TRENDS OF THE F-REGION PARAMETERS *F* AND THEIR POSSIBLE CAUSES

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The results of determining long-term trends of the ionospheric *F* 2 layer parameters are considered: critical frequency, height, total electron content, and half-thickness. It is shown that recent results of determining *foF* 2 trends are consistent with the results of a detailed analysis of data from stations in both hemispheres, published by the authors. Possible causes of negative trends in the *F* 2 layer parameters during cooling and subsidence of the thermosphere due to anthropogenic effects are discussed. The most likely causes of negative trends in *foF* 2 during winter months today are the decrease in the atom-to-molecule ratio in thermospheric gas and the increase in the rate of ion-molecular reactions as temperature decreases in winter conditions. A comparison of trends in various parameters is conducted, showing that these trends are consistent with each other.

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1. INTRODUCTION

The problem of long-term changes (trends) in the parameters of the upper atmosphere and ionosphere is well known and has been addressed in many works. We will note only the recent reviews by Laštovička [2023] and Cnossen et al. [2024]. The problem of cooling and subsidence of the middle and upper atmosphere was first clearly formulated in the work of Laštovička et al. [2008]. Subsequently, the problem has been discussed in many publications (see the relevant references in the reviews mentioned above).

New results from the study of trends in the parameters of the middle and upper atmosphere and ionosphere were discussed at the 12th Symposium on Long-term Changes and Trends in the Atmosphere, May 6 − 10, 2024, in Ourense (Spain). In the report by a large group of authors [Elias et al., 2024], trends in a number of ionospheric parameters were considered. We will repeatedly refer to this work below.

It is already completely clear today that the number of CO_2 molecules in the mesosphere and lower thermosphere is increasing by 5-7% per decade [Cnossen et al., 2024]. This leads to a number of phenomena in the middle and upper ionosphere. One of the important aspects of the problem is the change in the parameters of the ionospheric layers and, first of all, the $F2$ layer. The reason for this importance is obvious - even small changes in the parameters of this layer can lead to noticeable changes in the characteristics of radio wave propagation [Fagre et al., 2018].

The authors have repeatedly addressed the analysis of the critical frequency $foF2$ and the height $hmF2$ of the $F2$ layer. A description of the works of the previous period can be found in the review paper by Danilov and Konstantinova [2020]. Recent publications [Danilov et al., 2024a; b] analyze in detail the trends of these parameters until 2023. These results, as well as new results from other authors on $foF2$ and $hmF2$ trends will be discussed below.

The study of the problem of ionospheric trends has become noticeably more intensive in recent years. This applies to both the "classical" parameters $foF2$ and $hmF2$, as well as parameters such as the total electron content TEC and slab thickness ST.

The emergence of works on trends in various parameters of the $F2$ layer makes it urgent to compare these trends. This paper aims to provide a brief description of works on these trends that have appeared in the last few years , and to carry out the indicated comparison. We structured the presentation as follows. The results of determining the trends of each of the mentioned parameters are considered separately. Then, a comparison of the results obtained by different methods and for different parameters is conducted.

Note here that an important aspect of identifying ionospheric trends is the choice of solar activity (SA) index, which is used to eliminate SA effects in variations of a given ionospheric parameter. We have considered this problem in detail [Danilov and Berbeneva, 2024; Danilov and Berbeneva, 2023] and found that the best SA indices when searching for trends in $foF2$ and $hmF2$ are the indices $F30$, $MgII$ and $Ly\,\alpha$. This conclusion is consistent with the findings of most similar studies. In particular, the description of $foF2$ using these three indices was analyzed in the work of Deminov [2024]. To avoid dwelling on the problem of SA indices in the following discussion, we will simply indicate (if the authors specify) which indices were used to identify a particular trend.

2. CURRENT TREND DATA

2.1. *Critical frequency foF2*

As already mentioned above, $foF2$ trends have been discussed in our publications repeatedly. Here we will focus on the works [Danilov et al., 2024a; Danilov et al., 2024], which analyzed $foF2$ trends using data from three Northern Hemisphere stations (Juliusruh, Moscow, and Boulder) and three Southern Hemisphere stations (Townsville, Hobart, and Canberra) for the period 1996−2023. A significant element of the study was that the same months were winter for the Northern Hemisphere and summer for the Southern Hemisphere, and vice versa. This added additional reliability to the conclusions about the seasonal variation of trends.

Trend values were considered for five near-noon times: 10:00, 11:00, 12:00, 13:00, and 14:00 LT. The following SA indices were used: $F30$, $MgII$ and $Ly\,\alpha$.

The main results of the works under consideration can be formulated as follows. Trends for each situation (month, station, SA index) but at different LT times agree well with each other and give reasonable trend values ($k(foF2)$) with small standard deviations (SD).

Averaging these values for a given month and station using three SA indices also gives reasonable values with small SDs. For example, for Moscow station in February, the values of $k(foF2)$ are -0.027, -0.030, and -0.042 MHz/year with SD within 0.003-0.006 MHz/year. Comparison of trends obtained for each month after averaging across all LT moments and SA indices at different stations also gives good results. In January, it is -0.025 MHz/year for Moscow station and -0.028 MHz/year for Boulder station. In February, these values are -0.036 MHz/year and -0.033 MHz/year, respectively. Better agreement is simply impossible to expect.

The results of data analysis from Southern Hemisphere stations for winter months (June and July) gave similar results. If we average the conditionally obtained values of $k(foF2)$ across all three Northern Hemisphere stations, we get -0.028 MHz/year for January and -0.038 MHz/year for February. And the corresponding averaging across three Southern Hemisphere stations gives -0.027 MHz/year for June and -0.024 MHz/year for July.

It is appropriate to mention that recently, the trends of $foF2$ up to 2024 for another mid-latitude station - Sverdlovsk [Danilov and Ryabukhin, 2025] were analyzed, and approximately the same values of $k(foF2)$ were obtained, averaged across three SA indices: -0.038 and - 0.035 MHz/year for January and February, respectively.

Note that all the analysis was conducted in the mentioned works for near-noon hours. This is related to the fact that there is a diurnal variation of negative trends in $foF2$– they are maximum in amplitude during the day and minimum at night. In the work of Danilov et al. [2023] based on data from Juliusruh station, it is shown that during daytime hours in the diurnal variation of $k(foF2)$, a "plateau" is observed: for 5-7 hours, the values of $foF2$ barely change.

This conclusion is consistent with many studies of recent years (see the recent review by Laštovička [2023]). In particular, the conclusion that the amplitude of negative trends in $foF2$ has a pronounced diurnal variation (greater during the day than at night) was also obtained in the work of Yue et al. [2018] based on data from Wuhan station.

In the paper by Zossi et al. [2024a], changes in $foF2$ were analyzed using data from 10 stations located in both the Northern and Southern Hemispheres. Various SA indices were used to eliminate SA effects. For different stations, significantly varying values of $k(foF2)$ were obtained, ranging from zero (Boulder, $F30$) to −0.19 MHz per year (Townsville, $MgII$). The values averaged across all 10 stations were −0.05 and −0.03 MHz per year for $MgII$ and $F30$ respectively.

In a publication by the same group of authors [Zossi et al., 2024b], a similar analysis of $foF2$ measurements was performed at 9 vertical sounding stations using five SA indices. When considering the station data separately, significantly different values of $k(foF2)$ were also obtained. However, the combination of these data, which the authors designated as PC1($foF2$) and which provides the best agreement with SA changes, gives a $foF2$ trend of approximately −0.02 MHz per year for $MgII$ and $Ly\alpha$ and −0.03 MHz per year for $F30$.

The work of [Duran et al., 2023] was specifically devoted to the problem of diurnal and seasonal variations of $foF2$ trends. Observations from 9 stations in the Northern and Southern Hemispheres were analyzed. As in the work of Danilov et al. [2024a], it was found that the strongest negative trends are observed in December–February for Northern Hemisphere stations and in June–August for Southern Hemisphere stations. The diurnal variation of $k(foF2)$ was also found: the strongest negative trend is observed during daytime hours, while at night it is weak. It was found that the maximum negative trends during the day can reach −(0.03–0.04) MHz per year. This is close to the values of $k(foF2)$ obtained by Danilov et al. [2024a] and described above.

The fact that for the five near-noon LT moments in each situation relatively similar results were obtained confirms the conclusion [Danilov and Berbeneva, 2023; Danilov et al., 2023] that in the diurnal variation of $foF2$ trends there is a "plateau" during daytime hours, when the values of $k(foF2)$ are practically unchanged. This conclusion is important for selecting data for analyzing the critical frequency trends. For example, in Laštovička [2024], the trends of $foF2$ for 11:00-13:00 LT are analyzed, which eliminates the interfering influence of diurnal variations on the obtained trend values.

Gnabahow et al. [2020] analyzed the trends of $foF2$ based on observational data from Dakar station. To eliminate the effects of SA, the $F10.7$ index was used. For daytime conditions, a relative trend value equal to –(0.13-2.27)% per year was obtained.

In a recent paper by Jakovski et al. [2024], changes in four parameters of the $F2$ layer were analyzed: critical frequency, height, total electron content and half-thickness for 1996-2022. The $F10.7$ index was used to eliminate SA effects. Negative trends were obtained for all four parameters. In particular, for $foF2$, trends equal to -0.07, -0.18 and -0.05 MHz per year were obtained for Juliusruh, Boulder and Kokubunji stations, respectively. It should be noted that the $foF2$ trends obtained by Jakovski et al. [2024] for Juliusruh and Boulder stations are noticeably higher than the trends for these stations described above, which were obtained in a recent paper by Danilov et al. [2024a].

The work of Rios et al. [2024] is dedicated to the role of various SA indices in the analysis of long-term changes in the electron concentration at the maximum of layer $F2$ $NmF2$. Observations at Juliusruh station for 1957-2023 and three indices are considered: $F10.7$, $MgII$ and $F30$. It was found that the trend of $NmF2$ depends on SA. At the value of $F10.7 = 90$, this trend is maximal and equals −0.44% per year. This gives a trend of $foF2$ equal to −0.22% per year. With an average value of $foF2 \sim 8$ MHz, this corresponds to $k(foF2) \sim -0.028$ MHz per year, which is close to the values given above in this subsection.

A detailed analysis of $foF2$ trends based on data from six stations in both hemispheres was performed by Laštovička [2024]. He considered six indices for removing SA effects and concluded that the only index that gives a stable negative trend of $foF2$ is $F30$. Laštovička [2024] also found that the magnitude of the obtained trends depends on the analyzed time interval. He compared the periods 1976-1999, 1996-2014, and 1976-2014 and concluded that the strongest negative trends (about –(0.03-0.04) MHz per year) for all six stations are obtained for the period 1976-1999.

Summarizing the materials of this subsection, it can be stated that recent studies lead to a confident conclusion about the existence of a negative trend in the critical frequency of about –(0.02-0.05) MHz per year. Taking conventionally the average value of $foF2$ as 8 MHz, we get a relative trend of –(0.3-0.6)% per year. For $NmF2$, this will be –(0.6-1.2)% per year.

2.2. Layer height hmF2

A description of works on determining $hmF2$ trends during previous decades can be found in the review by Danilov and Konstantinova [2020]. Here we will focus only on recent publications. It should be noted that both for $foF2$ and for $hmF2$ in the works of Danilov et al. [2024a, b], an effect of trend intensification in the last few years was discovered. Although this effect, if it really exists, may be very important, we will not return to it here, since there are no indications of the existence of this effect in the works of other authors.

Danilov et al. [2024b] analyzed measurements of $hmF2$ up to 2023 . using the VS method at Moscow and Juliusruh stations. Two winter months (January and February) and two summer months (June and July), five near-noon times 10:00 − 14:00 LT and the same solar activity indices ($F30$, $MgII$ and $Ly\ \alpha$) as in most papers on $foF2$ trend analysis were considered. It was found that for different LT moments, different solar activity indices, and both months, the negative trends of $hmF2$ were quite close in absolute value. The standard deviation values (SD) obtained during averaging are quite small, making the averaging results statistically significant. The trends for January were somewhat larger than for February. This difference seems quite realistic to us based on the possible existence of annual variations in $k(hmF2)$.

For Moscow station, the $hmF2$ trends ($k(hmF2)$) were found to be –0.92 and –0.64 km per year for January and February respectively. The same values for Juliusruh station were –0.44 and –0.56 km/year. It was also found that unlike $foF2$ trends, noticeable negative $hmF2$ trends are also observed in summer months, but their reliability is lower since the agreement between different data is worse than for winter months.

In Duran et al. [2024], $hmF2$ trends were analyzed in detail using data from Juliusruh and Rome stations for different time periods, using various indices to eliminate solar activity effects. Duran et al. [2024] considered two methods for obtaining $hmF2$ values – using the well-known Shimazaki formula and directly from VS data through automatic digitization of ionograms. For the period 1976–2022, it was found that the most pronounced negative trends in $hmF2$ are observed for those three solar activity indices ($F30$, $MgII$ and $Ly\ \alpha$)) that are recognized as the best for analyzing $foF2$ trends (see above).

For Juliusruh station, Duran et al. [2024] obtained a notable diurnal variation in $k(hmF2)$ values: negative trends are stronger at night than during the day. During daytime hours, there is a "plateau" when $k(hmF2)$ values hardly change and are about − 0.5 km per year. Both methods for determining $hmF2$ give fairly similar results. For Rome station, the picture is different – there is practically no diurnal variation, and $k(hmF2) \sim$ –0.2 km per year for daytime LT hours are obtained only from digitization data.

In the previously mentioned work by Jakowski et al. [2024], the trend of $hmF2$ height according to Juliusruh station data is reported as –1.21 km per year.

Summarizing the results of this subsection, it can be stated that negative trends in the height of the $F2$ $hmF2$ layer are observed, i.e., the layer is systematically descending over time. The absolute values of the negative trend of $hmF2$ during daytime are 0.5–1.0 km per year.

2.3. Trends in total electron content TEC

In the first known publication on TEC trends [Lean et al., 2011], a small positive trend was obtained. As a result of further discussion [Lean et al., 2016; Laštovička et al., 2017], it was found that this trend is negative, although small. However, Emmert et al. [2017] discovered a decrease in the global average TEC by 9.3% between the solar minima of 1996 and 2008, which cannot be attributed to changes in solar (*F* 10.7) and geomagnetic (*Kp*) activity. If this is the case, assuming the period between minima is 11 years, we get a TEC trend approximately equal to –0.8% per year.

The inaccuracy of small or positive TEC trends obtained in the works of Lean et al. [2011, 2016] was also shown in the work of Andima et al. [2019] based on TEC measurements at the equatorial station Malindi (Kenya).

In a recent work by Urbář and Laštovička [2024], TEC trends are analyzed based on global TEC maps for 2003–2023. After analyzing six SA indices, the authors selected *F* 30 to eliminate SA effects. Data for near-noon hours (10:00–14:00 LT) are considered.

Urbář and Laštovička [2024] discuss in detail the latitudinal and longitudinal features of the global distribution of TEC trends. For this consideration, the main result of this work is important - the average value of the TEC trend is obtained to be -0.108 TECU per year. Although the TEC value is quite variable, one can conditionally assume the average TEC value for middle latitudes to be 20 TECU. In this case, the above-mentioned TEC trend value equals -0.5% per year. This is only slightly less than the value given above according to Emmert et al. [2017].

In a recent work by Natali et al. [2024], TEC trends are examined using global TEC maps for 1999-2023. Four indices were used to eliminate solar activity effects: *F* 10.7, *F* 30, *MgII* and *Rz* . The strongest negative trends at middle latitudes of about -0.4 TECU per year (with trend intensification toward the equator up to -0.8 TECU per year) were obtained for *MgII* . If we relate the trend of -0.4 TECU per year to the same average TEC value of ~20 TECU, we get a negative trend of about 2% per year, which is higher than the values obtained by several other authors and presented in this subsection.

In the already mentioned work by a large group of authors [Elias et al., 2024], estimates of TEC trends based on data from Chilton (Slough) station are provided, with solar activity effects removed using the *MgII* index. It was found that the strongest negative trends are observed during the period 10:00-15:00 LT in winter months (October-March) and equal approximately -7×10^{14} el/m^2 (or -0.07 TECU) per year. This is less than the trend according to Natali et al. [2024], but close to the trend value obtained by Urbář and Laštovička [2024].

In the work by Jakowski et al. [2024], higher TEC trends were obtained, equal to -0.46, -0.90, and -0.58 TECU per year for Juliusruh, Boulder, and Kokobunji stations, respectively. With an average TEC value of 20 TECU, this corresponds to relative trends of 2.4, 4.5, and 2.9% per year.

Although the scatter of available TEC trend estimates is quite large, it can be conditionally assumed that the TEC value decreases at a rate of about 3% per year.

2.4. Equivalent thickness of the F2 layer

Using data from four VS stations of the European region for 1996-2020, the "slab thickness" of the ionosphere ST (the ratio of VTEC (vertical total electron content in the ionospheric column) to *NmF* 2) was calculated and its trends were determined [Jakowski et al., 2017]. Negative trends ranging from 3 to 5 km per year were obtained for all four stations. This result is important because it qualitatively agrees with the negative trends of the critical frequency *foF* 2 and with the aforementioned estimates of negative TEC trends.

In a recent paper [Jakowski et al., 2024], ST values for the period 1996-2022 are analyzed, and a slightly smaller negative ST trend of 2.6 km per year is obtained. The results for Juliusruh and Kokubunji stations were similar, while for Boulder station, the negative trend was 2-4 km per year stronger.

In a presentation by a large group of authors at the 12th Trends Symposium (May 6-10, 2024, Ourense (Spain)) [Elias et al., 2024], estimates of ST trends made by various research groups are provided. In particular, data from Port Stanley station showed an ST trend from -1.4 to -2.3 km per year, depending on the method of eliminating SA effects. The same presentation includes ST trends from Slough station, which, depending on the extraction method, vary from zero or slightly positive to -8 km per year.

Thus, today it is only clear that ST trends are negative. However, there are discrepancies in estimates of the amplitude of this trend. Apparently, it is several km per year. If we take the average ST value as 250 km and the ST trend as -5 km per year, we get a conditional relative ST trend equal to -2%.

3. COMPARISON OF TRENDS OF DIFFERENT PARAMETERS AND DISCUSSION

Before proceeding to compare the trends described in the previous paragraph, let us address the following problem. It is known that the Earth's magnetic field changes over time. A natural question arises whether these changes could be the cause of the observed changes in the parameters of the F *F* region. For most studies that typically consider trends at middle latitudes, the answer is negative. As emphasized in the work of Cnossen et al. [2024], the effects of magnetic field changes in the thermosphere and ionosphere are very "location-dependent," i.e., they manifest noticeably only in certain regions, for example, in the equatorial area, or the region of the North Atlantic anomaly.

We believe that the discussed trends of all four parameters of the F *F* 2 layer have an anthropogenic nature, i.e., they are the result of processes occurring in the thermosphere and ionosphere during cooling and subsidence of the upper atmosphere.

A natural question arises as to whether it is possible to compare the obtained trends of all four parameters. To what extent they are consistent with each other, at least qualitatively.

The key parameter for such comparison is the trend of the height *hmF* 2. The decrease in the value of *hmF* 2 over time is apparently a natural consequence of the thermosphere subsidence. The latter occurs due to its cooling as a result of the increase in the amount of CO_2 and a number of other gases [Cnossen et al., 2024].

In this case, naturally, the height of the fixed density level should decrease. If the concept is correct (see Rishbeth and Edwards [1989]) that the F *F* 2 layer "floats" at a constant pressure level, then the height *hmF* 2 should decrease due to the indicated subsidence. This is exactly the decrease we obtain by analyzing the trends of *hmF* 2.

At the same time, the neutral composition of the thermosphere may change. Particularly important is the change in the ratio [O]/[N_2. The change in this ratio should occur primarily due to the change in the barometric situation (temperature decrease). But the enhancement of turbulent diffusion, which increases the outflow of oxygen atoms through the turbopause into the region of their stronger recombination, may also contribute (for more details, see [Danilov and Konstantinova, 2014]).

In this case, first of all, the electron concentration value at the maximum of the layer *F* 2 *NmF* 2 should decrease, since during daylight hours it is proportional to the ratio [O]/[N_2. The critical frequency *foF* 2 should behave in the same way, since $NmF2 \sim (foF2)^2$.

This part of the scheme is perfectly confirmed by the obtained diurnal variation of *foF* 2 trends. The indicated dependence of *foF* 2 on neutral composition works during the day, and we see significant negative trends in *foF* 2. At night, when there is no ionization by solar ultraviolet radiation, the behavior of *NmF* 2 is determined by completely different processes, and sensitivity to changes in [O]/[N2] should disappear. And indeed, we do not see significant trends in *foF* 2 during nighttime hours, although negative trends in the height *hmF* 2 are observed during these hours.

In summer months, negative trends in layer height are also observed, but there are no significant trends in *foF* 2. In our opinion, this is related to the temperature *T* dependence of photochemical reaction constants. This issue is discussed in detail in the work of Danilov et al. [2024c], so here we will give only the main conclusion.

Due to the different temperature *T* dependence of the constants of corresponding ion-molecular reactions in summer and winter, in summer, the temperature decrease resulting from the general cooling process of the upper atmosphere should lead even to a slight increase in electron concentration (and, consequently, *foF* 2), rather than to its decrease, as in winter (negative trend).

Since the systematic decrease in *hmF* 2 values is indeed occurring, TEC values must inevitably decrease, as this means that the entire *F* 2 layer descends to heights with higher molecular content, and therefore with higher recombination rates.

Thus, our estimates of the trends in the height of the *F* 2 layer lead to the conclusion about the inevitability of negative trends in the layer's critical frequency and total electron content. Such trends have been obtained by different authors , as shown in subsections 2.1 and 2.3.

Comparison of trends in all four parameters of the *F* 2 layer is analyzed in detail in the works of Elias et al. [2024] and Danilova and Konstantinova [2024]. Below we provide a brief comparison of these trends using the values obtained in the previous paragraph.

The ST value is defined as TEC/ *NmF* 2 [Elias et al., 2024]. Both TEC and *NmF* 2 demonstrate negative relative trends. Since, according to the corresponding estimates at the end of subsections 2.1 and 2.3, the relative trend of *NmF* 2 is ~ 1% per year, and the relative trend of TEC is ~3% per year, according to this formula, a relative trend of ST of ~2% per year should be expected. This is exactly the value given at the end of subsection 2.4. Of course, this comparison is very conditional, since there is a spread of trends for all parameters, but it shows, at least, that there are no noticeable contradictions between the definitions of trends for different parameters of the *F* 2 layer.

4. CONCLUSION

In the last few years, there has been a noticeable increase in publications studying long-term trends in the parameters of the ionospheric *F* 2 layer. In addition to the two "classical" parameters *foF* 2 and *hmF* 2 , data on two other parameters are analyzed: the total electron content TEC and the equivalent slab thickness ST.

The analysis conducted in this work allows us to draw several conclusions.

First, different indices of solar activity are used to eliminate the effect of SA when identifying trends in ionospheric parameters. In many works on trends, much attention is paid to choosing the best SA index. In most of such works, the best indices for trend search are $F30$ and $MgII$.

Second, publications of recent years confirm the presence of negative trends in the critical frequency of the $F2$ $foF2$ layer and provide values close to the trends obtained by the authors based on the analysis of observations at six stations in both the Northern and Southern hemispheres. At the same time, different authors also confirm the fundamental patterns of diurnal and seasonal changes in these trends: strong negative trends during the day in winter months and the absence of significant trends during nighttime hours and in summer months.

Thirdly, the same applies to the trends of the layer height $hmF2$ with the difference that well-pronounced negative trends of $hmF2$ are observed in summer months as well.

Fourthly, the trends of all four parameters of the $F2$ layer are found to be negative, which provides a coherent picture of the layer's change during cooling and subsidence of the thermosphere. Comparison of the relative trends of all these parameters shows that within the currently achieved accuracy of their determination, they are quite consistent with each other.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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