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Physics and Chemistry of the Earth 31 (2006) 34–40

PHYSICS and CHEMISTRY of the EARTH
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# Progress in studies of the trends in the ionosphere F region

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Received 8 September 2004; accepted 2 February 2005
Available online 11 April 2006

**Abstract**

A detailed analysis of the hmF2 data obtained at the network of ionospheric stations is performed to reveal long-term trends independent of the geomagnetic activity variations during the recent decades (nongeomagnetic trends). The method developed and tested by the author earlier is applied. Unlike the results on foF2 published by the author earlier, the picture of hmF2 trends is not homogeneous. For 17 ionospheric stations positive significant trends are obtained. Six stations give negative trends in hmF2. For three stations no trends were derived. The behavior of the positive trends is considered. It is shown that these trends depend neither on geomagnetic latitude nor on local time, both facts confirming their independence of geomagnetic activity. The averaging of the positive trends over all 17 stations gives a relative trend of 0.0011 per year with the standard deviation of 0.0005. At the average height of the F2 layer of about 300 km this means an increase in hmF2 by 0.33 km per year. Possible interpretations of the obtained trends in foF2 and hmF2 from the point of view of anthropogenic changes in the thermosphere are considered.


## 1. Introduction

Studies of the long-term changes (trends) in the parameters of the upper atmosphere and ionosphere are currently very popular. Several groups of authors (Bencze et al., 1998; Bremer, 1996, 1998, 2001; Danilov, 2002a,b, 2003; Danilov and Mikhailov, 1998, 1999, 2001; Givishvili and Leshchenko, 1993, 1994; Jarvis et al., 1998; Marin et al., 2001; Mikhailov and Marin, 2001; Ulich and Turunen, 1997; Ulich et al., 1997; Upadhyay and Mahajan, 1988), studied trends of the F2-layer parameters, hmF2 and foF2. The results of these studies differ significantly both, by the used methods of trend revealing and the results obtained. The detailed review by Danilov (2002a) is already in some points out of date, especially concerning the new approaches published by the Mikhailov and Deminov groups. The most throughout review of the problem was recently published by Bremer et al. (2004). We will not discuss here in detail the reason for such "popularity" of the searches for long-term trends in the F2-layer parameters. Neither are we going to discuss different approaches to the searches of the long-term trends in foF2 and hmF2 referring the reader to the Bremer et al. (2004) and Danilov (2002a) papers.

We merely note that the main aim is to find an answer to the question whether there happen in the recent decades variations in the thermosphere state independent of solar and geomagnetic activity. In other words, whether there is an anthropogenic component in the long-term variations of the thermosphere parameters and if it exists, how large it is. Evidently out of all ground-based measurements the vertical sounding data are the best material to try to answer the above-formulated question.

There is no sense in describing here two principal approaches (absolute and relative) to the looking for trends in foF2 и hmF2. These approaches were described in detail by Danilov (2002b). In the majority of later papers (Deminov et al., 2002; Mikhailov, 2002; Mikhailov et al., 2002) the relative approach is used. Bremer et al. (2004) presented mainly the results of the absolute approach.

In this paper dedicated to particular results obtained by the particular method there is no place for the discussion

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1474-7065/$ - see front matter 
doi:10.1016/j.pce.2005.02.002

on various methods of elimination of the effects of long-term variations of the geomagnetic field from the observed long-term variations in foF2 and hmF2 used by different authors (Danilov, 2002b; Deminov et al., 2002; Mikhailov, 2002; Mikhailov et al., 2002). Below we describe the results of application of the method developed and published by the author earlier (Danilov, 2002b) and used to analyze the trends in foF2 at the network of the vertical sounding stations (Danilov, 2003).

It is worth reminding only that during the recent years Mikhailov with coauthors (the references see above) have been actively developing a concept that the trends in foF2 having found earlier by him and the author of this paper (Danilov and Mikhailov, 1998, 1999, 2001) are a manifestation of the long-term trends in geomagnetic activity (Ap index in particular).

However Danilov (2002a,b, 2003) showed that the long-term changes in geomagnetic activity cannot alone be responsible for the observed trends in foF2. During some time intervals (detailed examples may be found in Danilov (2002a,b, 2003) no systematic variations of Ap, is observed, however the ionospheric data demonstrate significant trends in foF2. This was a starting point of the concept suggested by Danilov (2002b) according to which the foF2 trends derived by the relative trend method and analyzed in detail by Danilov and Mikhailov (1999, 2001) and Mikhailov and Marin (2000, 2001) present a combination of two effects: geomagnetic trend produced by the long-term variations in geomagnetic activity and "nongeomagnetic" trend (that is the trend independent of geomagnetic activity). The nature of the latter is not finally clear, but it is very probably that it (if exists) has an anthropogenic origin.

Danilov (2002b) developed a method of revealing "nongeomagnetic" trend in parameters of the F2 layer on the background of the variations of these parameters with geomagnetic activity and described the work of the method in detail using the data of foF2 measurements at Sverdlovsk ($\varphi = 56.7$ N, $\Phi = 48.4$ N) and Irkutsk ($\varphi = 52.7$ N, $\Phi = 41.1$) ionospheric stations. At both stations a significant "nongeomagnetic" trend ($k(\text{tr}) = -0.00115$ and $-0.00128$, respectively) was obtained.

The method developed and tested by Danilov (2002b) was applied by Danilov (2003) to a large number of ionospheric stations and the obtained results were analyzed to look for the trend dependence on geographic and geomagnetic latitudes and local time.

The results of the analysis showed that the data of all 23 analyzed stations gave a negative trend in foF2 for the period from 1958 to the mid-1990s of the same order of magnitude. When two stations giving the largest ($-0.00340$ per year) and the smallest ($-0.00042$ per year) values were rejected, the results of the rest of 21 stations gave the mean trend in foF2 $k(\text{tr}, \text{fo})$ equal to $-0.0012$ per year with the standard deviation $\sigma = 0.00043$. No significant dependence of $k(\text{tr}, \text{fo})$ neither on station geomagnetic latitude nor local time was found. It is worth noting that the concept of geomagnetic control of the foF2 trends requires a dependence of the latter on both indicated parameters because the characteristics of the ionosphere reaction to geomagnetic disturbances depend on these parameters very strongly (Mikhailov, 2002).

In this paper similar approach of the search for long-term trends independent of geomagnetic activity is applied to the data on the height of the F2 layer, hmF2.

## 2. Method and data

Danilov (2002b) proposed two methods for revealing of "nongeomagnetic" trends. It was shown that both methods provide almost the same results. That is why in this paper to analyze the hmF2 trends we used only one method (called by Danilov (2002b) Method I). This method was used also by the author to analyze the entire data base on foF2 (Danilov, 2003).

There is no need to describe here the above indicated method because it was described in detail (and step-by-step) in the first paper and briefly described in the second paper with illustration of the main principles on the example of analysis of various stations. It is worth reminding only that the method is based on the assumption that the observed trend in foF2 (or hmF2), $k(\text{obs})$, is a result of the linear combination of two different trends: geomagnetic (i.e. produced by the long-term changes in geomagnetic activity) and "nongeomagnetic" $k(\text{tr})$. It was assumed also that the variations in geomagnetic activity are described by the annual mean values of the Ap index and that the geomagnetic trend in foF2 (or hmF2) is proportional to variations of Ap (the Ap gradient, $k(\text{Ap})$) during the considered period. In this case we have a very simple formula for $k(\text{tr})$

$$k(\text{tr}) = k(\text{obs}) + a_1 k(\text{Ap}). \tag{1}$$

The $a_1$ coefficient is first of all a scale coefficient and takes into account the difference in the values of $k(\text{obs})$ and $k(\text{Ap})$ due to the difference in absolute values of δfoF2 and Ap. However, Danilov (2002b) assumed that the $a_1$ coefficient includes also the efficiency of the magnetic activity impact on foF2 and so can vary with local time and from one station to another. The results obtained for the entire database of the foF2 data confirmed this assumption completely.

The data of the vertical sounding at the ionospheric stations network were the initial data for looking for hmF2 trends. The data on hmF2 (in the same way as in the case of foF2) were collected using various sources including CD-discs, Internet, World Data Center B in Moscow and the Geophysical Database collected in the Moscow Regional Center of the International Space Environment Service (ISES).

The first requirement to the hmF2 data was the same as to the foF2 data: there should be not less than 30 + 5 years of continuous observations. Number 5 is the least number of 30-year intervals for which the procedure is stable and provides reliable results. This number has been found empirically by the way of experimenting with the program. This approach was found completely reasonable looking for the foF2 trends (Danilov, 2003), because led to a coordinated picture of the foF2 trends for all considered stations.

The rest of the requirements to the initial series of data (see Danilov (2003)) had to be softened. The matter is that at many ionospheric stations the measurements of hmF2 began later than those of foF2 so the corresponding series of data are shorter than for foF2. Due to this, for example, there was no possibility to compare (as it has been done for the foF2 trends) the trends obtained for the later period (from 1958 to mid-1990s) to the trends for the earlier period (from 1948 to mid-1980s). Moreover, to increase the number of stations we had even to try to use shorter intervals (25 years instead of 30 years), the fact being mentioned below. With the same aim the geographic latitude lower boundary of the considered stations was reduced. Analyzing the foF2 trends it was taken 30°. In this paper the lower boundary was chosen at a latitude of 25°. Near-equatorial stations were ignored in both papers because the relation of the F2 layer parameters to geomagnetic activity in the equatorial region is very complicated and elimination of the impact of long-term changes in Ap may be too complicated.

We succeeded in finding the data satisfying the main requirement (a series $30 + 5$ years and more long) for 26 ionospheric stations. The results of the analysis were not so well coordinated as in the case of foF2. For 13 stations statistically significant positive trends were obtained. Averaging of the values $k(\mathrm{tr,ave2})$ obtained for each station gave $k(\mathrm{tr,hm}) = 0.0012$ per year with the standard deviation $\sigma = 0.0006$. The data on the indicated 13 stations and the obtained trends are shown in the top part of Table 1. (Here we use the designations used in the previous papers: $k(\mathrm{tr,ave1})$ is the trend for the given station for the given moment of LT, $k(\mathrm{tr,ave2})$ is the trend for the given station obtained by averaging of $k(\mathrm{tr,ave1})$ over all LT, and $k(\mathrm{tr,hm})$ is the final value of the trend obtained by the averaging of all accepted values of $k(\mathrm{tr,ave2})$ over all stations).

As a result of the analysis, stable positive trends in hmF2 were derived not for all stations. For six stations significant negative trends were obtained. The corresponding data are presented in Table 2. For three stations (Sodankyla, Irkutsk and Slough) the picture of δhmF2 with years was unstable and no significant trend in hmF2 was obtained.

The data of the majority of ionospheric stations do not fulfill the main requirement $30 + 5$ (see above) because the hmF2 data series available are too short. An attempt was undertaken to reduce the main period from 30 to 25 years. It was noted above (Danilov, 2002b, 2003) that the optimal period is 30-year. The reduction of the period leads to a less stable relation between δhmF2 and δAp (the value of $r(\delta\mathrm{hmF2,Ap})$ changes sign from one year to another and the calculation of $k(\mathrm{tr})$ becomes impossible).

Nevertheless because of a small number of the stations satisfying the $30 + 5$ requirement, we considered also stations satisfying the $25 + 5$ condition. As we had expected, the picture for the majority of these stations was unstable and it was impossible to derive the hmF2 trends by the method considered. However, the picture was stable for four stations presented in the bottom of Table 1 and statistically significant trends were obtained.

Thus, positive trends in hmF2 were obtained for 17 stations. For six stations statistically significant negative trends were obtained and for three stations satisfying the main conditions the trends were not obtained.

Table 1
Stations with positive trends in hmF2

| Station | $\Phi$ | $\varphi$ | $\lambda$ | years | $k(\mathrm{tr,ave2})$ | $\sigma$ |
|---|---|---|---|---|---|---|
| Arg.Isl. | −65 | −54 | 296 | 1958–1994 | 0.00145 | 0.00023 |
| Luskcele | 63 | 65 | 19 | 1958–1998 | 0.00056 | 0.00022 |
| Yakutsk | 51 | 62 | 130 | 1958–1990 | 0.00051 | 0.00019 |
| Leningrad | 56 | 60 | 31 | 1958–1998 | 0.00072 | 0.00020 |
| Sverdlovsk | 48 | 57 | 61 | 1958–1993 | 0.00173 | 0.00019 |
| Tomsk | 46 | 57 | 85 | 1958–1996 | 0.00080 | 0.00013 |
| Moscow | 51 | 56 | 37 | 1958–1998 | 0.00191 | 0.00025 |
| Khabarovs | 38 | 49 | 135 | 1960–1992 | 0.00118 | 0.00056 |
| Boulder | 49 | 40 | 255 | 1959–1993 | 0.00138 | 0.00001 |
| Wallops | 49 | 38 | 285 | 1958–1998 | 0.00063 | 0.00020 |
| Ashkhabad | 30 | 38 | 58 | 1958–1998 | 0.00213 | 0.00040 |
| Mundarin | −43 | −32 | 116 | 1960–1993 | 0.00193 | 0.00049 |
| Okinava | 16 | 26 | 128 | 1958–1993 | 0.00055 | 0.00028 |
| Alma-Ata | 33 | 43 | 80 | 1958–1988 | 0.00148 | 0.00052 |
| Canberra | −44 | −35 | 149 | 1958–1990 | 0.00091 | 0.00028 |
| Akita | 30 | 40 | 149 | 1958–1988 | 0.00076 | 0.00021 |
| Norf. Isl | −34 | −29 | 168 | 1965–1993 | 0.00086 | 0.00059 |
| All positive $k(\mathrm{tr,ave3}) = 0.0011$ | | | | | | sigma = 0.0005 |

Table 2
Stations for which negative trends were obtained

| Station | $\Phi$ | $\varphi$ | $\lambda$ | years | $k$(tr, ave2) | $\sigma$ |
|---|---|---|---|---|---|---|
| Murmansk | 64 | 69 | 33 | 1958–1993 | −0.00048 | 0.00009 |
| Uppsala | 58 | 60 | 18 | 1958–1997 | −0.00079 | 0.00012 |
| Novosibir | 44 | 55 | 83 | 1959–1992 | −0.00041 | 0.00019 |
| Stanley | −41 | −52 | 302 | 1958–1995 | −0.00041 | 0.00001 |
| Rugen | 54 | 54 | 13 | 1958–1998 | −0.00083 | 0.00035 |
| Poitiers | 49 | 46 | 0 | 1958–1995 | −0.00128 | 0.00050 |

## 3. Discussion

Trends in hmF2 different by sign for different stations were obtained by many authors (Bremer, 1998, 2001; Marin et al., 2001) (it is also illustrated in the recent review by Bremer et al. (2004)) in spite of different methods of trend derivation. The most probable explanation of this is related to the fact that the reliability of the hmF2 data determination is considerably lower than that for the foF2 data. The latter are read directly (and with high accuracy) from vertical sounding ionograms, whereas the former are recalculated from the initial data (foF2 and M3000), and there exist two methods of recalculation giving somewhere different results.

The comparison of Tables 1 and 2 shows that there is no system in geographic distribution of the stations giving negative values of $k$(tr, hm). If by the "majority method" we accept that correct (more typical) are positive trends in hmF2, than the existence of the stations for which negative trends are obtained or no trends were derived should be explained by the in irregularity of the hmF2 time series used for the analysis. While deriving long-term trends in hmF2, it is enough to have a small changes in the method of hmF2 determination within the 30–40 analyzed years to make the picture unstable (at least in the scope of the method used in this paper) and as a result a derivation of trends to become impossible or to lead to negative values of $k$(tr, hm).

Bremer (2001) in his Fig. 8 presents a good illustration of the cases when there were well pronounced discontinues in trends in hmE caused by technical changes. Evidently similar discontinues may be found in the series of hmF2 data. It is obvious that with such data series it is impossible to obtain corrected values of hmF2 trends. Table 3 shows six stations what have been considered both in this paper and in the Bremer (1998) analysis and for which no positive trends has been obtained in this paper. A typical feature is that for five out of six stations the Bremer's results give negative trends. If we believe that the positive trends are "correct" (more typical), Table 3 confirms that there is something wrong with the series of the initial hmF2 data, because two different methods give negative trends or no trends at all.

As far as we have no other (physical) explanations for obtaining negative hmF2 trends, we will consider "correct" (typical) positive trends presented in Table 1. In the same way as in the case of the foF2 trends (see Danilov (2003)) we first of all should check that the obtained positive trends actually are "nongeomagnetic", i.e. are not related to the variations of magnetic activity. To do that we should consider their dependence on the geomagnetic latitude and local time.

Fig. 1 shows the dependence of the obtained trends on the geomagnetic latitude of the station $\Phi$. One can see that there is no pronounced systematic dependence of nongeomagnetic trends (obtained for each individual station) on $\Phi$. Neither is there any pronounced dependence of $k$(tr, ave2) on the geographic latitude $\varphi$ (Fig. 2). Both figures show a scatter of the data but there is no statistically significant dependence neither on $\varphi$ nor on $\Phi$. The approximations drawn formally (the lines in Figs. 1 and 2) give such a small slope that it is statistically insignificant (the values of correlation coefficient squared $R^2$ which determines the Fisher parameter are 0.002 and 0.003, respectively).

The consideration of the diurnal variations of the $k$(tr, ave2) value presents slightly more difficult task. We have already seen above that (in the same way as in the case of determination of the foF2 trends) for many stations not

Table 3
Trends in hmF2

| Station | $\Phi$ | $\lambda$ | years | This paper | Bremer (1998) |
|---|---|---|---|---|---|
| Murmansk | 64 | 33 | 1958–1993 | Negative | Negative |
| Sodankula | 64 | 27 | 1958–1997 | tr < $\sigma$ | Negative |
| Uppsala | 58 | 18 | 1958–1997 | Negative | Negative |
| Rugen | 54 | 13 | 1958–1998 | Negative | Negative |
| Slaugh | 54 | 0 | 1958–1996 | tr < $\sigma$ | Positive |
| Poitres | 49 | 0 | 1958–1995 | Negative | Negative |

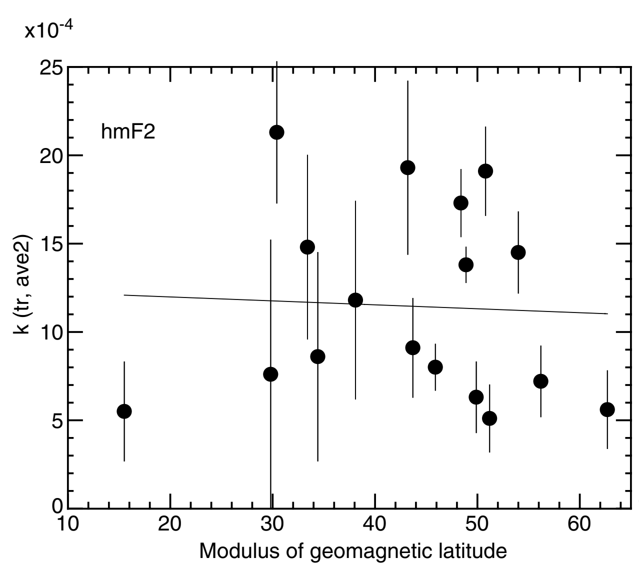


Fig. 1. Dependence of the nongeomagnetic trends $k$(tr, ave2) obtained for various stations on the magnitude of the geomagnetic latitude (points). The line shows the formal approximation of the points. The vertical bars are standard deviations.

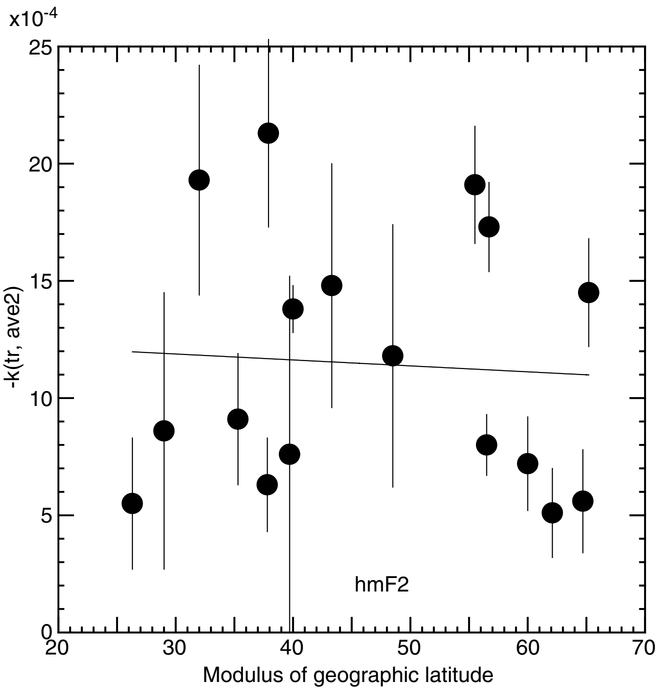


Fig. 2. Dependence of the nongeomegnetic trends $k(\text{tr, ave2})$ obtained for various stations on the magnitude of the geographic latitude (points). The line shows the formal approximation of the points. The vertical bars are standard deviations.

all LT moments were taken for the further averaging because of three criteria superposed. For some stations some sort of the $k(\text{tr, ave1})$ variations with LT is observed, but no coordinated picture is observed if all stations are considered. To illustrate this statement Fig. 3 is shown. For three stations located in different latitude and longitude zones we calculated for each LT moment (for which the value $k(\text{tr, ave1})$ has been accepted) the ratio of

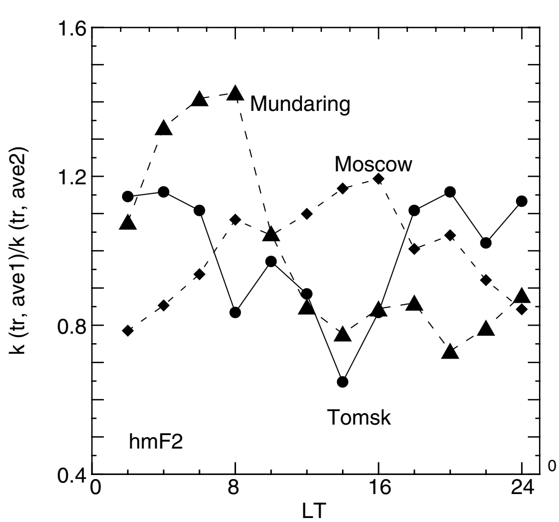


Fig. 3. The ration of nongeomagnetic trends $k(\text{tr, ave1})$ derived for each LT moment to the daily mean value for the given station $k(\text{tr, ave2})$ versus local time (1 Mundaring, 2 Moscow, and 3 Tomsk).

$k(\text{tr, ave1})$ to the mean value for this station $k(\text{tr, ave2})$ shown in Table 1. The obtained ratio is plotted in Fig. 3. One can easily see that there is no systematic variation of the considered ratio (and so $k(\text{tr, ave1})$) with LT.

Thus, we can state that the obtained trends in hmF2 demonstrate no pronounced dependence on geomagnetic latitude or local time. Both these dependences are typical for the trends induced by variations in geomagnetic activity (Marin et al., 2001; Mikhailov and Marin, 2000, 2001). Therefore we can state that the trends obtained in this paper are actually nongeomagnetic.

If we average the values of $k(\text{tr, ave2})$ over all 17 stations giving positive trends (Tables 1 and 3) we obtain the value $k(\text{tr, ave3}) = 0.0011$ per year with the standard deviation $\sigma(3) = 0.0005$. Thus the finally accepted value of $k(\text{tr, ave3})$ is more than $2\sigma$. This value shows that from 1958 to the mid 1990s the hmF2 value was systematically increasing by 0.11% per year. If we conventionally take for hmF2 the mean value of 300 km, the above indicated relative trend means absolute increase in the height of the F2-layer maximum by 0.33 km per year.

The above-presented value may seem rather small. However it means the increase in hmF2 from the 1950s to our days approximately by 17 km (if we compare identical conditions) the latter value being not very small for the vertical sounding.

However, more important is the following consideration. We have indicated in Section 1 that the main importance of looking for nongeomagnetic trends is closely related to their probable connection to the problem of possible changes in the thermosphere due to the antropogenic impact on the latter. Bremer et al. (2004) quite correctly noted that the trends both in foF2 and hmF2 obtained by various groups are too small to be taken into account in current empirical ionospheric models (like IRI or COST). However the presence of the trends in the parameters of the F2 layer should be considered together with trends in other parameters (temperature, density) to analyze the nature of the thermospheric and ionospheric trends.

Now we have two nongeomagnetic trends of the F2-layer parameters: of the critical frequency foF2 and the height of the layer maximum hmF2. The trends have opposite signs: foF2 decreases with time and hmF2 increases. As far as by the definition both trends are free from any influence of the long-term variations of solar and geomagnetic activity, there are serious arguments to believe that they manifest the long-term changes in the thermosphere at altitudes of F2 layer.

Fig. 4 gives one more visual illustration of the foF2 trend behavior indication to its probable anthropogenic origin. Actually, if the foF2 trends are of such origin one would expect their systematic increase with time during the recent decades. One example of such increase was presented by Danilov (2003) who compared trends for 1948–1985 and 1958–1995 for eight stations and found that the trends for the later period are systematically (on the

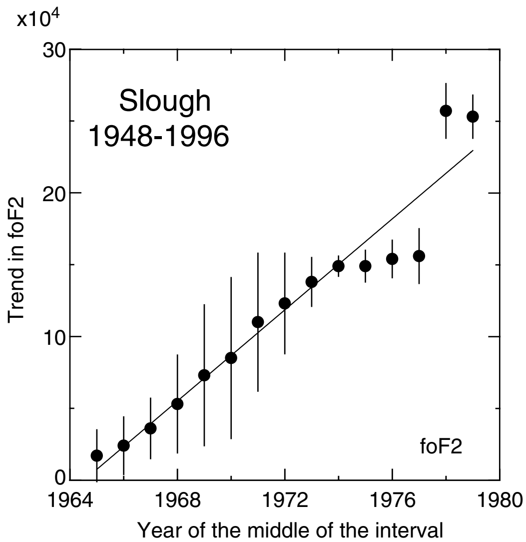


Fig. 4. The values of $k$(tr, ave2) for Slough for 35-years periods from 1948 to 1998.

average by a factor of 1.6) are higher than for the earlier period. Fig. 4 illustrates the same idea using the data on one station Slough. The tendency of foF2 trend to increase from earlier years to the later is obvious.

Any review of the problem of the trends in the parameters of middle and upper atmosphere is out of the scope of this paper. We remind only that changes of the thermosphere parameters because of the anthropogenic contamination have been predicted theoretically and recently are detected experimentally (Keating et al., 2000; Emmert et al., 2004).

According to the satellite drag data (Keating et al., 2000; Emmert et al., 2004) the density decrease is about 5% per decade. That gives about 20% for the 40-year period of ionospheric sounding considered in many publications.

It is worth trying to compare the results obtained by the satellite drag and by vertical ionospheric sounding in the scope of current theory of the F2-layer formation. As a connecting tool we will use the Rishbeth and Roble (1992) calculation of the ionospheric effects of the $CO_2$ doubling. Their results give a density decrease at heights of the F2-layer maximum be about 20% at the $CO_2$ doubling. Corresponding decreases in $T$ and $[N_2]$ are according to Rishbeth and Roble (1992) 30 K and 25%.

If the dynamical effects are neglected, the electron concentration in the F2-layer maximum is written as (Mikhailov et al. (1995))

$$[e](\max) = [O]^{2/3} T^{-5/6} ([O]/[N_2])^{2/3} \quad (2)$$

Substituting the above indicated values into (2) one obtains a decrease of [e](max) by 7%. By the order of magnitude it is close to the value obtained by Danilov (2003): 4.4% in foF2 trends for 40 years.

So the trends currently observed are close to the value predicted for the $CO_2$ doubling. However, we still are very far from the $CO_2$ doubling! According to different estimates the $CO_2$ increase as compared to the pre-industrial epoch is only about 20%. So the agreement between the satellite drag data and ionospheric trends only is an indirect confirmation of the correctness of both evaluations of the trends. However the question still arises: what is the cause of these trends?

The dependence of foF2 and hmF2 on thermosphere parameters may be written (taking into account the plasma drift) in a simplified form (see. Rishbeth and Barron (1960); Mikhailov et al. (1995)):

$$\lg[e](m) = 1.08 \lg[O]_{300} - 0.65 \lg \beta_{300} + 10^{-2} W_i \quad (3)$$

$$hm = 50 \lg[O]_{300} + 50 \lg \beta_{300} + 1.55 W_i \quad (4)$$

These formulae show that both considered parameters of the F2 layer depend on the atomic oxygen concentration at a height of 300 km $[O]_{300}$, linear recombination coefficient $\beta_{300}$ at the same altitude, and also the vertical plasma drift $W_i$. In its turn, the $\beta_{300}$ value depends on the concentration of the molecular constituents of the thermosphere gas $N_2$ and $O_2$ and also (via complicated dependence of rate constants of ion-molecular reactions on $T$) on the temperature.

If we accept the above-obtained results that the foF2 and hmF2 trends are negative and positive, respectively, then according to (3) and (4) the only thermosphere parameter which can directly explain this fact is the recombination coefficient $\beta_{300}$ because it enters into the formulae for $n_e$ (foF2) and hmF2 with opposite signs. However if the obtained trends have been a result of the increase of the greenhouse gases and corresponding cooling of the thermosphere, the effect would have been opposite to the observed one because $\beta_{300}$ should decrease with a decrease of I.

One of explanations of the observed trends may be the following. There are indications that there are trends in the vertical dynamical processes in the E region bringing down the NO molecules (Danilov, 2002a). If so, it is inevitable that the O atoms are also brought down by the same process into their recombination region near 100 km. The amount of the atomic oxygen should then decrease in the entire atmospheric column and [O] at any particular height should decrease. Since foF2 is much more sensitive to a decrease of [O] than hmF2, one would expect a negative trend in foF2. At the same time the trends at various heights should inevitably lead to changes in the global circulation. hmF2 is much more sensitive to the changes in circulation than foF2, so the effect of changing wind system may dominate in hmF2 leading to a positive trends.

One of the hypothetical possibilities of a systematic increase in $\beta_{300}$ is an appearance in the thermosphere gas composition (as a result of space flights) of minor constituents leading to an increase of $\beta_{300}$. Even a small admixture of some chemical forming a stable ion with a high recombination coefficient is able to increase the total recombination rate (i.e. $\beta_{300}$) and so decrease the electron concentration.

One can see from the above said that currently there is no unambiguous explanation of the detected effects in foF2 and hmF2. However, the author believes that there are serious indication to the fact that there exist long-term trends in the parameters of the F2 layer independent of long-term variations of geomagnetic activity and therefore most probably having an anthropogenic origin.

## 4. Conclusion

The method proposed by the author earlier (Danilov, 2002b) and used to find long-term trends in foF2 independent of geomagnetic activity (Danilov, 2003) is applied to the data on hmF2. The obtained results give positive and negative trends for 17 and 6 stations, respectively. No trends are obtained for three stations having long enough series of hmF2 data. This situation is apparently due to the fact that the determination of hmF2 is much less reliable (than determination of foF2) and depends among others on the method of hmF2 recalculation from the initial data.

If (by the "majority method") we accept as true the positive values of $k(\mathrm{tr}, \mathrm{ave2})$ then an averaging over 17 stations provides a mean trend $k(\mathrm{tr}, \mathrm{hm}) = 0.0011$ per year. Under the mean value of hmF2 equal to approximately 300 km the latter value provides the absolute trend in hmF2 equal to 0.33 km per year.

No variations of the obtained nongeomagnetic trend with geomagnetic and geographic latitude or local time are found. This fact makes it possible to assume its anthropogenic origin. Joint consideration of the nongeomagnetic trend in foF2 obtained earlier (Danilov, 2003) ($k(\mathrm{tr}, \mathrm{fo}) = -0.0012$ MHz per year) shows that the F2-layer critical frequency during the recent 50 years is systematically decreasing, whereas the height of the maximum is increasing. Evidently both these facts are a manifestation of the processes occurring in the thermosphere. Qualitatively the obtained trends in foF2 agree to the trends in atmospheric density obtained on the basis of the satellite drad data (Keating et al., 2000; Emmert et al., 2004). However, it is still difficult to say, changes in what thermosphere parameters lead to the observed picture of the foF2 and hmF2 trends.

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