studying spatial variations of the effect in question.

An example of latitudinal (left-hand side) and longitudinal (right-hand side) δfoF2 behaviour for one month (April) is given in Fig. 1. One can see that for the data chosen, according to the principles described above, there are negative trends for all stations. All the trends are significant with the confidence level not less than 95% using the Fisher's criterion. Slope *k* (in 10^{-4} units per year) of the regression line is given in Fig. 1 for each station. Negative *fo*F2 trends are seen in annual mean *k* values as well (Table 1). An obvious latitudinal dependence for the slope *k* (a pronounced decrease) takes place when we move from high-latitude stations to low-latitude ones.

A dependence of April and annual mean absolute k values on geomagnetic latitude is shown in Fig. 2 for all stations in question. A difference by more than an order of magnitude in *k* values is seen when high- and low-latitude stations are compared.

An analysis has shown that the *k* dependence on geomagnetic latitude is more pronounced than on geographic latitude. So a geomagnetic control of trend magnitude dominates over the geographic one. Indeed, the stations with similar geomagnetic but different geographic latitudes (e.g. Sverdlovsk, $k_{\text{aver}} = -14.2 \times 10^{-4}$ and Boulder, $k_{\text{aver}} = -15.5 \times 10^{-4}$) give close values of *k* averaged over a year and vice versa the stations with close geographic latitude but different geomagnetic latitude – for example, Ottawa ($k_{\text{aver}} = -13.7 \times 10^{-4}$) and Alma-Ata ($k_{\text{aver}} = -0.82 \times 10^{-4}$) give strongly different values of the trend. This is a general tendency, but exceptions are possible as well (see Table 1). For example, Yakutsk has a very large *k* corresponding to higher latitude stations, while Magadan, Tomsk, Rome with relatively high geomagnetic latitudes have too low *k* values. Novokazalinsk and Ottawa with close geographic latitudes but quite different geomagnetic have close *k* values.

Longitudinal variations of *k* values are given in Fig. 1 (right hand side) for stations with geomagnetic latitudes $\Phi = 41.57°$. All of them except for Magadan have close *k* around - 18×10^{-4}. This manifests the absence of global scale strong longitudinal variations in *fo*F2 trends at least for midlatitude stations. But additional analysis of longitudinal variations is needed. Apart from the problem with Magaden, Irkutsk with relatively low geomagnetic latitude $\Phi = 41.06°$ demonstrates as large trend as Ottawa ($\Phi = 56.78°$) does. This means that besides geomagnetic control some additional factors are responsible for the observed *fo*F2 trends.

4 Seasonal variations

Using the 12-month running mean values of both sunspot numbers and F2 critical frequencies Danilov

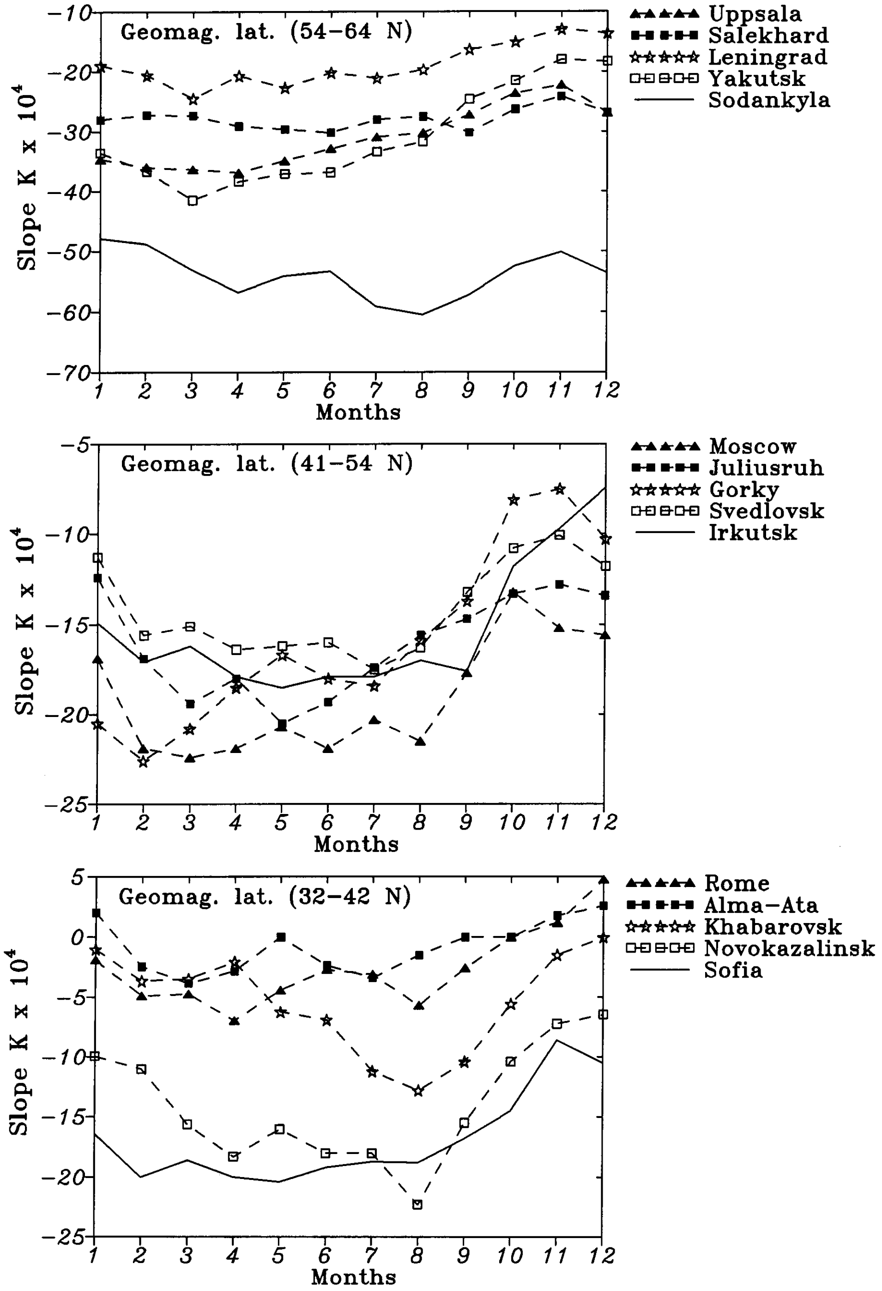

Fig. 3. Annual variations of *k* for high, middle, and low latitude ionospheric stations

and Mikhailov (1998b) expected that there should be no month-to-month variations of the trend. But the present analysis demonstrates that there do exist seasonal variations of *k*. Fig. 3 shows typical annual variations of *k* values for high, middle, and low latitude stations. Annual variations are well pronounced at all latitudes with an increase to low ones. At high-latitudes the largest negative *fo*F2 trends take place around the vernal equinox and the smallest – in October-November with the amplitude range of 1.3–2.2. At middle and low latitudes the largest negative trends are observed in spring-summer months and the smallest trends take place in winter. The magnitude of seasonal variation is a factor of 2 at middle latitudes and larger for low-latitude stations. For stations with small trends (Rome, Alma-Ata, Tashkent, Tomsk) the sign of the trend turns out to be even positive in winter months. One hardly may consider these positive values of *k* as significant because they are small enough. On the other hand this effect may have physical origin keeping in mind a geomagnetic control of the trend magnitude (Fig. 2) and its possible relationship with geomagnetic disturbances.

5 Discussion

The method proposed by the authors earlier is applied to more data of the vertical ionospheric sounding. If all the years for which the data are available are considered, the trends may be of any sign and amplitude with no systematic dependence on the latitude. For example, at Tomsk for 1946–1995 the April *k* is negative

(-3.0×10^{-4}), whereas at Moscow for the same years k is positive ($+0.92 \times 10^{-4}$). A strong negative trend ($k = -12.4 \times 10^{-4}$) may be found over 1949–1991 at Irkutsk, whereas a positive ($k = +0.12 \times 10^{-4}$) trend takes place at Leningard for 1950–1992. Some system in the k values appears only if the M(3) + m(3) years after 1965 are used. Then the values of k averaged over the year are negative for all the stations considered. There also appears to be some system in the latitudinal dependence of k illustrated by Fig. 2 and Table 1 with a pronounced decrease of the trend magnitude towards lower geomagnetic latitudes. The trends demonstrate also seasonal variations with a tendency to decrease in the summer months (see fig. 3).

It should be stressed that our conclusions contradict those in the recent publication by Bremer (1998). He found no latitudinal effect in the trends, but detected some separation of the stations to two longitudinal groups with positive trends in Eastern Europe and negative ones in Western Europe.

We believe that the reason for the above contradiction lies in the differences of the approaches used by Bremer (1998) and in this paper. Bremer used absolute deviations from some model (which describes the dependence of *fo*F2 on solar and geomagnetic activity) and all the years available for a given station. In this case the length of the data series used is inevitably quite different depending on the duration of the vertical sounding observations at this particular ionosonde. The most important point is the hysteresis effect at the rising and falling phases of the solar cycle which may completely distort real long-term trends. We get rid of this effect by limiting our consideration with the M(3) + m(3) years.

Thus, the results of this paper confirm our previous conclusions on the negative trends of *fo*F2 since 1965. The origin of the trends is still a matter of discussion. Danilov and Mikhailov (1998) showed that the combination of the data on the trends in *fo*F2 and *hm*F2 (the height of the F2-layer maximum) leads to some suggestions on possible mechanisms responsible for these trends and related these mechanisms with a systematic increase in downward plasma drift velocity and/or atomic oxygen content decrease.

The *fo*F2 latitudinal dependence derived in this study (especially the fact that the latitude in question is the geomagnetic one) do not contradict the above mechanism but trends to suggest further that the mechanism may be in some way related to ionospheric disturbances (ionospheric storms) following geomagnetic storms. The seasonal dependence may be a manifestation of the same process because it is well known that there are seasonal effects in occurrence and development of ionospheric storms (see e.g. Prölss, 1995). It is worth mentioning that there are indications to some long-term trends in the occurrence frequency of ionospheric storms [see Sergeenko and Kuleshova (1994, 1995)]. Anyway, the question on the physical mechanisms of the *fo*F2 trends is still open and hopefully the results of this paper provide some ground for further consideration of the problem.

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