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DEPENDENCE OF THE F2-LAYER CRITICAL FREQUENCY MEDIAN AT MIDLATITUDES ON GEOMAGNETIC ACTIVITY

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Abstract. We put forward a method of separating the geomagnetic activity contribution to the F2-layer critical frequency median, f_oF2$_{med}$, at middle latitudes. It is based on the analysis of δf_oF2, which is the ratio f_oF2$_{med}$/f_oF2$_q$ in percent, where f_oF2$_q$ is the F2-layer critical frequency for quiet conditions. The quantities f_oF2$_q$ and δf_oF2 depend on solar and geomagnetic activity respectively. These dependences are taken into account using indices F_{12} (annual average solar radio emission flux at 10.7 cm) and Ap_m (monthly average Ap index), thus facilitating the use of this method for forecasting f_oF2$_{med}$. With this method, from Slough station (51.5° N, 0.6° W) data for midday and midnight for 1954 to 1995 we have found that at midnight the δf_oF2 dependence on Ap_m is significant at the 95 % confidence level for equinoxes and summer. For midday, this dependence is less pronounced and is significant only from April to July. At equinoxes and summer, an Ap_m increase causes a δf_oF2 decrease. For midnight, this feature is more pronounced than for midday. This regularity is also valid for annual average Ap_m and δf_oF2.

Keywords: midlatitude ionosphere, F2 layer, critical frequency, median, geomagnetic activity, regularity.

INTRODUCTION

The average monthly median of the F2-layer critical frequency f_oF2$_{med}$ is considered to be an optimal characteristic of the F2-layer critical frequency for long-term ionospheric forecasting [Zolesi, Cander, 2014]. For example, the basic version of the international reference ionosphere IRI gives exactly f_oF2$_{med}$ [Bilitza et al., 2014]. The dependence of f_oF2$_{med}$ on solar activity is taken into account in all known ionospheric models, including IRI, through solar activity indices or effective ionospheric indices. An effective ionospheric index is determined from experimental values of f_oF2$_{med}$ so as to minimize the error of f_oF2$_{med}$ by replacing the normal solar activity index with the ionospheric index [Liu et al., 1983; Caruana, 1990; Mikhailov, Mikhailov, 1995]. This replacement often allows us to improve the accuracy of the f_oF2$_{med}$ prediction for a particular station [Liu et al., 1983; Caruana, 1990; Mikhailov, Mikhailov, 1995]. This advantage of the effective ionospheric index is explained by the fact that f_oF2$_{med}$ variations with solar activity cycle depend not only on the level of this activity, but also on a number of other factors, including geomagnetic activity, which are implicitly taken into account in the ionospheric index.

The explicit dependence of f_oF2$_{med}$ on geomagnetic activity has been analyzed only in several works and was based on the search for the dependence of f_oF2$_{med}$ on monthly average Ap index Ap_m [Sole, 1998] or annual average Ap index Ap_{12} [Xu et al., 2008]. Moreover, the dependence on geomagnetic activity was considered in the analysis of long-term variations in f_oF2$_{med}$ [Bremer, 1998; Laštovička et al., 2006; Mielich, Bremer, 2013]. The said works assumed linear or nonlinear dependences of f_oF2$_{med}$ on solar and geomagnetic activity indices.

However, there may be another approach to estimating the contribution of geomagnetic activity to f_oF2$_{med}$. It is based on the analysis of the dependence of f_oF2$_{med}$/f_oF2$_q$ on geomagnetic activity, where f_oF2$_q$ is the F2-layer critical frequency for quiet conditions, which is dependent on solar activity and independent of geomagnetic activity. This allows us to suppose that the ratio f_oF2$_{med}$/f_oF2$_q$ depends only on geomagnetic activity for fixed month and universal time. A similar approach was used to analyze effects of geomagnetic storms in relative changes of the F2-layer critical frequency or maximum concentration of this layer [Pietrella, Perrone, 2008; Pietrella, 2012; Deminov et al., 2015].

The main purpose of our work is to assess, for the first time, the feasibility of using this approach to identify the contribution of geomagnetic activity to f_oF2$_{med}$. We try to maintain the prognostic orientation of f_oF2$_{med}$ by accounting for the solar and geomagnetic activity indices, for which a long-term forecast is possible. Below are the results obtained by analyzing data from the ionospheric station Slough (51.5° N, 0.6° W) for local noon and midnight for 1954–1995. We present the method of separating the geomagnetic activity contribution to f_oF2$_{med}$, the results of the analysis of this contribution, discussion and main conclusions.

METHOD

At the first stage, it is necessary to construct an empirical model of the F2-layer critical frequency for quiet conditions – the f_oF2$_q$ model. This model is represented as

$$foF2_q=c_0+c_1F_{12}+c_2F^2_{12} \quad (1)$$

with a set of coefficients c_j (j=0, 1, 2) for each hour of UT with an hourly discreteness and for every month of the year (M=1 is January, M=12 is December), where F_{12} is the annual average (centered on a given month) solar radio emission flux at a wavelength of 10.7 cm.

The coefficients c_j of equation (1) for each fixed value of UT and M are determined from the dataset on f_oF2 (in our case, these are the hourly f_oF2 values obtained at Slough station in 1954–1995), from which the data that do not satisfy the condition

$$ap(\tau)<7 \quad (2)$$

are excluded, where $ap(\tau)$ is the weighted average of the geomagnetic activity ap index with a characteristic time T=14 hr or $\tau=\exp(-3/T)\approx0.8$ [Wrenn, 1987]:

$$ap(\tau)=(1-\tau)(ap_0+ap_{-1}\tau+ap_{-2}\tau^2+\ldots), \quad (3)$$

ap_0, ap_{-1}, etc. are the values of the ap index in a given, previous, etc. three-hour intervals. The ap indices are determined with an interval of 3 hr, and $\tau=\exp(-3/T)$ shows how much the contribution of the previous ap index value to $ap(\tau)$ decreases as compared to the given value in this three-hour interval. It is thus considered that the midlatitude ionosphere reacts to the change in geomagnetic activity as a low transmission filter, smoothing out the response of ionospheric parameters with a characteristic time T; and the response at every instant depends on the prehistory of geomagnetic activity variations.

Along with the solar activity index F_{12}, the index R_{12} – the relative number of sunspots averaged over 12 months (centered on a given month) – is used in problems of long-term ionospheric forecasting [Zolesi, Cander, 2014]. The index F_{12} is more accurate than R_{12} for constructing the f_oF2 median [Deminov, 2016]. Note that to construct the empirical model of f_oF2$_q$, more accurate solar activity indices have also been used, including daily values of the solar radio emission flux at 10.7 cm [Deminov et al., 2009]. In this case, F_{12} is chosen because empirical model (1) can be used for the long-term forecast of f_oF2$_q$ based on the F_{12} forecast.

The index ap (τ) and its analogs were employed as indicators of the contribution of geomagnetic activity to thermospheric parameters [Picone et al., 2002] and f_oF2 [Wrenn, Rodger, 1989; Shubin, Anakuliev 1995; Fuller-Rowell et al., 2000; Kutiev, Muhtarov, 2001, 2003; Pietrella, Perrone, 2008; Pietrella, 2012; Deminov, Deminova, 2015; Deminov et al., 2015] during geomagnetic storms but not during substorms [Deminov et al., 2013]. In the above works, τ values vary from 0.7 to 0.9, and $\tau\approx0.8$ we take corresponds to the average of these values. Criterion (2) for the quiet ionosphere is similar to that given in [Pietrella, Perrone, 2008; Deminov et al., 2009; Pietrella, 2012]. This criterion seems to be the best compromise between the desire to exclude all magnetically disturbed periods from consideration and to retain a sufficiently large dataset on f_oF2$_q$ to obtain reliable statistical estimates of coefficients in regression equation (1). In this case, the number of f_oF2$_q$ values for calculating the coefficients of equation (1) varies from 215 to 395 for different months and hours of UT.

Implementation of the first stage of this method yields empirical model (1) with known coefficients of the model. This allows us to determine f_oF2$_q$ values over this station for any universal time and month from the known F_{12} values. At the next stage, we should construct an empirical model of the dependence of relative deviations of the F2-layer critical frequency median

$$\delta f_o\mathrm{F2}=\left(\frac{f_o\mathrm{F2}_{\mathrm{med}}}{f_o\mathrm{F2}_q}-1\right)100 \quad (4)$$

on geomagnetic activity in percent. This model has the form of equation

$$\delta f_o\mathrm{F2}=a_0+a_1Ap_m \quad (5)$$

with a set of coefficients a_0 and a_1 for each hour of UT and month of year M, where Ap_m is the monthly average Ap index of geomagnetic activity. The coefficients a_0 and a_1 in this equation for each fixed value of UT and M are determined from the dataset on foF2$_{med}$ from Slough for 1954–1995 (with known foF2$_q$ and Ap_m), with data that do not satisfy the condition

$$Ap_m<32 \quad (6)$$

excluded.

According to the Ap_m index array for 1954–1995, condition (6) has been violated in less than 2 % of cases. Furthermore, relatively low geomagnetic activity usually corresponds to the foF2 median [Deminov, Deminova, 2015]. Therefore, condition (6) yields typical mean dependences of δf_oF2 on Ap_m, without strong and rare deviations.

In addition to model (5), we have constructed a model that is described by regression equation

$$\delta f_o\mathrm{F2}_{12}=b_0+b_1Ap_{12} \quad (7)$$

for each hour of UT and month, where δf_oF2$_{12}$ and Ap_{12} are 12 -month running mean δf_oF2 and Ap_m values for a given hour of UT, centered on a given month.

Below we present the results of the analysis of properties of equations (5) and (7) as derived from Slough data for 1954–1995 for noon and midnight. The long-term forecast of geomagnetic activity involves some problems [Joselyn, 1995]. Only general trends of its variations can be identified. One of these trends is the existence of semiannual geomagnetic activity variations with maxima during equinoxes [Cliver et al., 2002]. This trend can be considered through Ap_m. Another trend refers to variations in geomagnetic activity with solar cycle. These variations can be considered through Ap_{12} [Echer et al., 2004]. The choice of the Ap_m and Ap_{12} indices in (5) and (7) is based on such estimates.

RESULTS

Figure 1 shows annual variations in the average (over 1954–1995) geomagnetic activity index Ap_{ave} for each month, the coefficient a_1 of equation (5), and the correlation coefficient K between the δfoF2 values calculated from this equation and measured for noon and midnight. Below, for brevity, the coefficient K is called the correlation coefficient of equation (5). When calculating Ap_{ave}, we take into account condition (6), i.e. exclude the Ap_m data that do not satisfy this condition. The coefficients a_1 and K were obtained from Slough data for 1954–1995 with the above method.

Figure 1 shows semiannual variations in Ap_{ave} with maxima during equinoxes, predominantly in spring. In spring, relatively high values were observed for the longest time. For example, the condition Ap_{ave}>15 held for four months in the first half of the year (from February to May) and for two months in the second half of the year (September and October).

In winter at noon, the coefficient a_1>0, i.e. an increase in the geomagnetic activity index leads to an increase in $\delta f_o F2$ and hence f_oF2_{med} because f_oF2_q does not depend on geomagnetic activity (see Figure 1 and equations (4) and (5)). Such a change in $\delta f_o F2$ is a positive disturbance of f_oF2_{med}, which is associated with an increase in geomagnetic activity.

All other months at noon and midnight feature a negative disturbance of f_oF2_{med} (coefficient a_1<0) with a higher value of $|a_1|$ at midnight. In winter at midnight, a_1 can change sign: $a_1 \approx 0$ in November, a_1<0 in December, and a_1>0 in January.

The annual variations in the correlation coefficient K of equation (5) for noon and midnight are in many respects similar to the annual variations in Ap_{ave}: they are maximum in April and minimum on average in winter, but in summer there is an additional maximum of K, which is absent for Ap_{ave} (see Figure 1). The statistical analysis with the Fisher criterion shows that dependence (5) is significant for K>0.3 at a confidence level of 95% [Ramachandran, Tsokos, 2009]. It can be seen (Figure 1) that for midnight the dependence of $\delta f_o F2$ on Ap_m is not significant in winter (November, December, and January) and is significant in all other months of the year. At noon, the dependence of $\delta f_o F2$ on Ap_m is significant in a narrower interval – from April to July – since the average correlation coefficient K for noon is lower than that for midnight. Figure 1 indicates that at midnight and noon for significant dependences the condition a_1<–0.3 %/nT holds, i.e. only quite distinct negative disturbances of f_oF2_{med} associated with an increase in geomagnetic activity are significant.

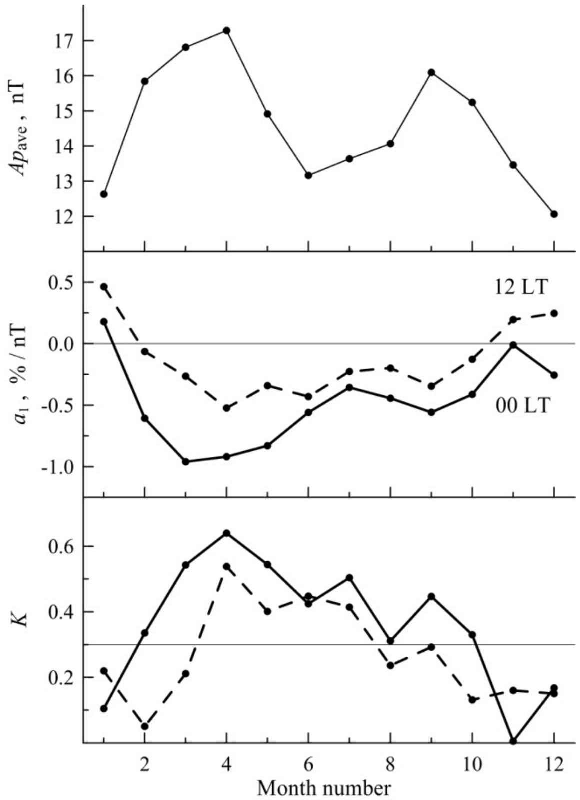

Figure 1. Annual variations in the average geomagnetic activity index Ap_{ave}, coefficient a_1, and correlation coefficient K of equation (5) for midnight (00 LT, solid lines) and noon (12 LT, dashed lines)

Figure 2 graphically portrays the nature of the dependence of $\delta f_o F2$ on Ap_m in January, April, and July for noon and midnight. Here, σ is the standard deviation of the measured $\delta f_o F2$ values from those calculated from equation (5).

From the data in Figures 1 and 2 it follows that in January the Ap_m values were less than 20 nT at Ap_{ave}=12.6 nT. These values of Ap_m were too low to cause systematic deviations of $\delta f_o F2$ from the quiet level; therefore, in January the dependence of $\delta f_o F2$ on Ap_m is not significant for noon and midnight. In April, Ap_m reached 30 nT at Ap_{ave}=17.3 nT, thereby providing a relatively high average level of geomagnetic activity and a wide range of its variations. Therefore, in April, the dependence of $\delta f_o F2$ on Ap_m is significant for noon and midnight. For midnight, this dependence is most pronounced, providing the highest value of the coefficient K=0.64 during the year (see Figure 1). In July, Ap_m could even exceed 30 nT, but the average value was relatively low (Ap_{ave}=13.6 nT); higher Ap_m values were observed less often than in April. Presumably for this reason, the dependence of $\delta f_o F2$ on Ap_m is significant in July but less pronounced than that in April.

For midnight, the dependence of $\delta f_o F2$ on Ap_m is significant almost throughout the year. The sole exception constitutes winter months. We can therefore expect that the linear dependence of $\delta f_o F2_{12}$ on Ap_{12} is also significant for midnight (see equation (7)), where $\delta f_o F2_{12}$ and Ap_{12} are 12-month running means of $\delta f_o F2$ and Ap_m, centered on a given month. The explicit form of regression equation (7), derived from Slough data for midnight for all months in 1954–1995 is

$$\delta f_o F2_{12} = 2.3 - 0.51 Ap_{12} \pm 2.3, \quad K = 0.65, \qquad (8)$$

where K is the correlation coefficient between $\delta f_o F2_{12}$ values measured and calculated from this equation. A similar regression equation for noon is

$$\delta f_o F2_{12} = 1.5 - 0.24 Ap_{12} \pm 1.7, \quad K = 0.49. \qquad (9)$$

From the values of the correlation coefficient K it follows that the dependence of $\delta f_o F2_{12}$ on Ap_{12} is significant for midnight and noon; it is more pronounced for midnight than for noon. This also follows from the higher absolute value of the coefficient b_1 for midnight in these equations: b_1=–0.51, whereas for noon b_1=–0.24. It can also be seen that a negative disturbance (coefficient b_1<0) is typical for δf_oF2$_{12}$ at noon and midnight. This is due to the fulfillment of the condition a_1 <0 in (5) for noon and midnight almost throughout the year, except probably for winter months (see Figure 1).

More clearly, the dependence of δf_oF2$_{12}$ on Ap_{12} can be seen from the data in Figure 3. It is obvious (Figure 3) that the values of δf_oF2$_{12}$ lie mainly in the range –10–0 % at midnight and –5–0% at noon, and regression equations (8) and (9) reflect this regularity. Consequently, at noon and midnight, the typical deviations of δf_oF2$_{12}$ from the background value, which are associated with the Ap_{12} rise, do not exceed 5 and 10 %. In many cases, such slight deviations can be ignored. It makes sense to take them into account only when analyzing ionospheric effects with relatively low amplitude, including long-term variations and earthquake effects.

So, the results of the analysis of medians of the F2-layer critical frequency$f_o f_o$F2$_{med}$ based on Slough data for 1954–1995 for noon and midnight allow us to establish that the dependence of f_oF2$_{med}$ on geomagnetic activity is sufficiently distinct for δf_oF2 – relative deviations of these medians from the quiet level. For equinoxes and summer, an increase in the monthly average geomagnetic activity index Ap_m leads to a decrease in δf_oF2. For midnight, this regularity is more pronounced than for noon. This regularity is also valid for the annual average Ap_m and δf_oF2.

DISCUSSION

In the above method of separating the dependence of the F2-layer critical frequency monthly median f_oF2$_{med}$ on geomagnetic activity, we use approximate solar and geomagnetic activity indices F_{12}, Ap_m, and Ap_{12} (see equations (1), (5) and (7)), for which a long-term forecast is possible. These indices are likely to be optimal for the long-term forecast of f_oF2$_{med}$. This conclusion is based on the results of comparison of the exact indices P and $ap(\tau)$ with the approximate indices F_{12} and Ap_m, where P=F_1+F_{81}, F_1 is the solar radio flux at 10.7 cm on a given day and F_{81} is the flux value averaged over 81 days and centered on a given day; $ap(\tau)$ is determined by equation (3) for τ≈0.8 [Deminov, Deminova, 2015].

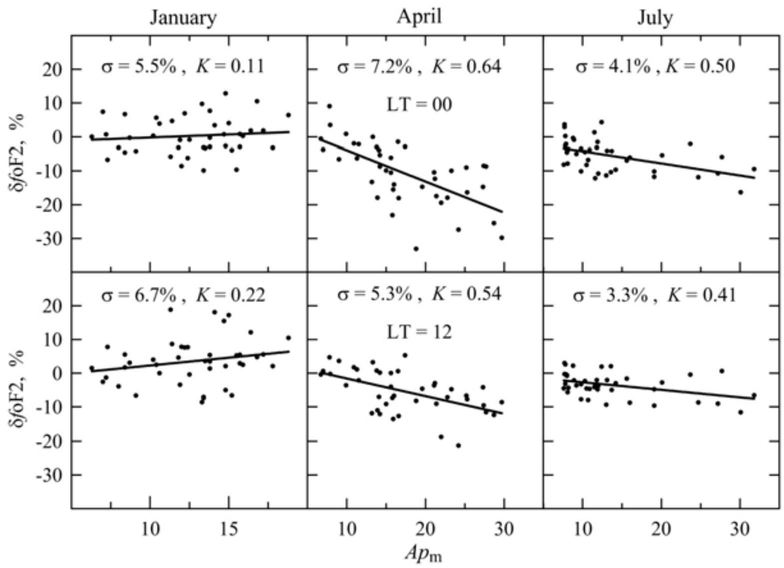

Figure 2. Dependences of the relative values of the F2-layer critical frequency δf_oF2 median on Ap_m for three months at midnight (upper panel) and noon (lower panel): as derived from Slough data for 1954–1995 (dots); as calculated from regression equation (5) (solid lines)

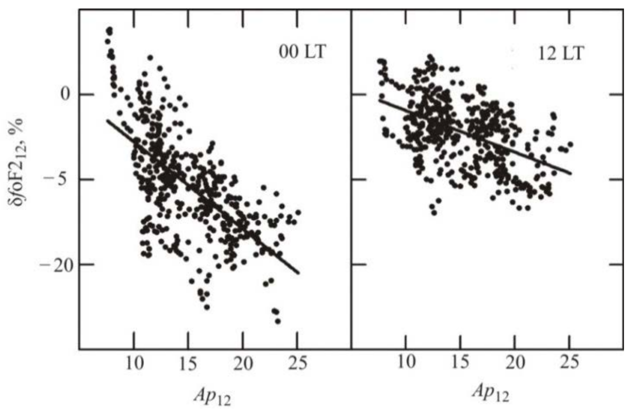

Figure 3. Running annual mean δ f_oF2$_{12}$ versus Ap_{12} at midnight (00 LT) and noon (12 LT): as derived from Slough data for 1954–1995 (dots); as calculated from regression equations (8) and (9) (solid lines)

The f_oF2 median for a particular month at fixed universal time corresponds to a certain day of this month (for an odd number of measurements of f_oF2 during this month) such that f_oF2=f_oF2$_{med}$, and the exact activity indices are determined for this day of the month. The analysis of Slough data for 1954–1995 has revealed that there is no systematic difference between exact and approximate solar activity indices, and, for example, for noon $P \approx 1.0 F_{12} \pm 15$ with the correlation coefficient K=0.96 [Deminov, Deminova, 2015]. Therefore, F_{12} is a quite adequate indicator of solar activity in the long-term forecast of f_oF2$_{med}$. The results reported in [Deminov, Deminova, 2015] allow us to conclude that there is a systematic difference between $ap(\tau)$ and Ap_m and in average $ap(\tau) \approx 0.8 Ap_m$ all year round. Hence, there is a certain relationship between $ap(\tau)$ and Ap_m, which allows us to use Ap_m as a geomagnetic activity indicator for the long-term forecast of f_oF2$_{med}$.

To separate quiet conditions, we take the inequality $ap(\tau)<7$, which coincides with that adopted in [Pietrella, Perrone, 2008; Deminov et al., 2009; Pietrella, 2012]. It is often considered that $ap(\tau)<9$ corresponds to quiet conditions [Fuller-Rowell et al., 2000; Deminov et al., 2015]. An additional analysis has shown that both these conditions give almost identical results for Slough station.

Deviations of f_oF2 (in percent) from the quiet level, caused by geomagnetic storms, have a number of regularities: at middle latitudes at all hours of the day they are more positive in local winter than in local summer; for equinoxes and summer, these deviations are largely negative, and at midnight they are greater than at noon [Buonsanto, 1999]. Negative deviations of f_oF2 from the quiet level during a geomagnetic storm are also called the negative phase of an ionospheric storm. This ionospheric storm phase is attributed to corresponding variations in temperature and composition of the thermosphere [Buonsanto, 1999]. Deviations of the f_oF2 median from the quiet level obtained from Slough data have similar properties: they are negative in all seasons, except for winter; and other conditions being equal, such negative deviations at midnight are greater than at noon (see Figures 1 and 2).

The difference between ionospheric storm properties and deviations of the f_oF2 median from the quiet level is more likely to be quantitative and is due to the fact that the condition Ap<32 generally holds for the f_oF2 median as derived from Slough data, whereas the ionospheric storm is usually related to disturbances with Ap>48. As a result, effects of geomagnetic disturbances for the f_oF2 median do not exceed 35 % (see Figure 2), for ionospheric storms they can be an order of magnitude stronger [Buonsanto, 1999]. Regression equation (5), which reflects the linear dependence of δf_oF2 on Ap_m for the f_oF2 median, is derived taking into account the relatively low amplitudes of δf_oF2 variations. For ionospheric storm effects, these dependences are presented in the form [Wrenn, Rodger, 1989; Pietrella, 2012]

$$\ln(f_o\mathrm{F2}/f_o\mathrm{F2}_q)=\exp(c_0+c_1 ap(\tau)).$$

In the linear case, this equation has the form of (5) when f_oF2 is replaced by f_oF2$_{med}$ and $ap(\tau)$ by Ap_m, thus indirectly showing that the dependences of the f_oF2 median on geomagnetic activity and ionospheric storm effects are due to the same reasons.

The range of Ap_m variations largely determines properties of the dependences of δf_oF2 on Ap_m for the f_oF2 median. In winter months (December, January, February), the average values of Ap_{ave} and the range of Ap_m variations are minimum. Exact values of the geomagnetic activity indices $ap(\tau)$ for the f_oF2 median are even smaller, for example, for December Ap_{ave}=12.1 and $ap(\tau)=0.8 Ap_{ave}$=9.7. The condition $ap(\tau)<9$ is often referred to as quiet geomagnetic conditions [Fuller-Rowell et al., 2000; Deminov et al., 2015]. The weak deviation of geomagnetic activity for the f_oF2 median in winter from quiet conditions seems to be the main reason for the absence of a significant dependence of δf_oF2 on Ap_m for this season. Nevertheless, even for such low geomagnetic activity, the general trend continues toward the occurrence of positive disturbances in the daytime hours in winter (see Figure 1).

Other months are characterized by a negative disturbance of the f_oF2 median when an increase in Ap_m causes a decrease in δf_oF2, significant at least at midnight. It is most pronounced for equinoctial conditions because under these conditions the average values and the range of Ap_m variations are maximum (see Figures 1 and 2). The negative disturbances of the *f*oF2 median is likely caused by a change in temperature and composition of the thermosphere due to an increase in geomagnetic activity, as with the negative phase of the ionospheric storm. Other conditions being equal, such changes in thermospheric parameters in summer and equinoxes extend to lower latitudes than those in winter, thereby ensuring the predominance of the ionospheric storm negative phase during these periods (Prolss, 1977; Buonsanto, 1999].

The predominance of the negative disturbance of the f_oF2 median all year round, except for winter, leads to the fact that a significant negative disturbance, which is more pronounced at midnight than at noon, is typical for the annual average δf_oF2 values. The amplitude of δfoF2$_{12}$ in absolute value does not exceed 5–7 % at noon and 10–13 % at midnight for the conditions analyzed based on Slough data (see Figure 3). Such slight deviations of δf_oF2$_{12}$ from background associated with geomagnetic activity Ap_{12} increase should probably be considered only when analyzing effects in the ionosphere with relatively low amplitude, including long-term variations or earthquake effects.

CONCLUSION

We have proposed a method of separating the contribution of geomagnetic activity to the median of the F2-layer critical frequency f_oF2$_{med}$. It is based on the analysis of this contribution to δf_oF2 – the ratio f_oF2$_{med}$/f_oF2$_q$ in percent, where f_oF2$_q$ is the F2-layer critical frequency for quiet conditions. Values of f_oF2$_q$ and δf_oF2 depend on solar and geomagnetic activity respectively. These dependences can be taken into account through the approximate indices F_{12} (annual average solar radio flux at a wavelength of 10.7 cm) and Ap_m (monthly average geomagnetic activity index *Ap*), thereby facilitating the use of this method for forecasting f_oF2_{med}.

This method with the use of Slough data for 1954–1955 for noon and midnight allowed us to establish that for midnight the dependence of δf_oF2 on Ap_m is significant (at a confidence level of 95 %) in equinoxes and summer, and for noon it is less pronounced and significant from April to July. In equinoxes and summer at noon and midnight, negative disturbances of δf_oF2 predominate, i.e. an increase in Ap_m causes a decrease in δf_oF2. The predominance of a negative disturbance of the f_oF2 median for the main part of the year leads to the fact that a typical feature of the annual average δf_oF2_{12} is a significant negative disturbance, which at midnight is stronger than at noon. The amplitude of δf_oF2_{12} in absolute value does not exceed 5–7 % at noon and 10–13 % at midnight for the conditions we analyze. Such slight deviations of δf_oF2_{12} from background, which are associated with increasing geomagnetic activity Ap_{12}, should probably be considered only when analyzing ionospheric effects with relatively low amplitude, for example, long-term changes in the ionosphere or earthquake effects.

The Slough data on f_oF2 and the solar and geomagnetic activity indices were taken from Space Physics Interactive Data Resource (SPIDR) [http://spidr.ngdc.noaa.gov/], the World Data Center for Solar-Terrestrial Physics , Chilton [http://www.ukssdc. ac.uk/wdcc1/], and World Data Center for Geomagnetism, Kyoto [http://wdc.kugi.kyoto-u.ac.jp/]. The work is partially supported by the Russian Foundation for Basic Research (Grants No. 17-05-00427 and No. 17-55-45094) and Program 1.7 of the Presidium of the Russian Academy of Sciences.

REFERENCES

Bilitza D., Altadill D., Zhang Y., Mertens C., Truhlik V., Richards P., McKinnell L.A., Reinisch B. The International Reference Ionosphere 2012 — a model of international collaboration. *J. Space Weather Space Clim*. 2014, vol. 4, A07. DOI: 10.1051/swsc/2014004.

Bremer J. Trends in the ionospheric E and F regions over Europe. *Ann. Geophysicae*. 1998, vol. 16, no 8, pp. 986–996.

Buonsanto M.J. Ionospheric storms – a review. *Space Sci. Rev*. 1999, vol. 88, pp. 563–601. DOI: 10.1023/A:1005107532631.

Caruana J. The IPS monthly *T* index. *Solar-Terrestrial Prediction: Proc. Workshop at Leura, Australia (October 16–20, 1989)*. 1990, vol. 2, pp. 257–263.

Cliver E.W., Kamide Y., Ling A.G. The semiannual variation of geomagnetic activity: phases and profiles for 130 years of *aa* data. *J. Atmos. Solar-Terr. Phys*. 2002, vol. 64, no. 1, pp. 47–53. DOI: 10.1016/S1364-6826(01)00093-1.

Deminov M.G. Solar activity index for long-term ionospheric forecasts. *Cosmic Research*. 2016, vol. 54, no. 1, pp. 1–7. DOI: 10.1134/S0010952516010068.

Deminov M.G., Deminova G.F. What solar and geomagnetic activities does F2-layer critical frequency median correspond to in midlatitudes? *Geomagn. Aeron*. 2015, vol. 55, no. 3, pp. 326–332. DOI: 10.1134/S0016793215030068.

Deminov M.G., Zherebtsov G.A., Pirog O.M., Shubin V.N. Regular changes in the critical frequency of the F2 layer of the quiet midlatitude ionosphere. *Geomagn. Aeron*. 2009, vol. 49, no. 3, pp. 374–380. DOI: 10.1134/S0016793209030116.

Deminov M.G., Deminova G.F., Zherebtsov G.A., Polekh N.M. Statistical properties of variability of the quiet ionosphere F2-layer maximum parameters over Irkutsk under low solar activity. *Adv. Space Res*. 2013, vol. 51, no. 5, pp. 702–711. DOI: 10.1016/j.asr.2012.09.037.

Deminov M.G., Deminova G.F., Zherebtsov G.A., Polekh N.M. Properties of the F2-layer maximum density variability over Irkutsk under different levels of the solar and geomagnetic activity. *Solnechno-zemnaya fizika* [Solar-Terrestrial Physics]. 2015, vol. 1, iss. 1, pp. 56–62. DOI: 10.12737/6558. (in Russian).

Echer E., Gonzalez W.D., Gonzalez A.L.C., Prestes A., Vieira L.E.A., Dal Lago A., Guarnieri F.L., Schuch N.J. Long-term correlation between solar and geomagnetic activity. *J. Atmos. Solar-Terr. Phys*. 2004, vol. 66, no. 12, pp. 1019–1025. DOI: 10.1016/j.jastp.2004.03.011.

Fuller-Rowell T.J., Araujo-Pradere E., Codrescu M.V. An empirical ionospheric storm-time correction model. *Adv. Space Res*. 2000, vol. 25, no. 1, pp. 139–146. DOI: 10.1016/S0273-1177(99)00911-4.

Joselyn J.A. Geomagnetic activity forecasting: the state of the art. *Rev. Geophys*. 1995, vol. 33, no. 3, pp. 383–401. DOI: 10.1029/95RG01304.

Kutiev I., Muhtarov P. Modeling of midlatitude F region response to geomagnetic activity. *J. Geophys. Res*. 2001, vol. 106, no. A8, pp. 15501–15509. DOI: 10.1029/ 2001JA900018.

Kutiev I., Muhtarov P. Empirical modeling of global ionospheric *f*oF2 response to geomagnetic activity. *J. Geophys*. Res. 2003, vol. 108, no. A1, 1021. DOI: 10.1029/ 2001JA009134.

Laštovička J., Mikhailov A.V., Ulich T., Bremer J., Elias A.G., Ortiz de Adler N., Jara V., Abarca del Rio R., Foppiano A.J., Ovalle E., Danilov A.D. Long-term trends in *f*oF2: a comparison of various methods. *J. Atmos. Solar-Terr. Phys*. 2006, vol. 68, no. 17, pp. 1854–1870. DOI: 10.1016/ j.jastp.2006.02.009.

Liu R., Smith P., King J. A new solar index which leads to improved *f*oF2 predictions using the CCIR atlas. *Telecommun. J.* 1983, vol. 50, no. 8, pp. 408–414.

Mielich J., Bremer J. Long-term trends in the ionospheric F2 region with different solar activity indices. *Ann. Geophys*. 2013, vol. 31, pp. 291–303. DOI: 10.5194/angeo-31-291-2013

Mikhailov A.V., Mikhailov V.V. A new ionospheric index *MF*2. *Adv. Space Res*. 1995, vol. 15, no. 2, pp. 93–97.

Picone J.M., Hedin A.E., Drob D.P., Aikin A.C. NRLMSISE-00 empirical model of the atmosphere: statistical comparisons and scientific issues. *J. Geophys. Res*. 2002, vol. 107, no. A12, 1468. DOI: 10.1029/ 2002JA009430.

Pietrella M. A short-term ionospheric forecasting empirical regional model (IFERM) to predict the critical frequency of the F2 layer during moderate, disturbed, and very disturbed geomagnetic conditions over the European area. *Ann. Geophysicae*. 2012, vol. 30, no. 2, pp. 343–355. DOI: 10.5194/ angeo-30-343-2012.

Pietrella M., Perrone L. A local ionospheric model for forecasting the critical frequency of the F2 layer during disturbed geomagnetic and ionospheric conditions. *Ann. Geophysicae*. 2008, vol. 26, no. 2, pp. 323–334. DOI: 10.5194/angeo-26-323-2008.

Prolss G.W. Seasonal variations of atmospheric-ionospheric disturbances. *J. Geophys. Res.* 1977, vol. 82, no. 10, pp. 1635–1640. DOI: 10.1029/JA082i010p01635.

Ramachandran K.M., Tsokos C.P. *Mathematical statistics with applications.* Oxford, Elsevier Academic Press, 2009. 824 p.

Shubin V.N., Anakuliev S.K. Ionospheric storm negative phase model at middle latitudes. *Geomagn. Aeron.* 1995, vol. 35, no. 3, pp. 363–369.

Sole J.G. Relations between hourly monthly median values of *f*oF2 and some geophysical indices. Their application to an ionospheric single station model. *Acta Geophys. Polonica*. 1998, vol. 46, no. 1, pp. 77–88.

Wrenn G.L. Time-weighted accumulations *ap*(τ) and *K*p(τ). *J. Geophys. Res*. 1987, vol. 92, no. A9, pp. 10125–10129. DOI: 10.1029/JA092iA09p10125.

Wrenn G.L., Rodger A.S. Geomagnetic modification of the mid-latitude ionosphere: toward a strategy for the improved forecasting of *f*oF2. *Radio Sci*. 1989, vol. 24, no. 1, pp. 99–111. DOI: 10.1029/RS024i001p00099.

Xu T., Wu Z-S., Wu Jian, Wu Jun. Solar cycle variation of the monthly median *f*oF2 at Chongqing station, China. *Adv. Space Res.* 2008, vol. 42, no. 1, pp. 213–218. DOI: 10.1016/j.asr.2008.01.012.

Zolesi B., Cander L.R. *Ionospheric Prediction and Forecasting.* Berlin, Heidelberg, Springer-Verlag, 2014, 240 p. DOI: 10.1007/978-3-642-38430-1.

URL: http://spidr.ngdc.noaa.gov (accessed 30.06.2017).

URL: http://www.ukssdc.ac.uk/wdcc1 (accessed 11.06.2017)

URL: http://wdc.kugi.kyoto-u.ac.jp (accessed 01.07.2017)

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