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Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 1854–1870

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

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Long-term trends in foF2: A comparison of various methods

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Available online 24 April 2006

Abstract

Results of various authors on long-term trends in foF2, which is equivalent to the maximum electron density in the ionosphere, and their interpretation do not reveal a consistent pattern. Therefore, a joint analysis of one carefully selected dataset was performed by six teams, which used different approaches to trend determination. High-quality data of station Juliusruh (54.6°N, 13.4°E) for noon (average from 10 to 14 UT) were used for the period of two solar cycles from minimum to minimum (1976–1996). Juliusruh is relatively sensitive to geomagnetic activity as an almost subauroral station, which might play some role in interpretation of trend results. Various methods provide results, which differ to some extent, even when one co-author applies different methods. Another source of differences is application of various ways of removal (or at least large suppression) of the effect of solar (and geomagnetic) activity. Nevertheless finally most teams obtained quite comparable results. Interpretation of the observed trends is not unique—co-authors consider either the long-term change in geomagnetic activity, or anthropogenic effects to be predominantly responsible for trends. There is some generally accepted output from the joint analysis. All trends are either negative or insignificant. Data corrections with sunspot number (*R*), F10.7 adjusted to the Sun–Earth distance, observed F10.7, adjusted E10.7 and observed E10.7 result in somewhat different trends; the observed F10.7 and E10.7 appear to be the best correcting factor. The trends in foF2 are very small, of the order of -0.01 MHz/year, much smaller than the solar cycle effect and, therefore, sensitive to the solar activity correction. The Juliusruh dip angle increased very little over the period 1976–1996 and the possible impact of that increase on trends is negligibly small.

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Keywords: Ionosphere; foF2; Long-term trends; Anthropogenic effects

1. Introduction

The increasing concentration of greenhouse gases in the atmosphere results in enhanced greenhouse

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1364-6826/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2006.02.009

warming of the troposphere and cooling of the higher levels of the atmosphere. Ramaswamy et al. (2001), Beig et al. (2003) reviewed such a cooling in the stratosphere and mesosphere, respectively. This should result in changes of other atmospheric parameters and, therefore, also in long-term changes and trends in the ionosphere, as modelled, e.g., by Rishbeth and Roble (1992). However, the solar and geomagnetic activity changed significantly throughout the 20th century. It was remarkably lower at its beginning than at its end. Therefore, both the anthropogenic and solar/geomagnetic effects can affect observed long-term trends, particularly in the ionosphere, which is under strong solar/geomagnetic activity control. Laštovička (2005) recently published a brief overview on the role of solar and geomagnetic activity in long-term trends in the atmosphere–ionosphere system. Moreover, the cooling in the middle atmosphere is not uniform; whereas it is quite strong in the mesosphere (2–4 °C/decade), there is no change of temperature in the mesospause region (Beig et al., 2003). In the thermosphere, at F2 region heights, analyses of satellite drag data revealed an evident tendency to a decrease of atmospheric density (e.g., Keating et al., 2000; Emmert et al., 2004; Marcos et al., 2005), as expected based on thermospheric cooling.

Which trends have been observed in the ionosphere? Laštovička and Bremer (2004) reviewed trends in the lower ionosphere. Below about 90 km, trends obtained from different methods and datasets at least qualitatively agree and provide an essentially consistent pattern. Above 90 km, there is an evident contradiction between ground-based and rocket data but ground-based trends from different methods are consistent; the scarce rocket measurements seem to reveal a less reliable long-term trend. The overall trend appears to be an increase of electron concentration at fixed heights due to thermal shrinking of the mesosphere and decreasing concentration of neutral and ionized nitric oxide with resulting weaker recombination.

Contemporary long-term trends in the E-region qualitatively agree with the expected greenhouse effect on that region (Rishbeth and Roble, 1992). The critical frequency of the E region, foE, slightly increases, while the apparent height (close to real height) of the maximum electron concentration in the E region, h'E, reveals a tendency to decrease (e.g, Bremer, 2001). However, as Mikhailov and de la Morena (2003) showed, the trend in foE had predominantly been controlled by geomagnetic activity before the end of the 1960s, but later an additional more powerful non-geomagnetic mechanism has switched on.

Trends in the F1 region have been studied little but the observed trends are in line with model expectations. Bremer (2001) analysed observations of 51 different ionosonde stations and found predominantly positive trends in foF1 with an average trend of 0.027 MHz/decade, which was statistically significant at 95% level.

Long-term trends in the F2 region parameters (foF2, hmF2, hmF2-h'F) have been studied more broadly than in other layers of the ionosphere, but the results of individual authors are more contradictory, both as for the trends themselves and their interpretation in terms of anthropogenic or geomagnetic origin. Even the recent 3rd IAGA/ICMA workshop "Long-Term Changes and Trends in the Atmosphere" (Sozopol, Bulgaria, June 2004) did not help to resolve contradictions between various authors. Therefore, a proposal was approved to run a campaign of comparison of various methods (and interpretation of results) applied to a carefully selected homogeneous dataset, selected in a way to reduce the effects of solar and geomagnetic activity. However, the dataset was requested to be sensitive to geomagnetic activity in order to help clarify the origin of trends. The aim of the paper is to present the result of this comparison.

2. Trends in the F2 region parameters—previous results

The trends have essentially been studied in foF2 (critical frequency of the F2 layer, which corresponds to maximum electron concentration in the ionosphere) and hmF2 (height of ionospheric maximum). Bencze (2002, 2005) studied long-term trends in hmF2-h'F. He found a negative trend, which means an average cooling of the bottom-side F2 layer, as expected (Rishbeth, 1997; Rishbeth and Roble, 1992). This cooling was interpreted for solar cycle minimum years as caused probably by solar activity variability and the greenhouse effect with an insignificant contribution of geomagnetic activity (Bencze, 2005).

Some authors studied only single station trends, but mostly for stations with very long data records. Chandra et al. (1997) and Sharma et al. (1999) studied trends for Ahmedabad (23°N, 73°E) in India. They found in foF2 a negative trend of

−0.04 MHz/year over 40 years. Foppiano et al. (1999) analysed trends for Concepción (36.8°S, 73.0°W), Chile. They observed a negative trend in foF2 and increasing amplitude of the diurnal variation of hmF2 due to positive and negative trends at different times of day. They suggested that part of these long-term changes might by associated with a long-term increase of the geomagnetic dip angle at Concepción. Ortiz de Adler et al. (2002) dealt with observations at Tucuman (26.9°S, 65.4°W), Argentina. The observed trend in hmF2 was −0.2 km/year over 30 years. Ulich and Turunen (1997) used a 39-year long data series from Sodankylä (67.4 °N, 26.7°E), northern Finland. They observed a relatively strong negative trend in hmF2, −0.39 km/year. Hall and Cannon (2002) and Cannon et al. (2004) analysed trends for Tromsø (69°N, 19°E) in Norway, where foF2 was available since 1935 and hmF2 since 1947. They found negative trends in both parameters: −0.013 MHz/year and −0.106 km/year; the trend in hmF2 was much weaker than in the relatively nearby Sodankylä. They found some impact of such trends on HF radio systems on long time scales. Xu et al. (2004) analysed a 45-year long series of ionosonde measurements at Kokubunji (35.7°N, 139.5°E), Japan, in the E, F1 and F2 regions. The observed trends differed for various times of day and months, even with altering signs (except for hmF2). The average trends for foF2 and hmF2 were approximately −0.0035 MHz/year and −0.4 km/year. They found no significant effect of geomagnetic activity in regression models at Kokubunji.

Some authors focused their investigations to southern high latitudes. Alfonsi et al. (2001) found a negative trend in foF2 for three Antarctic stations. Further analysis of high-latitude stations (Alfonsi et al., 2002) confirmed the negative trend in foF2 and revealed its value of −0.0035 MHz/year. That trend was claimed to be of non-geomagnetic origin. Jarvis et al. (1998) found for two stations a negative long-term trend in hmF2 of a similar order of magnitude as that predicted by models based on increasing concentration of greenhouse gases.

Most studies treated trends at middle and moderate latitudes, and some of them used global datasets. Upadhyay and Mahajan (1998) analysed 31 stations with data series longer than 30 years. They found an unclear trend pattern with 17 positive and 14 negative trends in foF2 and 7 positive and 7 negative trends in hmF2. Bremer (1992, 1998, 2001) studied first data from Europe and then from global network. Bremer (1998) found in Europe negative trends in foF2 and hmF2 west of 30 °E, but positive trends in foF2 and hmF2 east of 30°E. This difference was observed only in the F2 region, not in the F1 and E regions. The trends were independent of latitude. Bremer (2001) confirmed regional differences in trends in the F2 region on global scale and noticed significant differences in trends between individual stations. Danilov and Mikhailov (1999) analysed for each solar cycle only 3 years around solar maximum and 3 years around solar minimum, 12-month running mean values of foF2, northern middle and higher latitudes. They found negative trend for all individual stations. The trends increased with increasing geomagnetic latitude, but globally they were longitude-independent. Based on a similar approach but with another correction for geomagnetic activity, Mikhailov and Marin (2000, 2001), Mikhailov (2002) developed a concept of geomagnetic control of long-term trends in F2 region. Mikhailov and Marin (2000) analysed data of 30 northern hemisphere stations. They observed negative trends in foF2 in periods of long-term increases of smoothed geomagnetic activity, and vice versa positive trends in foF2 in periods of long-term decreases of geomagnetic activity, and also other features consistent with geomagnetic rather than anthropogenic origin of trends in foF2. Mikhailov and Marin (2001) found latitudinal and diurnal variation of trends to correspond to the geomagnetic storm-like behaviour concept. They showed the trends in the F2 region parameters to depend strongly on long-term variations of geomagnetic activity, which effects cannot be removed from trends by means of application of conventional geomagnetic indices. Mikhailov (2002) summarized and described in detail the geomagnetic control concept of trends in foF2 and hmF2. Mikhailov et al. (2002) developed an approach how to obtain a trend component of non-solar and non-geomagnetic origin, but for Slough (55 years of data) they found such a trend to be negligibly small and of no practical importance. They claim that the trends observed in foF2 and hmF2 are of natural, geomagnetic and solar origin rather than of man-made origin. On the other hand, Danilov (2002b) developed another method of determination of long-term trends of non-geomagnetic origin. With this method Danilov (2003a) obtained an average non-geomagnetic trend of −0.012 MHz/year for 21 stations over the period 1958–1995. That trend was independent of geomagnetic latitude and local time, and it was substantially weaker for an earlier period of 1948–1985 (a few stations only), which supported its anthropogenic origin.

Since the trends in foF2 and hmF2 are weak, quality and homogeneity of data and correct approach to data reduction are critical issues in trend calculations. M(3000)F2 (the ratio of the maximum usable frequency at a distance of 3000 km to foF2) has been used to compute hmF2. Ulich (2000) demonstrated that the selection of adequate formula for the computation of hmF2 from M(3000)F2 is a critical issue and application of different formulas can result even in opposite trends in hmF2 for some stations. Different formulas were derived from experimental data for different stations and/or regions. Clilverd et al. (2003) analysed in detail the residual solar cycle influence on trends in hmF2, which remain after removal of solar cycle influence from data. They found a ringing effect, which became unimportant only after about 40 years. Their approach is also a sensitive test of homogeneity of data. They found an average trend for 11 studied stations to be a decrease by 0.1–0.2 km/year. They strongly recommend check consistency of trends from neighbour stations. Alfonsi et al. (2002) also discussed data validation. Other examples of data problems were presented by Bremer (1998, 2001).

First trend information at heights near 350 km from the Millstone Hill incoherent scatter radar reveals a decrease of ion temperature by 50 K over 30 years, and a tendency to decreasing electron density (Zhang et al., 2005).

Danilov (2002a) presented overview of long-term trends in the ionospheric E and F2 regions. Ulich et al. (2003) reviewed briefly long-term trends in F2 region parameters with special attention paid to data problems. A review of European results obtained within the COST271 project was given by Bremer et al. (2004).

The above results demonstrate broad contradiction of results on trends in the F2 region and their interpretation and/or origin.

3. Data

The first step for method intercomparison is a selection of appropriate test dataset. Such a dataset has to fulfil four conditions: (i) length of two solar cycles at least; (ii) minimum data gaps; (iii) homogeneous and high-quality data; (iv) location such that the data are sensitive to geomagnetic activity in order to check possible geomagnetic activity control.

There are two main F2-region parameters used in trend investigations: foF2 and hmF2. We shall use only foF2 to avoid additional problems with the above-mentioned correctness/adequacy of re-calculation of M(3000)F2 into hmF2. Burešová (1997) tested quality and reliability of foF2 data from nine European stations with empirical model UNDIV developed for European area. She found Juliusruh (54.6°N, 13.4°E), northern Germany data to be the best even though they were not used for derivation of the UNDIV model. Juliusruh data are affected by geomagnetic activity. We have selected the period of 1976–1996 (solar cycle minimum to solar cycle minimum), which covers two solar cycles of comparable amplitude. That interval was selected to reduce the solar effect on trends by suitable selection of the period under study. The number of data gaps is small and no month has to be excluded due to data gaps. Thus the Juliusruh 1976–1996 data fulfill all four conditions.

For simplicity we use noontime values of foF2 (average over 10–14 UT to smooth individual hour deviations). Data gaps are filled in by interpolated values based on Juliusruh data at other times of that day, Juliusruh data of neighbour days, and data of neighbour stations of that day (for the purpose of method comparison it essentially does not matter how we fill in data gaps). Fig. 1 shows the raw data of foF2 and their trend obtained by simple linear regression. The two solar cycles are similar. However, the second cycle has slightly weaker average foF2 due to slightly different shape of cycles and the cycle rising branches are shorter than the decay branches in solar activity and, thus, also in foF2. Therefore the obtained trend of −0.062 MHz/year is affected by the solar cycle; real trend should be less negative. Thus the solar cycle effect on the trend determination cannot be avoided even by the optimum selection of the interval under study. This is the reason why authors usually use data corrections for solar activity. Different solar and geomagnetic activity corrections might be one of the sources of differences/discrepancies between the results of various authors.

The selected period of two solar cycles may be too short to draw a final conclusion about the precise value and nature of the trend in foF2 at Juliusruh. Let us refer to H. Rishbeth (private communication, 2004), who has said: “A cautionary point must be made. The different ionospheric response in

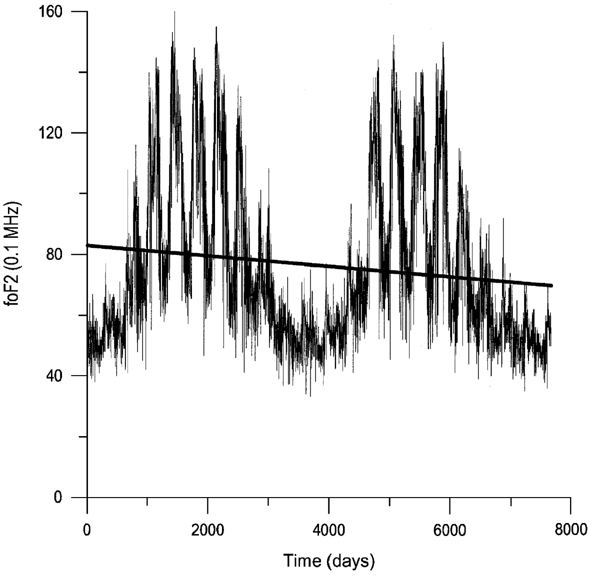

Fig. 1. Raw foF2 noontime data, Juliusruh station (54.6°N, 13.4°E), 1976–1996. Straight line—long-term trend computed without any reduction of data to solar and geomagnetic activity.

different solar cycles teaches a lesson: long-term changes can only be reliably detected over intervals of time that greatly exceed the 11-year solar cycle". However, the main purpose of the paper is to answer the questions whether and to which extent different methods applied by different authors contribute to the differences and even contradictions in investigations of trends in foF2. For this purpose the quality of data is of primary importance and, therefore, we selected only the above two solar cycles of data.

4. What is the trend?

Most authors understand the term "trend" as a "long-term trend", i.e. as a long-term quasi-stable tendency of essentially monotonic linear/quasi-linear change, either an increase or decrease of the values of the studied quantity/variable with time. If the long-term behaviour is substantially unstable or oscillatory, the term "long-term change" is used. Strictly speaking, trends are often not quite linear. However, in most cases (as with foF2) the linear trend approximation is sufficient.

Ideally, a trend continues to infinity. In reality, a period of quasi-stable trends begins and ends in concrete years/periods. It is most evident with the Antarctic ozone hole, which appeared in the late 1970s, at present is peaking and stagnating, and is expected to disappear near or shortly after the middle of this century. This behaviour is caused by development of man-made emissions of ozone-depleting substances and their ban by the Montreal protocol and its amendment. Such behaviour may be characterized by a sophisticated mathematical curve, but quite sufficient approximation by three time-limited linear trends of decrease, stagnation and increase of ozone concentration is being used for simplicity. The ionospheric linear trends should be understood in such a way. A different understanding of the term trend may lead to some of the contradictions referred to in Introduction.

Chilean co-authors use more strictly mathematical and a little different approach. A trend in a time series is by definition always located at the infinity, i.e. it corresponds to the ultra lower frequencies that are not taken into account in a spectral decomposition. More precisely, quoting Kendall (1973) "The essential idea of the trend is that it shall be smooth", which is equivalent to a continuous slowly varying change in a time series over long time scales (Graigmile et al., 2004). Therefore, supposing that the trend is not part of main cycles, or roughly cycle-stationary modes, or stochastic processes, which may affect the estimate of a true trend, then there are two possibilities. (a) To estimate the trend related to the oscillatory modes (if the different forcing are known), and (b) to estimate the trend by computing a decomposition, which allows separating the oscillatory from the non-oscillatory components.

5. Results of the comparison

Six authors and/or groups took part in the campaign of comparison of different methods of trend calculation and interpretation: Bremer, Danilov, Mikhailov, Ulich, Argentinean group (Elias, Ortiz de Adler) and Chilean group (Jara, Abarca del Rio, Foppiano, Ovalle). Authors usually applied several methods each, thus the comparison is very complicated.

5.1. Bremer's results

The method of trend determination and data correction was described by Bremer (2001) using monthly mean values of $X =$ foF2. First, empirical models (1)–(3) were constructed from analysed data to compute "model" values corresponding to the given level of solar (and geomagnetic) activity:

$$X_{mod} = A + BR \tag{1}$$

or

$$X_{mod} = A + BR + C\,\mathrm{Ap} \tag{2}$$

or

$$X_{mod} = A + BR + CR^2. \tag{3}$$

In addition to R (sunspot number) also F10.7 (solar radio noise at $\lambda = 10.7\,\mathrm{cm}$), and R_{12} (12-month smoothed sunspot number) were tested. Then the residual ΔX was calculated as a difference between experimental and model value in order to avoid or at least much suppress the influence of solar (and geomagnetic) activity:

$$\Delta X = X_{\exp} - X_{mod} \tag{4}$$

and linear trend of residuals was calculated:

$$\Delta X = \alpha\,\mathrm{year} + \delta. \tag{5}$$

The results of the trend analyses are summarized in Table 1. Here the derived trends are shown together with the error limits with 95% reliability of the trends. The last term in this table describes the mean variance calculated from the yearly ΔfoF2 values and the derived linear trends. In all cases the significance levels of the estimated trends are lower than 95%. The best significance levels are obtained if F10.7 values are used in the analyses. In Fig. 2, however, sunspot numbers are used because most of the other authors used them in previous studies. Fig. 2 displays seasonal variation of trends. Both negative and weak positive trends are observed with evident predominance of negative trends. There is probably no systematic seasonal variation of trends; March and particularly September values "destroy" tendency to more positive trends in the first half of the year and more negative trends in the second half of the year.

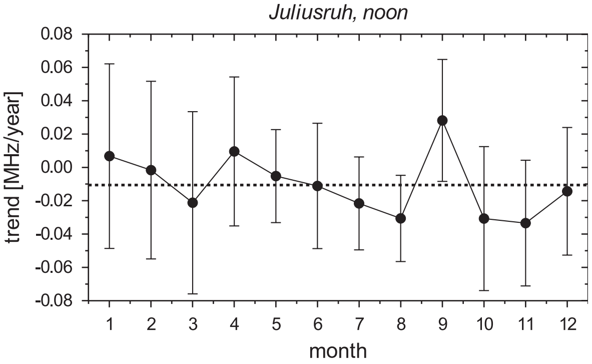

Fig. 2. Monthly foF2 trends (Juliusruh, noon) together with 95% error bars. The dashed line represents the yearly mean trend. The solar and geomagnetic influences have been eliminated by a twofold regression analysis after Eq. (2) depending on R and Ap.

All the trends shown in Table 1 and Fig. 2 are much smaller than that obtained from Fig. 1, which clearly demonstrates necessity of careful data reduction/correction for solar (and geomagnetic) activity.

Table 1
Yearly foF2 trends (Juliusruh, noon) derived by different methods of the elimination of the solar and geomagnetic influence

	Trend (Jan–Dec) (MHz/year)	Error (95%) (MHz/year)	Variance (MHz)
$f(R)$	−0.0117	±0.0192	0.249
$f(R, \mathrm{Ap})$	−0.0104	±0.0192	0.249
$f(R, R^2)$	−0.0098	±0.0171	0.221
$f(\mathrm{F10.7})$	−0.0174	±0.0185	0.239
$f(\mathrm{F10.7, Ap})$	−0.0147	±0.0165	0.213
$f(\mathrm{F10.7, F10.7^2})$	−0.0132	±0.0138	0.178
$f(R12)$	−0.0066	±0.0214	0.276
$f(R12, \mathrm{Ap})$	−0.0049	±0.0214	0.277
$f(R12, R12^2)$	−0.0065	±0.0211	0.273

5.2. Argentinean group results

After calculating monthly mean values, the trend of foF2 was estimated with two methods: (i) a linear regression after filtering the solar activity effect on foF2, and (ii) through a multiple regression analysis.

In the first case, the solar activity variation was filtered out from the 12-month running mean data series using Eq. (1) but with the 12-month running mean of a solar activity proxy (R or F10.7). Then the residuals were computed using Eq. (4) and finally, the linear trend was estimated with Eq. (5); coefficients were determined through the least-squares method.

With the second method, the trend was estimated from a multiple regression analysis (using also 12-month running mean foF2 and solar activity proxy data) where the independent variables considered were a solar activity proxy (R or F10.7) and time, that is

$$\mathrm{foF2} = \alpha\,\mathrm{year} + \gamma\,R + \delta$$

or

$$\mathrm{foF2} = \alpha\,\mathrm{year} + \gamma\,\mathrm{F10.7} + \delta. \tag{6}$$

Table 2
Linear trend of monthly mean foF2 measured at Juliusruh averaged in the interval 10–14 UT over the period 1976–1996

Method	Trend value (MHz/year)	Error (1σ) (MHz/year)
Method (1) with Rz	−0.009	±0.003
Method (1) with F10.7	−0.015	±0.003
Method (2) with Rz	−0.009	±0.003
Method (2) with F10.7	−0.016	±0.003

Table 2 shows trend values (α) obtained with the two methods and using R and F10.7 as a solar activity proxy. Both methods provide the same results, and results similar to those in Table 1. However, according to the t-test, and considering the degrees of freedom taking into account the running mean applied to the series (Maddala, 1997), all the trend values are significant at a 99% level. Application of F10.7 instead of R again provides much stronger and evidently statistically more significant trends. Applying the 4σ criterion only, the trend estimated using F10.7 is significant at the 99% level. Those estimated with R are significant at about the 95% level (3σ). To explain the difference in statistical significance between Tables 1 and 2, the trends in foF2 monthly mean series were estimated removing the solar activity effect through a linear regression between foF2 and R (or F10.7) without previous smoothing the series with a 12-month running mean. The trend is almost the same as that obtained when the solar activity effect is filtered out from the smoothed series, but the significance level do decrease to levels lower than 95%, essentially identical with those following from Table 1. The point is that, although the degrees of freedom to test the trend decrease by 1/12 when smoothed series are used it is more than compensated by removing the great seasonal variability and some random deviations in foF2 via 12-month smoothing. The smoothing is made with weight 1 for each data point. Six values are lost at the beginning and the end of data series by the applied smoothing.

Both methods were applied also to monthly non-smoothed values of foF2 and F10.7 and trend was computed separately for each month. The obtained monthly trend behaviour was quite similar to that obtained by Bremer in Fig. 2.

Application of F10.7 instead of sunspot number R again provides much stronger and evidently statistically more significant trends.

Long-term changes of the main geomagnetic field of the Earth could play some role in trends in foF2. In the case of Juliusruh, the dip angle has increased over the period 1976–1996 from 68.6 to 68.8 (estimated with the International Geomagnetic Reference Field model issued by IAGA and available at http://nssdc.gsfc.nasa.gov/space/model/magnetos/igrf.html), but the sin(I)cos(I) factor has decreased from 0.340 to 0.337. Besides a 0.8% decrease in the sin(I)cos(I) factor over a period of 20 years being too small, this negative trend should induce an increasing trend in foF2 by day, which is not the case of Juliusruh. For Juliusruh this factor (change of geomagnetic coordinates of the station) appears to be negligible.

5.3. Ulich's results

The trend was determined by modelling the raw, i.e. daily foF2 values by means of statistical inversion. First a time-dependent model $M(t)$ was formulated, which essentially is a sum of functions of time:

$$M(t) = \sum_i x_i f_i(t), \tag{7}$$

where t is time, x_i are the unknowns, which are determined by fitting the model to the data, and $f_i(t)$ are the so-called base functions. Such a model is called "linear in the parameters." The model can subsequently be written in matrix form. Ideally, the measured data is equal to the sum of model and measurement errors:

$$\text{foF2}_j = \sum_i x_i f_{ij} + \varepsilon_j. \tag{8}$$

Here, the index j refers to the discreet measurement time t_j and ε_j is the individual measurement error. For the test data set, no error limits were provided at all and therefore we set $\varepsilon_j = 1\,\text{MHz}$ for all j including instrumental as well as ionospheric noise. The matrix equation was then inverted by means of singular value decomposition determining the fit parameters x_i and their probable errors.

A crucial part of this approach is the choice of a good combination of base functions. While the choice of base functions is largely determined by the physics behind the foF2 time series, there is some room for arbitrariness. Solar activity, e.g., can be expressed in terms of R, F10.7 or E10.7 (Tobiska's index for description of solar EUV flux). Moreover, there are two versions of the F10.7 and E10.7 indices available: observed and adjusted. The adjusted indices are normalized to a distance between Earth and Sun of 1 a.u. Moreover, it is well known that the ionosphere should reflect geomagnetic activity (e.g., Chaman Lal, 1992) and that a semi-annual as well as an annual variation can be observed in foF2 data (e.g., Rishbeth et al., 2000).

More than 200 models (combinations of base functions) were tested with the given data set. After each fit, the model, including the trend, was subtracted from the original foF2 and the standard deviation of the residual was estimated. The model yielding the smallest standard deviation and the smallest probable error of the fitted trend was selected as the best suitable model, viz.

$$M(t) = x_0 + x_1 t + x_2 F_o(t) + x_3 \sin(\omega_a t) + x_4 \cos(\omega_a t) + x_5 \sin(\omega_s t) + x_6 \cos(\omega_s t), \tag{9}$$

where x_1 is the slope of the linear trend, F_o is the observed 10.7 cm radio flux, and ω_a and ω_s represent annual and semi-annual variation. Instead of F_o, also the observed E10.7 indices can be used and lead to about the same result as F_o, but F_o was chosen here due to it being widely known and easily available.

The correlation of foF2 with sunspot numbers is much worse to the extent that they should not be used for ionospheric trend studies at all. Moreover, the F10.7 radio fluxes, which are corrected for the annual Earth-Sun distance variation of 6.9%, give a worse result than the uncorrected values, which is physically plausible, because the solar energy received on Earth does vary with the Earth–Sun distance. These results agree nicely with the findings of Bremer and the Argentinean group on F10.7 being better than R for correcting to solar activity.

Agreeing with Mikhailov and Marin (2000), the inclusion of the monthly Ap index only adds noise to the problem and does not have any effect on the trend magnitude. It might, however, lead to a larger error of the trend estimate and was therefore left out.

Note that only original unfiltered daily data were used in this part of the trend estimation. Low-pass filtering of the data was tested and in the case of smoothing over one solar rotation (27 days), the trend estimates become better, i.e. the errors are smaller, but the trend magnitude is little affected. However, filters have to be used with great care, because at some point increasing filter length has to lead to better, but meaningless, correlations, because all characteristic features will be removed from the data. Moreover, the longer the filter, the smaller is the resulting amount of filtered data or otherwise the filter window will overlap with the ends of the time series, i.e., it will not have enough data and thus introduce undesirable features to the data set, which can have a significant though unphysical effect on the trend estimate.

Using the method detailed above, the test data are found to have a negative trend of −0.0206 MHz/year with ±0.0019 probable error, which agrees with the results of Bremer and Argentinean group.

5.4. Chilean group results

Two basic approaches have been followed. No filtering of the known foF2 dependence on solar activity (as in Fig. 1) with two different methods of trend determination, and filtering the dependence by some means with three methods of trend determination. The resulting trends are shown in Fig. 3 for all five methods, for each month separately and with the mean value of these as representative of a trend of yearly values.

5.4.1. No solar activity dependence filtering

(a) *Regression of a linear trend*: A first-degree polynomial is fitted to each of the 12 monthly series (in the least-square sense) in order to derive the trend, without considering any forcing. Monthly

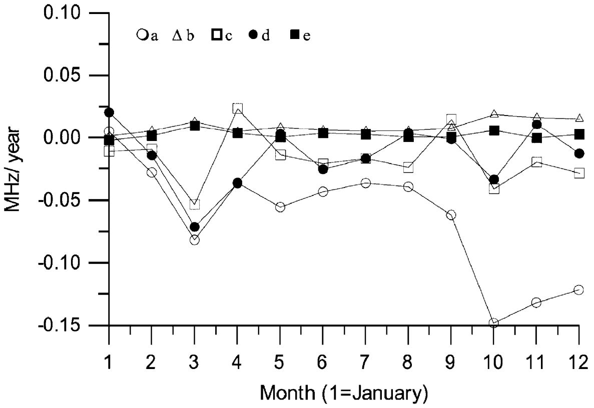

Fig. 3. Long-term trend coefficients (slopes) for each month calculated by methods (a), (b), (c), (d) and (e) of Chilean group.

values range from +0.0046 to −0.1484. Yearly trend is −0.0652, which is very close to the result obtained from Fig. 1.

(b) *Regression of a linear trend after a discrete wavelet analysis*: In this case a wavelet multi-resolution (WM) technique is chosen via discrete wavelet transform using a discrete Meyer mother wavelet (Percival and Walden, 2002). This method naturally separates the existing oscillations and also allows determination of amplitude modulations within the frequency domains. This may also affect somehow the trend estimation. For the analysis several tests are first made to determine a convenient degree of decomposition. This determination allows adequate separation of the different oscillatory components from those, which may content less (given that the computing is over just 20 years). The last level of the decomposition (the one containing the ultra lower frequencies, an approximation of the lower frequency components) is fitted to a first-degree polynomial in order to find the trend. Here trend values range from +0.0012 to +0.0183, all very small positive values with a yearly trend of +0.0086.

5.4.2. With solar dependence filtering

(c) *Linear regression*: The solar activity dependence of each of the 12 foF2 series is first filtered using a regression on F10.7, as published by Foppiano et al. (1999) for Concepción foF2 values. Then a first-degree polynomial is fitted to each of the 12 series in order to derive the trend. This method is equivalent to Bremer *f*(F10.7) method and to Argentinean first (using F10.7) method. The slight differences amongst these methods are treated in the Discussion. Trend values range from +0.0231 to −0.0537 with yearly mean of −0.0168, very close to those obtained by Bremer and the Argentinean group.

(d) *Singular value decomposition*: The solar activity dependence is filtered by means of singular value decomposition (SVD) on F10.7. In the first place, SVD of the foF2 and of the F10.7 series are constructed (12 decompositions in all). The singular value decomposition method is derived from the principal component analysis (Wall et al., 2003). This method allows deriving the principal component associated with the paired or covariant variability in the two time series or fields. Secondly, the covariant variability is extracted to F10.7 from the foF2, and a linear regression is computed on the remaining variability, using a first-degree polynomial, in order to determine the trend. Trend values range from +0.0201 to −0.0716, with a yearly mean of −0.0148, similar to those obtained by Bremer, Ulich and the Argentinean group.

(e) As with the 'd' method, the covariant variability is first extracted using a SVD on both vectors, then a discrete wavelet decomposition is applied to separate the ultra low frequency estimate associated to the trend. Then, again a trend is determined using a first-degree polynomial. Trend values range from +0.0092 to −0.0005, with a yearly mean of +0.0023.

In spite of the trend differences observed for some months, there is some similarity between results for 'a', 'c' and 'd' methods with predominantly negative trends, even though autumnal trends obtained by the 'a' method seem to be too strong. On the other hand, wavelet-based 'b' and 'e' methods produce almost no trends (negligibly small positive trends).

5.5. Mikhailov's results

Mikhailov et al. (2002) described in detail the method used for calculating the long-term trend in foF2. The method is based on 11-year (132 months) smoothed values of Ap_{132} and $\delta\mathrm{foF2}_{132}$. This means that a period longer than 1976–1996 is needed; 1971–1999 is used. This can introduce some but rather slight (definitely not principal) difference into the results in comparison with previous results based strictly on the period 1976–1996. Unlike Mikhailov's earlier method, where only years around solar cycle maxima and minima were analysed (e.g., Mikhailov and Marin, 2001), this method uses all years available.

The influence of the solar activity variation is removed with

$$\mathrm{foF2}_{\mathrm{reg}} = a + b(R_{12})\beta. \tag{10}$$

Eq. (10) is used separately for each month of the year. Eq. (10) is of general type and depending on β it can describe both linear and non-linear relationship of foF2 with $R_{12.}$ The optimal 12 different values of β (for each month of the year) are specified to provide the least standard deviation (SD) after a regression (Eq. (12)) of 11-year smoothed δfoF2 with Ap_{132} (11-year running mean Ap indices). All 12 values of β should be available simultaneously at each step of the SD minimization as we work with annual mean δfoF2 values. This implies an application of special multi-regression optimization methods (e.g. Mockus, 1997). A special iterative procedure was applied along with the optimization method. Values of β were searched alternatively for odd months (β values for even months being specified as a half-sum of two neighbouring odd values), then for even months (β for odd months were specified as a half-sum of two neighbouring even values). Such alternative approach allowed us to find reliably all 12 values of β at each of the SD minimization. It should be stressed that expression (10) does not provide the best approximation of the observed foF2 versus R_{12} dependence (other dependencies may give less sum of residuals), but it should be considered in terms of the following regression with Ap_{132} to find the minimal SD. Therefore, regression (10) is not a "model" in usual sense of this word as it is accepted in other approaches. This regression (10) is used to remove the solar activity part from the observed foF2 variations as a "pure" foF2 dependence on solar activity (presented by the R_{12} index) a priori is not known for each month.

Then monthly relative deviations are calculated:

$$\delta\mathrm{foF2} = (\mathrm{foF2}_{\mathrm{obs}} - \mathrm{foF2}_{\mathrm{reg}})/\mathrm{foF2}_{\mathrm{obs}}. \qquad (11)$$

Relative deviations for different months are combined together to get the annual mean relative deviation. Q-medians are used in the method instead of the usual monthly foF2 values. The Q-medians are obtained over quiet days of each month. A day is considered to be quiet if $\mathrm{Ap} \leqslant 10$ for the given day and the two previous days.

The geomagnetic activity effect is removed (or at least heavily suppressed) using the following regression of 11-year smoothed values:

$$\delta\mathrm{foF2}_{132\,\mathrm{reg}} = c + d\,\mathrm{Ap}_{132}(t+n) + e\,\mathrm{Ap}^2_{132}(t+n), \qquad (12)$$

where n is a time shift in years of Ap_{132} with respect to $\delta\mathrm{foF2}_{132}$. An analysis had shown that the best results could be obtained when an additional smoothing by a five-order polynomial was applied. Then the linear trend of residuals is computed:

$$\delta\mathrm{foF2}_{132} - \delta\mathrm{foF2}_{132\,\mathrm{reg}} = \alpha\,\mathrm{time(years)} + \delta. \qquad (13)$$

The linear trend, computed with Eq. (13) from such double-smoothed values, is shown in Fig. 4 together with calculated input parameters. Top panel shows the observed and polynomial approximated Ap_{132}, which seems to indicate a smoothed maximum near or just after 1985. Bottom panel displays long-term behaviour of $\delta\mathrm{foF2}_{132}$ and $\delta\mathrm{foF2}_{132\mathrm{reg}}$, and the linear trend computed from residuals with Eq. (13). The slope is −0.000086 in relative units. If we assume an average foF2 at noon to be 10 MHz, then the trend is −0.00086 MHz/year, which means a small and statistically insignificant (Fisher criterion) trend. Such a trend is much smaller than the trends obtained by other authors.

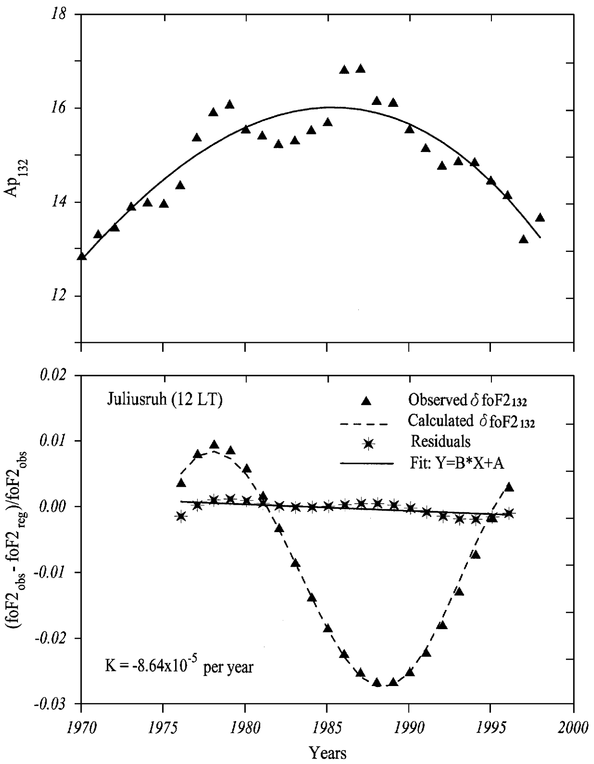

Fig. 4. Long-term trends in foF2 from Juliusruh. Top panel shows the observed and polynomial approximated Ap_{132}. Bottom panel reveals long-term behaviour of $\delta\mathrm{foF2}_{132}$ and $\delta\mathrm{foF2}_{132\mathrm{reg}}$, and the linear trend computed from residuals with Eq. (13).

5.6. Danilov's results

Danilov (2002b) developed two methods to derive the non-geomagnetic trend in foF2 (or hmF2). Then he used one of them (Danilov, 2003a) for calculating the non-geomagnetic component of the long-term trend in foF2. The same method is used here. The method deals with relative trends. The latter fact makes it possible to use jointly various local times and times of a year in spite of strong diurnal and seasonal variations in absolute values of foF2. To exclude the solar activity effect, the relative values δfoF2 that are deviations of the observed foF2 from the model (a third-degree polynomial in terms of the smoothed solar activity index) are analysed. This excludes the solar activity effect in the trends we are looking for. Three solar indices were tried by

Danilov (2003a): F10.7, *R*, and E10.7. He found that the best results were obtained with the latter index, so all the trends in foF2 and hmF2 in Danilov's publications were calculated using the E10.7 index. Danilov made calculations of trends for the Juliusruh 1976–1996 dataset with correction by F10.7 and E10.7 and came to the conclusion that for the particular dataset analysed here the corrections with F10.7 and E10.7 yield practically the same trends and their significance, -0.00079 ± 0.00018%/year and -0.00081 ± 0.00021%/year, respectively.

The method is based on the assumption that the observed trend coefficient in foF2, *k*(obs), is a result of linear combination of a geomagnetic trend caused by long-term changes in geomagnetic activity, and a non-geomagnetic (probably anthropogenic) trend, *k*(tr). The geomagnetic trend is assumed to be proportional to the slope *k*(Ap) of the linear approximation of the Ap values plotted versus the years of the given interval. The non-geomagnetic trend is obtained as the difference between the observed trend and the geomagnetic trend component. The method works with 30-year long-intervals, therefore the interval 1967–1997 is analysed. This again can introduce some but rather slight (definitely not principal) difference into the results in comparison with results based strictly on the period 1976–1996.

The results of calculations of the non-geomagnetic trends for each hour of the interval 10–14 h with E10.7 solar activity reduction are summarized in Table 3. The average value for 10–14 LT is −0.00081 per year. If we reasonably assume that the average foF2 is about 10 MHz, then the non-geomagnetic trend for the conditions considered would be −0.0081 MHz/year, which means a decrease by −0.16 MHz for the 20 years period 1976–1996. This trend is by an order of magnitude higher than Mikhailov's trend, comparable with total trends in Tables 1 and 2 computed with sunspot number, and about half of those computed with F10.7.

Table 3
The non-geomagnetic trends for Juliusruh, 1967–1997

LT	Trend per year	Standard deviation
10	−0.00132	0.00019
11	−0.00074	0.00021
12	−0.00073	0.00018
13	−0.00064	0.00026
14	−0.00064	0.00024

The average value for 10–14 LT is −0.00081 per year. Trend is in relative units per year. If we assume that the average foF2 is about 10 MHz, the non-geomagnetic trend would be −0.0081 MHz/year.

6. Discussion

All the above results including Fig. 1 clearly illustrate the importance of correction for the solar cycle effect in computing trends. If it is so important, it must be done carefully with the right proxies of solar activity. The only solar proxies available over the period of ionosonde measurements are the relative sunspot number, *R*, the solar radio noise at 10.7 cm, F10.7, and Tobiska's index E10.7 used as proxy of solar EUV flux. They correlate very well on long time scales, worse on short time scales, and to some extent differ in their time course (e.g., Donnelly, 1989). The observed F10.7 (non-adjusted to the Sun–Earth distance) has been obtained as a better solar proxy than *R* by Ulich, Bremer and Argentinean group (the other three teams did not study this problem) based on daily, monthly and 12-month running mean monthly values, respectively. This appears physically plausible. The solar cycle has in fact two maxima spaced by about 2 years. The sunspot number reveals the well pronounced first maximum and relatively weak, if any the second maximum (it differs from cycle to cycle, the difference between maxima is more pronounced for odd cycles). On the other hand, F10.7 often displays a better-pronounced and stronger second maximum, like in 1981, which is also the main maximum in the solar EUV radiation (e.g., Donnelly, 1989) ionizing the F region. Fig. 5 illustrates for yearly average values the different course of F10.7 and *R* around maximum of both solar cycles. This difference plays an important role when we deal with monthly data or 12-month running mean monthly data (e.g., Tables 1 and 2). As Burešová (1997) showed, the R_{12}-based prediction of monthly median foF2 fails just in the period of the second maximum of the solar cycle. On the other hand, the main reason of the difference, shown in Fig. 5, does not play a role when we are dealing with 132-month (11-year) running mean data (Mikhailov's method).

The difference between the results based on 12-month running means of *R* and F10.7, shown in Table 2, is not large but it is not negligible. Such a difference might be surprising in view of the fact

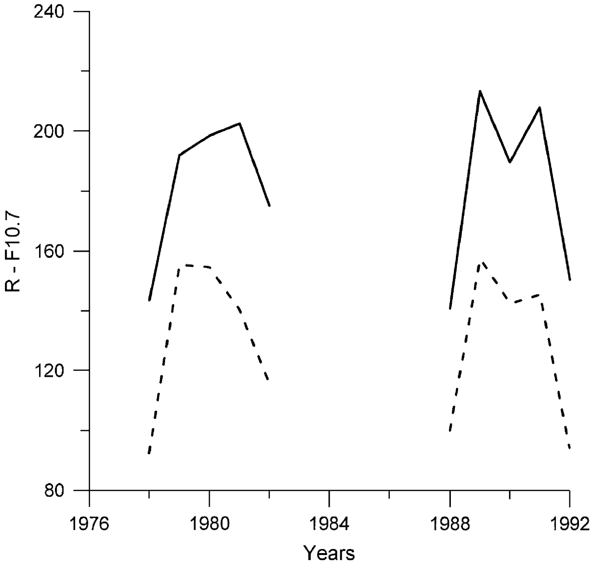

Fig. 5. Course of yearly average values of solar indices F10.7 (observed—full curves) and sunspot number *R* (dashed curves) around maxima of solar cycles 21 and 22.

that correlation between 12-month running means of *R* and F10.7 since 1948 reaches $r = 0.991$. However, the difference between yearly values course in maximum of the first solar cycle studied (Fig. 5) is unusually large in the analysed period, and the trend in foF2 is many times smaller than the effect of solar cycle. This is probably the reason why even a relatively very small difference between generally very well correlated *R* and F10.7 can have an impact on the calculation of trends.

Danilov (2003) claims that generally E10.7 is even a better proxy. Danilov's calculations (Section 5.6) show that for the Juliusruh dataset and his method the correction with F10.7 or E10.7 provides practically identical trend and its significance. Also Ulich (Section 5.3) obtained about the same results for F10.7 and E10.7, when he used observed, not adjusted E10.7. Physically plausible is the E10.7 correction comparable with or not worse than the F10.7 correction in view of the way of E10.7 derivation, if there is no mistake in E10.7 determination. Therefore the application of F10.7 or E10.7 seems to provide very similar results and both can be used.

The geomagnetic field is not constant, it has a westward drift and also its intensity and large-scale anomalies like the South Atlantic anomaly change on long time scales. Fortunately, during the period under study (1976–1996) the change of dip angle at Juliusruh was very small and, thus, the effect of long-term changes of geomagnetic coordinates of the station on trends in foF2 was very small and might be neglected (Section 5.2). However, it does not mean that such an effect may be neglected at any place; for some stations it could play a role. However, one should keep in mind that the secular variation of the global intensity of the geomagnetic field (even small) may affect (indirectly via particle precipitation, electric fields etc.) the global circulation pattern and the latter might affect ionospheric trends.

In spite of quantitative differences between trends obtained by different methods and different authors, they essentially qualitatively agree in the sense that all the trends are relatively weak, negative or statistically insignificant (even those are mostly negative or almost zero for yearly values). Nevertheless, large quantitative differences occur between trends provided by different authors, and even by different methods applied by the same group of authors (Chilean results).

There are two groups of results. Some methods do not apply correction to solar (geomagnetic) activity (correction to solar activity/solar cycle seems to be more important), namely Fig. 1, and methods 'a' and 'b' of Chilean group. The Chilean method 'a' and Fig. 1 reveal very similar trends, −0.065 and −0.062. These trends are several times larger than the trends, which apply the correction to solar activity, as it is the case with the large majority of presented results. This illustrates the necessity of correction to solar cycle/solar activity. Further on we shall deal only with solar-corrected data/results.

Even after correction of foF2 data for solar activity, different methods of calculations provide considerably different trends. Bremer, Ulich, Argentinean group, and Chilean methods 'c' and 'd' provide similar values of the trend within a range of about −0.015 to −0.020 MHz/year. Such values of trend are considered to be "basic" for comparison with other results. The small differences between trends may probably be accounted for by slightly different data handling (daily, monthly, 12-month running means of foF2 and F10.7), by computation of trends from all values versus computation of monthly trends and their averaging, and partly by different methods applied. The width of the above range of trends may serve also as an estimate of accuracy attainable in foF2 trend calculations.

Danilov developed a special method to determine the non-geomagnetic (anthropogenic) component of the overall trend. He obtained a trend of about

−0.008 MHz/year, which is about half of the "basic" trends. If we assume that the overall trend is partly of anthropogenic origin and partly of geomagnetic origin, then Danilov's trend is reasonably comparable with the "basic" trends. Danilov used longer interval, 1967–1997, but it had not substantial influence on resulting trends.

Chilean wavelet-based methods 'b' and 'e' reveal trends, which are rather insignificant, about seven times smaller in absolute values than the non-wavelet-based trends, and are positive. One of possible reasons is a kind of over-shoot effect, i.e. a case where a negative value associated with an ultra low frequency component is taken into account not exactly, in other words the correction is larger than necessary and, therefore, the residual (i.e. trend) becomes positive. Another possibility is that the trend found by standard methods may be not the same as the one detected by wavelet methods (particularly discrete wavelet)—see partly different definition of the term trend in Section 4. Wavelet-based trends for relatively short interval of two solar cycles are slightly non-linear.

Mikhailov used 11-year smoothed values, Q-medians and a partly different approach. His trend is negative, reaches a value of about −0.00086 MHz/year, which means statistically insignificant and about twenty times smaller trend than the "basic" trends of majority of other authors. Why there is such a difference?

Mikhailov uses monthly Q-medians (geomagnetically quiet day medians) instead of monthly average values of foF2. In order to check if it has an effect on the trend results, Elias (Argentinean group) repeated their calculations (results shown in Table 2) with Mikhailov's Q-medians. For the consecutive series of all data, after applying a 12-month running mean and filtering solar activity through F10.7, she obtained the trend of −0.018 ± 0.003 MHz/year, which is almost identical with −0.016 ± 0.003 MHz/year from Table 2. Thus application of Q-medians instead of monthly average values has no appreciable influence on trends, as expected, and cannot account for the big difference between small Mikhailov's trend (Section 5.5) and trends obtained by other authors.

Mikhailov provided Q-medians for the period 1971–1999. For that period the trend computed by Elias reaches a value of −0.013 ± 0.002 MHz/year. This is slightly lower than the trend for the period 1976–1996. Partly it might be affected by the length of the longer period, which is not a period of a few full solar cycles as the shorter period. Partly it can reflect the degree of stability of trends with different periods under study. Thus the use of partly longer analysed period can only insignificantly contribute to the difference between Mikhailov's and other results.

Mikhailov claims that practically all effects of geomagnetic and solar activity variations are removed from "his" trends, as Eqs. (10) and (12) are used together to minimize the standard deviations, and this is the main reason of the difference between his and other results. However, Ulich tested more than 200 combinations of solar proxies and his results differ principally from those of Mikhailov.

The removal of solar activity effects, which are (at least on solar cycle time scale) many times larger than the trend itself, is a problem, when we consider solar activity in the most general sense—variability of solar electromagnetic radiation and solar wind/magnetospheric activity. To remove their effects, we are using proxies, because long-term direct measurements are not available: F10.7, R or E10.7 for solar electromagnetic radiation, geomagnetic indices (mostly Ap) for solar wind/magnetospheric influences. We know that on short time scales like day-to-day changes the proxies do not perform well, but on longer time scales (months, years) the situation is much better. We believe that on solar cycle time scales the proxies describe solar activity variability sufficiently well for trend studies. However, even small imperfections or inadequacies in description of the solar activity effect variability by proxies might affect noticeably the computed trends, because they are many times smaller than the solar cycle effect itself. The application of R_{12} in Eq. (10) may introduce some error, but on the time scale used (11-year smoothing) this error is expected to be very small and can hardly contribute significantly to the difference between the results of Mikhailov and others.

Smoothing will generally reduce the magnitude of the trend, but hardly by a factor of 20 (E.C. Weatherhead, private communication, 2005). Also comparison of Ulich's (Section 5.3), Bremer's (Section 5.1) and Argentinean group (Section 5.2) results indicates slight weakening of trends as a consequence of smoothing. Thus the 11-year smoothing very probably contributes to the difference between the results of Mikhailov versus others, but can hardly explain the large difference.

Mikhailov makes various adjustments in his method and potential impact of such adjustments on resulting trends in foF2 is not clear.

Thus we find some factors, which can contribute to the difference between the results of Mikhailov and others, but they cannot quantitatively explain the difference. We present evidence that some other factors cannot contribute to the difference significantly. Further investigation is needed to find the reason of the difference between the results of Mikhailov and others.

The seasonal variations of the trends by Bremer and by Chilean group (Figs. 2 and 3) exhibit similar shapes albeit both do not seem to show a systematic variation. Elias also calculated the trend values for each month with Q-medians for 1976–1996 and longer Mikhailov's period, as shown in Fig. 6. Even though the general pattern of seasonal dependence of trends is similar to that based on monthly average values, as shown for Bremer's results in Fig. 2, there are substantial differences for some months, e.g. for March. Thus for datasets with small amount of data, like individual months, the use of Q-medians can lead to substantially different results. What is even more important, the seasonal variation of trends for the period 1971–1999 is evidently smoother and smaller than for the period 1976–1996. This means that the seasonal variation of trends (not yearly trends) cannot be reliably determined from such a short period as two solar cycles (1976–1996) due to a small amount of data in individual months. Therefore, the seasonal dependence of trends obtained by different co-authors of the paper must be considered with great care.

There are two basic possibilities how to explain the observed trends. Either anthropogenic (man-made) changes of the atmosphere, or increasing geomagnetic activity almost throughout the 20th century. Until now co-authors of the paper have not reached consensus as for the origin/mechanism of the observed trends—some prefer anthropogenic origin, others presented arguments in favour of geomagnetic origin. As Danilov's results (Section 5.6) suggest, i.e. his "non-geomagnetic" trend being about half of the "basic" trends, it is well possible that both mechanisms play an important role. Moreover, "anthropogenic" means for majority of authors the increasing concentration of greenhouse gases in the atmosphere, but Danilov (2003b) mentioned possible influence of increasing amount of space vehicle chemical contamination in the upper atmosphere, and Danilov (2005) discussed possible decreasing concentration of atomic oxygen in the upper atmosphere as potential source/contribution of anthropogenic origin to the observed trends in the F region. The question of origin of the observed trends remains open.

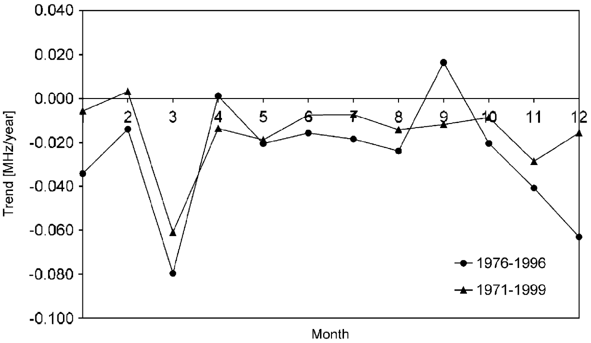

Fig. 6. Seasonal variation of trends computed from Q-medians for the periods 1976–1996 (dots) and 1971–1999 (triangles).

The following question arises: Why when correcting for geomagnetic activity the short-term geomagnetic effect is removed, but not the long-term geomagnetic effect. However, the short- and long-term geomagnetic effects may be in some sense independent, i.e. the applied correction need not remove the secular geomagnetic trend effect (like when we compute Lyman-alpha flux from F10.7 and F10.7$_{81}$, the 3-month average F10.7). The long-term geomagnetic activity trend is displayed best in aa-indices, whose data series begins in the 19th century. However, the trend in aa seems to level off near/at the end of the 20th century. Thus in a couple of years observational data probably allow to resolve the question of possible geomagnetic origin of trends in foF2. In this context it should be mentioned the result of Laštovička (2005) that during the 20th century the role of solar/geomagnetic factors in trends is decreasing and the role of the greenhouse effect is increasing from the beginning towards the end of the century, and from the F region downwards to the troposphere. This indicates the possibility that in the past the geomagnetic variability was the main driver of long-term changes in foF2, whereas at present it can turn to the greenhouse effect as the main driver. Mikhailov and de la Morena (2003) indicated such a change from geomagnetic to non-geomagnetic dominant driver of trends around 1970 in the E region.

We cannot reach agreement on the origin of trends, but it seems we could establish some constraints/conditions that limit possible mechanisms. Namely, they should simultaneously explain the observed trends in foF2, hmF2 and thermospheric density (from satellite drag). Therefore, first we have to reach sufficient agreement as regards the observational trends in foF2 and hmF2. The agreement is better for thermospheric density trends, where the results of various authors agree at least qualitatively (e.g., Emmert et al., 2004; Marcos et al., 2005). This constraint should hold if the main mechanism of the observed trends is the greenhouse cooling of the thermosphere, maybe also for the geomagnetic origin of trends. Even if the trend in foF2 is caused mainly by the trend in atomic oxygen concentration, such a mechanism can explain at least qualitatively also the observed trends in thermospheric densities (Danilov, 2005).

7. Conclusions

All results are based on the analysis of Juliusruh data over the period of 1976–1996. Various discrepancies remain unexplained but some conclusions may be drawn:

1. The selected Juliusruh 1976–1996 dataset is not only a high-quality dataset covering two solar cycles from minimum to minimum, but it is also free of possible influence of the secular drift of the geomagnetic coordinates of the station on the observed trends.
2. The methods of correction for the effect of the 11-year solar cycle on the trend determination in foF2 are responsible for a part of the differences found between various results. The correction with F10.7 (observed, not adjusted) is superior to that with sunspot number *R* for monthly data as well as 12-month smoothed monthly data; for 132-month (11-year) smoothed monthly data the difference is expected to be quite negligible. The corrections with F10.7 and E10.7 seem to provide very close results. Therefore both solar proxies appear to be well suited.
3. Even the optimum selection of the interval under study does not help to reduce sufficiently the effect of solar cycle on trend determination. Application of correction of data for solar activity is necessary. Trends without solar correction are artificially amplified to values several times larger than trends with solar activity correction.
4. Trends in foF2 for Juliusruh are relatively weak, either negative or statistically insignificant, mostly between −0.02 and −0.015 MHz/year.
5. The purely anthropogenic component of trends might be slightly smaller than full trends, as Danilov's results suggest.
6. Mikhailov's trends differ substantially from the other trends.
7. The seasonal variations of trends found by Bremer and by the non-wavelet Chilean group method (Figs. 2 and 3) exhibit similar shapes albeit both do not seem to show a systematic variation. Fig. 6 shows that monthly trends must be considered with great care due to relatively small amount of data, which makes them less stable and less reliable.
8. Chilean wavelet-based methods seem to be able to extract the ultra low frequency components so as to leave only a trend, which strictly would correspond, to the next larger frequency. This trend is not significant in the data set studied here, but it my be by its definition partly different from standard linear trends (all trends are weak), as it appears to be slightly non-linear for relatively short data series as two solar cycles.

Two open problems remain to be solved, both being important:

1. What is the predominant origin of trends in foF2—anthropogenic (greenhouse gases, or atomic oxygen trend, or space vehicle chemical contamination) or geomagnetic? Many authors prefer greenhouse origin of the observed trends, while others prefer geomagnetic origin or atomic oxygen mechanism. At present we have not enough observational information to resolve this problem
2. Why are (statistically insignificant) Mikhailov's trends much smaller than trends obtained by other authors? We found some factors contributing to the difference, we showed that some other factors cannot contribute significantly to the difference, but further investigation is needed to resolve the difference quantitatively.

We hope to remove and/or explain the remaining open problems in further work. A detailed analysis of a carefully selected hmF2 dataset is also desirable in order to clarify specific problems of hmF2 trend studies.

Acknowledgements

J.L. has been supported by the Academy of Sciences of the Czech Republic under Project no. AVOZ30420517.

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