DIFFERENCES IN MONTHLY MEDIANS OF *foF2* WITHIN SEASONS IN THE MID-LATITUDE IONOSPHERE DURING THE PERIOD OF LOW SOLAR ACTIVITY IN 2007–2008 YEARS

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Abstract. The paper presents a comparative analysis of diurnal variations in the monthly median critical frequency of the regular ionospheric *F*2 layer (*foF*2) for all “standard” seasons during the period of low solar activity in 2007–2008. The hourly data from manual processing of measurements taken at mid-latitude ground-based vertical ionospheric sounding stations Wakkanai (Japan) and Hobart (Australia) located almost symmetrically relative to the geographic equator were analyzed. It is found that the relative differences in the median of the third month of any of the "standard" seasons compared to the median of the second month of the season are significantly higher than the differences in the median of the first month of the season relative to the median of the second month of the season. It is also shown using a specific example of these two mid-latitude stations that, according to their characteristics, the median of November (the last month of the autumn season) corresponds to the beginning of the winter season, and the median of May (the last month of the spring season) – to the beginning of the summer season. It has been established that the relative contribution of solar radiation to changes in the value of the electron concentration at the maximum of the *F* region (*NmF*2) under conditions of low solar activity in equinoctial seasons, associated with variations in the value and rate of change of the solar zenith angle, is no less than half of the relative contribution to changes in *NmF*2 made by variations in the composition of the neutral atmosphere.

Keywords: *monthly median critical frequency, diurnal variations, mid-latitude ionospheric F2 layer, winter anomaly*

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1. INTRODUCTION

One of the most important parameters studied in ionospheric studies is the critical frequency of the regular *F2* (*foF2*) layer, since the maximum electron concentration in this layer (*NmF2*) is directly related to the critical frequency, since (see, for example, the monograph [Davis, 1973])

$NmF2 = 1.24 \cdot 10^4 (foF2)^{(2)}$, (1)

where *NmF2* is the value of the electron concentration in the maximum of the F2-layer *of* the ionosphere (in cm^{-3}), and *foF2* is the value of the critical frequency of the ordinary wave (in MHz). Thus, the picture of electron concentration distribution in the maximum of the *F2* layer can be interpreted in terms of the critical frequency. It is this frequency that is directly measured at the ground-based vertical sounding stations of the ionosphere (NSVSI, hereinafter, where possible, simply "stations" or "st."). In the following we will consider mainly the values of the critical frequency (*foF2*), since it is uniquely related to NmF2.

Since the beginning of ionospheric studies by radiophysical methods, it is the median values of *foF2* for each hour of day of the selected month that usually determine the "background" level relative to which variations of this parameter are considered (see, in particular, the manual [Manual..., 1977]). This choice of the "background" level is largely due to the fact that the median is a robust (outlier-resistant) estimate of the mean, as stated in the monograph [Otnes and Enockson, 1982] and is usually more representative of average conditions than the arithmetic mean according to the manual [Manual ..., 1977, p. 197]. At the same time, the term "robustness" in statistics means low sensitivity to various sharp deviations and heterogeneities in the sample, related to certain, generally unknown, causes.

A set of 12 distributions of daily variations of monthly *foF2* medians characterizes annual variations of this parameter, and every 3 consecutive distributions, starting from December, can be naturally attributed to one of the corresponding "standard" seasons (winter, spring, summer, autumn). However, with respect to the ionosphere, such a "standard" and natural partitioning by seasons is not adequate enough for physical reasons, associated, in particular, with differences in the magnitude and rate of change of the Sun's zenith angle (χ) as the Earth orbits. This angle, in turn, determines the magnitude and rate of ion formation at the heights of the ionosphere *F* region due to photoionization. Applied to the quiet mid-latitude ionosphere, the division into winter, summer and equinox seasons (4 months each) for the entire thickness of the ionosphere at different levels of the solar activity index *F10*.7 is "fixed" already in the monograph [Fatkullin et al., 1981]. The same approach in modeling the parameters of the maximum of the *F2-layer of* the quiet mid-latitude ionosphere at low solar activity is used in a rather modern work [Deminov et al., 2011], and in it the corresponding months are specified: WINTER (November, December, January, February), equinoxes (RNDV− March, April; RNDO− September, October) and SUMMER $_{(mia)}$ (May, June, July, August). Here it should be noted that exactly at low solar activity the state of the ionosphere region *F* will be closer to its "background" level, since during this period of time the number of magnetic storms that strongly influence it decreases (see, in particular, the works [Prölss, 1995; Mikhailov, 2000; Danilov and Laštovička, 2001; Mikhailov, 2009]).

A special study of the variations of *foF2* and *NmF2*, not related to magnetic perturbations, from data of a number of NSVSIs (and the Millstone Hill and EISCAT incoherent scattering radars, respectively) during the equinoxes was undertaken in [Mikhailov and Schlegel, 2001]. Strong diurnal deviations from the monthly medians of these parameters in the transition periods from winter to summer (spring-March, April) and from summer to winter (fall-September, October) were found. The main reason for such strong changes in the *F2* layer during the transition periods is, as the authors show, the change in the atomic oxygen content in the thermosphere associated with changes in the global thermospheric circulation. In this connection, attention is drawn to the fact that it is during these periods that the absolute value of the rate of change of the Sun's zenith angle is also maximal.

In general, for any point $P(\varphi, \lambda)$ at an altitude *h* above the Earth's surface measured along the Earth's radius (φ, λ are the geographic latitude and longitude of the projection of point *P* on the Earth's surface), the hour angle of the Sun in radians $\psi = (\pi/12)\cdot t(\text{Sun})\{P(\varphi, \lambda)\}$, where $t(_{\text{Sun}})\{P(\varphi, \lambda)\}$ is measured in hours (h). Here $t_{\text{Sun}}\{P(\varphi, \lambda)\} = \text{LT}_\lambda - 12$, and LT_λ is the local time in hours at longitude λ. Then $t_{\text{Sun}}\{P(\varphi, \lambda)\} \in [-12, 12]$ h when $\text{LT}_\lambda \in [0, 24]$ h. The value of the zenith angle (χ) at the point $P(\varphi, \lambda)$, which determines the degree of illumination by the Sun (and hence photoionization), can be determined from the relation

$$\cos\chi = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\psi, \quad (2)$$

where δ is the declination of the Sun (see also the article [Chapman, 1931]). Obviously, if the local time $\text{LT}_\lambda = 12$ h, then $t_{\text{Sun}}\{P(\varphi, \lambda)\} = 0$, and $\cos\psi = 1$ and the Sun is at zenith at the geographic meridian of the observation point $P(\varphi, \lambda)$.

It is known that unlike the ionospheric region *E*, which is very strongly tied to the changes of the Sun's zenith angle ($foE \propto \cos(\chi)$), the dynamical factors determining the behavior of the region *F* make the relation between *foF2* and χ much more complicated [Rishbet and Garriot, 1975]. However, a significant difference in the values of χ and its rate of change in different months of the same "standard" season can be a dominant factor in geomagnetically calm conditions. In the work [Legenka et al, 2019] it was obtained that at low solar activity during the winter period of 2007-2008 from the data of stations in the Japanese Wakkanai region (geographic coordinates φ = 45.16° N, λ = 141.75° E, and geomagnetic coordinates Φ = 36.4° N, Λ = 208.9° E) and Okinawa (geographic coordinates φ = 26.68°N, λ = 128.15°E, and geomagnetic coordinates Φ = 17.0°N, Λ =

198.6°E) the February $_{median}$ foF2$_{(medQ)}$ (on quiet days) is systematically significantly different from the December and January $_{medians}$. The maximum relative difference in absolute value with the January median reaches 40% at some hours of the day (and 15− 17% on average). At the same time, the relative difference of the December and January medians in absolute value does not exceed 20%, remaining, on average, within 8%. In general, the described differences increase with decreasing latitude. The analysis showed that these differences in the behavior of the monthly medians can be largely explained by a smaller value of the Sun's zenith angle during the day above the indicated stations and a larger absolute value of the rate of its change in February as compared to December and January. Thus, the last month of the "standard" winter season, which is transient from winter to spring, significantly differs by its ionospheric morphological characteristics from the "internal" winter months (December, January− when distinguishing the winter period as ZIMA$_{ndyaf)}$.

Only data of Wakkanai station and Hobart station located almost symmetrically relative to the geographic equator (geographic coordinates φ = 42.92° S, λ = 147.32° E, and geomagnetic coordinatesΦ = 51.6° S,Λ = 225.2° E, Australia) were used in this work. The choice of the studied time interval is related to the very low average level of solar and geomagnetic activity in 2007-2008. In the years of solar activity minimum, the perturbations in the ionosphere caused by magnetic storms are minimal; in addition, the upper atmosphere temperature is also minimal. The temperature of the exosphere in the years of quiet Sun is hundreds of degrees lower than in the years of maximum solar activity, and the general state of the ionosphere in this period of time corresponds to the maximum quiet ("background") level, which is why it was chosen for analysis. As indicated in [Deminov et al., 2011],$\langle$ F10.7$\rangle \approx$ 71 SFU and σ(*F10*.7) ≈ 3 SFU,$\langle$ *ap*$\rangle \approx$ 7 nTL and σ(*ap*) ≈ 4 nTL (σ is the standard deviation). At the same time, the averages for2008 г . values of the solar and geomagnetic activity indices ($\langle$ F10.7$\rangle \approx$ 69 SFU and$\langle$ *ap*$\rangle \approx$ 6.9 nTL) were the lowest for all years of regular measurements of these indices (*F10*.7 with1948 г ., *ap* c1932).

From the specified geographical coordinates of the stations, their proximity in terms of the intensity of illumination by the Sun, other things being equal, during the year follows, since from formula (2), for example at the equinox (δ =0), we obtain $\{\cos\chi\}_{(Wakkanai)}$ (LT=12 h)= cos(45.16)≅ 0.705, and $\{\cos\chi\}_{(Hobart)}$ (LT=12 h) = cos(-42.92)≅ 0.732, and the relative difference will be no more than 4%. At the same time, the geographic longitudes of the stations are very close, which means that the Sun at zenith will be at the meridian of the stations within the same hour of local time. The annual dynamics of the distributions obtained by us is considered mainly from the point of view of changes in the Sun's zenith angle and its average rate of change for the corresponding month.

In this paper, the main objectives of the study were as follows:

(*a*) Obtain a whole morphological picture of the daily distributions of monthly $foF2_{(med)\ medians}$ in the mid-latitude ionosphere during the period of low solar activity for all "standard" seasons by month, from December2007 г . to November2008 г . inclusive at the selected pair of Wakkanai and Hobart stations;

b) to estimate the value of difference of the $_{median}$ $foF2_{(med)\ of}$ any third month of the "standard" season from the second one, in comparison with differences $foF2_{(med)\ of}$ the first "standard" month of the season from the second one with the purpose of possible increase of homogeneity of the ionospheric data series at another method of their partitioning;

(*c*) Quantify the contribution of solar radiation to ionization of the *F* region under conditions of low solar activity in the equinox seasons, associated with variations in the magnitude and rate of change of the Sun's zenith angle χ, compared to the contribution to ionization made by variations in the composition of the neutral atmosphere;

d) identify the presence/absence of the winter seasonal anomaly at the selected stations during the study period.

Figure 1.

2. RESULTS AND DISCUSSION

Fig. 1 presents daily distributions of monthly $_{medians}$ $foF2_{med}$ for "standard" winter (left panels) and autumn (right panels) months for Wakkanai station in the Northern Hemisphere (lower panels) and almost symmetric to it relative to the geographic equator Hobart station in the Southern Hemisphere (upper panels). Dashed lines show the medians of the first month of the corresponding season, dashed lines - of the second month, and solid lines - of the third month.

It is well seen, first, that the median of the third month of the winter season lies systematically higher than the median of the first and second month for Wakkanai station (and lower for Hobart station). In autumn, on the contrary, the median of the third month of the autumn season lies systematically higher for Hobart station (and lower for Wakkanai station). At that, the differences are more pronounced in autumn. Second, the pattern of changes is consistent with the fact that for winter conditions (left panels, from early December to late February) χ for Hobart station at 12 LT varies in the interval ~ [20º; 36º] (and, most of the time, increases, while illumination and day longitude decrease), while for Wakkanai station at 12 LT there is mainly a decrease in the Sun's zenith angle (while illumination and day longitude increase). The angle χ during this period lies in the interval ~ [69º; 53º]. For the fall, this picture is more complicated and will be described further.

Figure 2.

Figure 2, similarly, shows the daily distributions of $foF2_{(med)\ medians}$ for the "standard" summer (left panels) and spring (right panels) months with the same labeling.

Again, as can be seen from Fig. 2, the differences in the behavior of $foF2_{med}$ (related to the magnitude of the zenith angle χ and the duration of the daylight hours) between August and July are larger than between June and July, but in general they are smaller compared to the winter season. This is probably due to the greater distance of the Earth from the Sun in summer compared to winter. As stated in the monograph [Rishbet and Garriot, 1975], the decrease in the solar ionizing radiation flux associated with the change in the distance from the Earth to the Sun during the transition from winter to summer is 6%. Under summer conditions (left panels, early June to late August), χ for Hobart station at 12 LT changes in the interval ~ [67º; 51º] (decreasing most of the time), whereas for Wakkanai station at 12 LT there are changes in χ in the interval ~ [22º; 38º] (mostly increasing). The peculiarities of spring $foF2_{med}$ distributions will also be discussed below, but we note that even here the median $foF2_{(med)\ of}$ May differs from the median of April much more strongly than the median of March from the median of April (the average month of the "standard" spring season).

Figure 3.

Figure 3 below shows the diurnal distributions of monthly $foF2_{(med)\ medians}$ for the "standard" winter (left panels) and summer (right panels) months in the same labels as in Figures 1, 2, with the medians of November (left panels) and May (right panels) plotted (solid lines with dots).

From Fig. 3 one can clearly see that by the character of the behavior of the medians, November should really be referred to the winter season (according to the classification $ZIMA_{ndyaf}$ it will be the first month of the season), and May - to the summer season (according to the classification $SUMMER_{mia}$ it will also be the first month of the season). This is especially clear for summer months on the example of Wakkanai station.

Thus $\chi\in$ [31º; 24º] for 12 LT in November (beginning of the season according to the $ZYMA_{ndiaf}$ classification) and $\chi\in$ [27º; 36º] for 12 LT in February (end of the season according to the $ZYMA_{ndiaf}$ classification) for Hobart station. Correspondingly, for Wakkanai station, $\chi\in$ [61º; 68º] for 12 LT in November (beginning of the season under the $ZIMA_{ndiaf}$ classification) and $\chi\in$ [62º; 53º] for 12 LT in February (end of the season under the $ZIMA_{ndiaf}$ classification).

Similarly, $\chi\in$ [59º; 65º] for 12 LT in May (beginning of the $SUMMER_{mia}$ season) and $\chi\in$ [61º; 51º] for 12 LT in August (end of the $SUMMER_{mia}$ season) for Hobart station. On this time interval for Wakkanai station, $\chi\in$ [30º; 24º] at 12 LT for May (beginning of the $SUMMER_{myia}$ classification season) and $\chi\in$ [28º; 38º] at 12 LT for August (end of the $SUMMER_{myia}$ classification season). It can be seen, in particular, that the May $_{median}$ $foF2_{med}$ (lower right panel) is almost everywhere higher than the August $_{median}$, and the range of changes in χ for 12 LT in May is significantly lower than that in August, providing more intense photoionization under otherwise equal conditions.

The question about the necessity of comparing the March and September $_{medians}$ of $NmF2_{med}$ (or, equivalently, $foF2_{med}$) in the global aspect is raised in a large-scale and complex study [Zou et al., 2000] , connected with the development and testing of the CTIP (Coupled Thermosphere-Ionosphere-Plasmasphere) model for geomagnetically calm conditions. The physical interpretation of the results of calculations using this model is given in detail in the paper [Rishbeth et al., 2000] following it on the basis of the physical mechanisms of interaction in this complex system (thermosphere− ionosphere− plasmasphere). The CTIP (Coupled Thermosphere Ionosphere Plasmasphere) model was further successfully developed in CTIPE (Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics, see in particular [Codrescu et al., 2008]), which has been successfully implemented into the working model of the currently operating Community Coordinated Modeling Center, USA, and is continuously improved within the framework of this project (see [https://ccmc.gsfc.nasa.gov/publication-policy]). In our case, it is possible to make a "point" comparison on the example of two specific NSVZIs, based on the general physical approach presented in the fundamental study [Rishbeth et al., 2000].

Table 1.

First of all, let us consider some general characteristics of the mentioned months given in Table 1.

Here$\langle d\chi/dt\rangle$ is the monthly average rate of change of the zenith angle (for a given LT hour), defined as the difference of χ values between the first day of the following month and the first day of the previous month, referred to the number of days contained in the previous month. The arrow indicates the increase/decrease of χ during the month.

Table 1 shows that the absolute values of the rates of change of zenith angles for both stations are very close both in different months and among themselves. The ranges of change of angles for March and September at each of the stations are also close. We emphasize here that exactly in these equinox months, the average rate of change of the Sun's zenith angle is maximum in absolute value.

Figure 4.

Fig. 4 compares the March and September $foF2_{(med)}$ $_{medians}$ for Hobart and Wakkanai stations.

One can see that in both hemispheres in the daytime hours, the $foF2_{med}$ value in March is higher than in September. For Hobart station (Southern Hemisphere), the transition to the night hours begins in September earlier than in March, and for Wakkanai station (Northern Hemisphere) - vice versa. This behavior agrees well with the fact that on average the day length in March for the geographical location of Hobart station is greater than 12 h, and in September - less. Correspondingly, for Wakkanai station, the situation is opposite.

A more interesting question is how (as indicated above) the values of the medians $foF2_{med}$(March)/$foF2_{med}$(September) for both stations relate to each other and what conclusions can be drawn from such a comparison. We remind here that strong deviations from the medians themselves at the periods of equinoxes are considered in detail in [Mikhailov and Schlegel, 2001]

From Fig. 4, it can be seen that the maximum values of $foF2_{med}$(March) at both NSVZIs are reached at 04 UT, near noon local time (LT). Using relation (1), we obtain

$$^{Wak}NmF2_{med}{}^{\{03/2008;04UT\}}/^{Wak}NmF2_{med}{}^{\{09/2008;04UT\}} =$$
$$= [^{Wak}foF2_{med}{}^{\{03/2008;04UT\}}/^{Wak}foF2_{med}{}^{(\{09/2008;04UT\})}]^2 = {}^{obs}\delta_{Wak} \cong 1.41 \ . \quad (3)$$

Accordingly,

$$^{Hob}NmF2_{med}{}^{\{03/2008;04UT\}}/^{Hob}NmF2_{med}{}^{\{09/2008;04UT\}} =$$
$$= [^{Hob}foF2_{med}{}^{\{03/2008;04UT\}}/^{Hob}foF2_{med}{}^{(\{09/2008;04UT\})}]^2 = {}^{obs}\delta_{Hob} \cong 1.37 \ .$$

(4)

As can be seen, the relative differences of the March and September medians are close to each other and differ by ≅± 1.5% from their arithmetic mean for Wakkanai and Hobart stations, respectively. Let us now carry out simplified model estimates of these quantitative relations obtained from observations using the approach adopted in the monograph [Rishbeth and Garriot, 1975] and developed in [Rishbeth et al., 2000] (see, in particular, formula (2) of this paper). Then we can obtain that (here and further in the above formulas $hmF2_{med}$ is the argument of the corresponding function, and its numerical value is taken according to the SMF2 model, see below

$$NmF2_{med}{}^{\{03/2008;04UT\}} \propto Q_{(med)}(hmF2_{(med)})/[N_2]_{med}\,(hmF2_{(med}{}^{))(\{03/2008;04UT\})}. \quad (5)$$

Here Q is the photoionization rate, $[N_2]$ is the concentration of molecular nitrogen, and $hmF2_{med}$ is the monthly median height of the ionospheric F2-layer maximum. In turn, for zenith angles $\chi \leq 70°$ (which allows us to replace Chapman's function by sec(χ) according to the monograph [Rishbet and Garriot, 1975])

$$Q_{med}\,(hmF2_{med}) \propto \langle F10.7\rangle\,[O]_{med}\,(hmF2_{(med)})\,\exp\{-\sec(\chi)\}_{med}, \quad (6)$$

where⟨ F10.7⟩ is the monthly mean solar radiation flux at wavelength10.7 см in SFU units, and [O] is the concentration of atomic oxygen. Hence, for a given month, year, and

$$NmF2_{med} \propto \langle F10.7\rangle\,\exp\{-\sec(\chi)\}_{med}\,[O]_{(med)}(hmF2_{(med)})/[N_2]_{med}\,(hmF2_{(med)}) \equiv NmF2^*{}_{(med}$$

(7)

or respectively:

$$NmF2^*{}_{med} \equiv \langle F10.7\rangle\,\exp\{-\sec(\chi)\}_{(med)}[O]_{(med)}(hmF2_{(med)})/[N_2]_{med}\,(hmF2_{(med)}). \quad (8)$$

Then we can assume that

$NmF2_{med}^{\{03/2008;04UT\}}/NmF2_{med}^{\{09/2008;04UT\}} \approx NmF2^{*}{}_{med}^{\{03/2008;04UT\}}/NmF2^{*}{}_{med}^{\{09/2008;04UT\}}$.

(9)

The values of $hmF2_{med}$ for the desired months at 04 UT on both NSVZIs can be estimated using the SMF2 model (SMF2 global model of F2 layer peak maximum from satellite and ground-based observation, IZMIRAN) []. [https://www.izmiran.ru/ionosphere/smf2/]. Then we obtain:

$^{Hob}hmF2_{med}^{\{03/2008;04UT\}} \cong 226$ км , $^{Hob}hmF2_{med}^{\{09/2008;04UT\}} \cong 216$ km (10)

$^{Wak}hmF2_{med}^{\{03/2008;04UT\}} \cong 218$ км , $^{Wak}hmF2_{(med}^{)(\{09/2008;04UT\})} \cong 209$ km. (11)

The relations $[O]_{(med)(}hmF2(_{med}))/[N_2](med)(hmF2(_{med}))$ are calculated using the neutral atmosphere model NRLMSISE-00 [https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php]. At the same time, quantitative model estimates of the corresponding relations (taking into account that the value of the monthly mean flux $\langle F10.7\rangle^{\{03/2008\}} = 73.0$ SFU and $\langle F10.7\rangle^{\{09/2008\}} = 67.0$ SFU according to Solar Cycle Progression [https://www.swpc.noaa.gov/products/solar-cycle-progression]) turn out to be as follows:

$^{Wak}NmF2^{*}{}_{med}^{\{03/2008;04UT\}}/^{Wak}NmF2^{*}{}_{med}^{(\{09/2008;04UT\})} = {}^{model}\delta_{Wak} = 1.30$ (12)

$^{Hob}NmF2^{*}{}_{med}^{\{03/2008;04UT\}}/^{Hob}NmF2^{*}{}_{med}^{(\{09/2008;04UT\})} = {}^{(model}{}_{)}\delta_{Hob} = 1.47$. (13)

Comparison of these values with similar ones obtained from observations shows that

$Rel_{Wak} = 100\ ({}^{(model}{}_{)}\delta_{Wak} - {}^{obs}\delta_{(Wak)})/{}^{obs}\delta_{(Wak)} \cong -8\%$ (14)

$Rel_{Hob} = 100\ ({}^{(model}{}_{)}\delta_{Hob} - {}^{(obs}{}_{)}\delta_{(Hob)})/{}^{obs}\delta_{Hob} \cong 7\%$. (15)

This is a good agreement if we take into account all simplifying assumptions made in deriving relation (8). The model estimates obtained here (close to those obtained from observations) are based on the conclusions of [Rishbeth et al., 2000], according to which diffusion equilibrium prevails in the quiet midlatitude ionosphere during the period of equinoxes, and the contribution to the NmF2 changes of vertical plasma drift in geomagnetically quiet conditions is on average zero.

It is now quite reasonable to use relation (8) to obtain a comparative estimate of the relative contribution to the *NmF2* variations of changes in the zenith angle (δ_χ) and neutral composition ($\delta_{O/(N)(2)}$) at fixed altitudes (10) and (11) for Hobart and Wakkanai stations, respectively, in March and September for the time instant 04 UT. We immediately note here that the relative differences due to changes in solar flux intensity in March and September are small, as $\langle F10.7\rangle_{03.2008}/\langle F10.7\rangle_{09.2008} = 73.0/67.0 \cong 1._{09}$. Next, in relation (8), we need to estimate the relative contribution of the terms $a = \exp\{-\sec(\chi)\}$ and $b = [O](hmF2_{med})/[N_2](hmF2(_{med}))$ to their product by choosing reference points at the beginning, middle and end of the corresponding month. Such points would be March 1, 15, and 31 and September 1, 15, and 30. Estimation of the relative changes in the product *ab*, i.e. value$\Sigma = [(a+\Delta a)(b+\Delta b)-ab]/ab$ and the sum$\Sigma = \delta_\chi + \delta_{O(/)(N)(2)} + \delta_\chi\delta_{(O)(/)(N)(2)}$ of the relative variations of the factors ($\delta_\chi = \Delta a/a$)and ($\delta_{O(/)(N)(2)} = \Delta b/b$) with respect to the midpoint of each month for both stations, i.e., March 15 and September 15, are given in Table 2. The values presented below in Table 2 are derived from the identity $(a+\Delta a)(b+\Delta b)/ab - 1 \equiv \Delta a/a + \Delta b/b + \Delta a \Delta b/ab$, taking into account the sign of the increments Δa and Δb and assuming that $a \neq 0$, $b \neq 0$. The multipliers a and b correspond to the midpoints of the months - March 15 and September 15, and their incremental products correspond to the boundaries of the months (points March 1 and 31 and September 1 and 30). The signs of the increments are obtained automatically, since the difference between the boundary point and the center point of the interval is always considered.

Table 2.

It is immediately apparent from Table 2 that the contribution to the sum of relative NmF2 changes associated with the quadratic term $\delta_\chi \delta_{O/(N)(2)}$ is always small compared to the corresponding linear terms and does not exceed 5% in absolute value. The contribution associated with the change in zenith angle (δ_χ) either exceeds the contribution $\delta_{O/(N)(2)}$ associated with the change in the $[O]/[N_2]$ ratio, or is more than half of this contribution in absolute value and does not fall below the 14% level in half a month. Obviously, the maximum relative deviations are reached when both contributions have the same sign, i.e., the changes in zenith angle and $[O]/[N_2]$ ratio are in "phase". On average, in absolute terms, the half-month total contribution $\langle\Sigma\rangle_{H(obart)} \cong$ is 22%, whereas $\langle\Sigma\rangle_{Wakkanai} \cong$ is 11%, which is half as large. Thus, the relative contribution of changes in NmF2 near local noon in March and September due to changes in the zenith angle χ is greater than or comparable to the contribution due to changes in the $[O]/[N_2]$ ratio for both stations.

Note here that the values obtained for the 15th day of the month are

$$ {}^{Wak}NmF2^{*\{15/03/2008;04UT\}} / {}^{Wak}NmF2^{*\{15/09/2008;04UT\}} \cong 1.47 \quad (16) $$

$$ {}^{Hob}NmF2^{*\{15/03/2008;04UT\}} / {}^{Hob}NmF2^{*\{15/09/2008;04UT\}} \cong 1.49 \quad (17) $$

are also close to the median model estimates obtained ${}^{model}\delta_{Wak} = 1.30$ and ${}^{model}\delta_{Hob} = 1.47$.

Let us now consider how the averaged values of $foF2_{med}$ medians for the first 2 months of the "standard" season and for the whole "standard" season (3 months) relate to each other. Let us introduce the following notations $\varepsilon = 100 [\langle foF2_{(med)}\rangle_3 - \langle foF2_{(med)}\rangle_2]/\langle foF2_{(med)}\rangle_{(2)}]$, where $\langle foF2_{(med)}\rangle_2$ denotes averaging over the first 2 months of any "standard" season, and $\langle foF2_{(med)}\rangle_3$ denotes averaging over the entire "standard" season. Then ε will serve as their quantitative measure of difference for each hour of the day.

Figure 5.

Fig. 5 shows the values of ε for "standard" winter and spring seasons.

From Fig. 5 it follows that $\varepsilon \in [-10, 0]$ in winter and $\varepsilon \in [-15, 5]$ in spring for Hobart station, whereas $\varepsilon \in [-1, 17]$ in winter and $\varepsilon \in [-7, 9]$ in spring for Wakkanai station. Thus, it turns out that the absolute value of the ε spread range at Hobart station in spring is twice as high as in winter and is≈ 20%. At the same time at Wakkanai station, the absolute value of the ε spread range has close values for both seasons and makes≈ 18% in winter and≈ 16% in spring.

Figure 6.

Figure 6 characterizes the value of ε for the "standard" summer and fall seasons.

According to Figure 6, it turns out that ε∈ [− 1, 10] in summer and ε∈ [− 1, 17] in autumn for Hobart station, whereas ε∈ [− 4, 4] in summer and ε∈ [− 12, 4] in autumn for Wakkanai station. In this case, the absolute value of the range of spread ε at Hobart station is ~1.6 times larger in the fall than in the summer and is≈ 18%, and at Wakkanai station the absolute value of the range of spread ε is≈ 16% in the fall, which is twice as large as in the summer.

It follows from the obtained consideration that a greater absolute relative difference of the median $foF2_{(med)}$ of any third month of the "standard" season from the second, compared to the differences $foF2_{(med)}$ of the first "standard" month of the season with the second, can lead differences of tens of percent when averaging medians $foF2_{med}$, depending on whether such averaging is carried out for two or three months of the "standard" season. Naturally, considering monthly averages instead of medians will lead to even larger differences. Apparently, to increase the homogeneity of ionospheric data, it is necessary to group them by two months in such a way: December and January, February and November, March and April, May and August, June and July, September and October, all other conditions being equal. Such a partitioning better accounts for changes in photoionization conditions due to variations in the Sun's zenith angle χ , as well as its rate of change in different seasons. At the same time, the grouping of the data is not always consecutive. Finally, within the division by three seasons (WINTER, SUMMER, EQUAL), one should distinguish the inner months of the winter season (December and January) and the outer months (February and November) precisely because of the more abrupt changes in the Sun's zenith angle. The same is true for the inner months of the summer season (June and July) and the outer months (May and August).

In conclusion, it is necessary to note a specific difference in the behavior of the midday medians $foF2_{med}$(12 LT) in different months of the year at the stations considered above, which is illustrated in Fig. 7.

Figure 7.

Fig.7 presents the annual variations (interval from 01.12.2007 to 30.11.2008, abscissa axis) of the Sun's zenith angle (χ) for 12 LT, left ordinate axes (open circles) and median values of $foF2_{med}$ (for the same local time), right ordinate axes (solid lines with shaded circles) for Hobart (upper panel) and Wakkanai (lower panel) stations, respectively. It is well seen that at Hobart station the solar control dominates, and larger values of the solar zenith angle at 12 LT correspond to lower values of $foF2_{med}$. For Wakkanai station, the situation is reversed and, for the winter months of the

Northern Hemisphere, $foF2_{(med)}$(12 LT) exceeds the values characteristic of the summer months, at that

$[foF2_{med}(\text{Wakkanai, 12 LT})_{December}]^2/[foF2_{med}(\text{Wakkanai, 12 LT})_{June}]^2 \cong 1.76,$ (18)

i.e., a seasonal (winter) anomaly is observed connected with the peculiarities of the thermospheric circulation in the neutral atmosphere leading to the increased values of the $[O]/[N_2]$ ratio in winter compared to summer at this geographical location (see [Zou et al., 2000; Rishbeth et al., 2000] for details). And, although [Zou et al., 2000] indicated that the midday seasonal anomaly almost disappears at low solar activity, for this case, when $\langle F10.7 \rangle \in [65, 78]$ SFU, the winter anomaly is very well pronounced.

The calculations using the neutral atmosphere model NRLMSISE-00 also show that for Wakkanai station at the height of the maximum $hmF2_{med}$ (obtained from the SMF2 model)

$[O](hmF2_{med})/[N_2](hmF2_{med})\{15.12.2007; 12\ LT\} \cong 2.12,$ (19)

whereas

$[O](hmF2_{med})/[N_2](hmF2_{med})\{15.06.2008; 12\ LT\} \cong 1.09,$ (20)

i.e., the $[O]/[N_2]$ ratio is more than twice as high in December compared to June.

5. CONCLUSIONS

1. A comparative analysis of monthly medians of daily variations of the critical frequency of the regular *F2-layer of* the ionosphere (*foF2*) for all "standard" seasons during the period of low solar activity in 2007-2008 was carried out on the basis of measurements at the mid-latitudinal ground stations of vertical sounding of the ionosphere Wakkanai (Japan) and Hobart station (Australia) located almost symmetrically relative to the geographical equator.

2. It was obtained that the greater in absolute value relative difference of the median $foF2_{(med)}$ of any third month of the "standard" season from the second, compared to the differences $foF2_{(med)}$ of the first "standard" month of the season with the second, can lead to differences in tens of percent when averaging the medians $foF2_{med}$, depending on whether such averaging is carried out for two or three months of the "standard" season. Apparently, to increase the homogeneity of ionospheric data, it is necessary to group them by two months in such a way: December and January, February and November, March and April, May and August, June and July, September and October, other things being equal. Such a partitioning better accounts for changes in photoionization conditions due to variations in the Sun's zenith angle χ, as well as its rate of change in different seasons. Using a specific example of two considered midlatitude stations, it is shown that by its characteristics, the median of November (the last month of the "standard" autumn season) corresponds to the beginning of the winter season, and the median of May (the last month of the "standard" spring season) corresponds to the beginning of the summer season.

3. It was found that the contribution of solar radiation to the ionization of the *F* region under conditions of low solar activity in the equinox seasons, associated with variations in the magnitude and rate of change of the Sun's zenith angle χ, is not less than half of the contribution to ionization made by variations in the composition of the neutral atmosphere.
4. For the selected time interval, a well pronounced winter (seasonal) anomaly in the behavior of $foF2_{med}$ for Wakkanai station is observed.
5. The results presented in para. 2 can be applied to the analysis of differences of the seasonal variations of the medians of critical frequencies *foF2* for any ground station of vertical sounding of the ionosphere, using the proposed method of partitioning of ionospheric data, when constructing the corresponding empirical models of the ionosphere (local, regional, global).

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Table 1. Range of solar zenith angles (χ) and their monthly average rate of change ($\langle d\chi/dt \rangle$) for the Wakkanai and Hobart NSVZIs at 12 LT

Hobart	
March, .2008 г	September, 2008
$\chi \in [37^o; 48^o]\uparrow$	$\chi \in [52^o; 41^o]\downarrow$
$\langle d\chi/dt \rangle = 0.393^o$/day	$\langle d\chi/dt \rangle = -\ 0.383^o$/day
Wakkanai	
$\chi \in [52^o; 40^o]\downarrow$	$\chi \in [38^o; 50^o]\uparrow$
$\langle d\chi/dt \rangle = -\ 0.397^o$/day	$\langle d\chi/dt \rangle = 0.393^o$/day

Table 2: Changes in the magnitudes of $\delta_\chi = \Delta a/a$, $\delta_{O/N2} = \Delta b/b$ and total $\Sigma = \delta_\chi + \delta_{O/N2} + \delta_\chi\delta_{O/N2}$ O(/)(N)(2) relative to the midpoint of the March and September months for the Hobart and NSVZIs

Hobart				
Interval	δ_χ, %	$\delta_{O/N2}$, %	$\delta_\chi\delta_{O/N2}$, %	Σ, %
March 1-March 15	14	25	4	43
March 31-March 15	-19	2	0	-17
Sept. 1-Sept. 15	-16	24	-4	4
Sept. 30-Sept. 15	15	8	1	25
Wakkanai				
Interval	δ_χ, %	$\delta_{O/N2}$, %	$\delta_\chi\delta_{O/N2}$, %	Σ, %
March 1-March 15	-17	3	-1	-14
March 31-March 15	16	-5	-1	10
Sept. 1-Sept. 15	14	1	0	15
Sept. 30-Sept. 15	-18	26	-5	3

Note. Rounding is done to units of percent.

Figure captions

Fig. 1. Diurnal distributions of monthly $foF2_{(med)\ medians}$ for the "standard" winter (left panels) and fall (right panels) months for the Wakkanai NSWHI in the Northern Hemisphere (bottom panels) and Hobart NSWHI in the Southern Hemisphere (top panels). Dashed lines show the medians of the first month of the corresponding season, dashed lines show the medians of the second month, and solid lines show the medians of the third month. Shaded rectangles under the abscissa axis mark local time (LT) intervals from 18 to 6 h, centered at the top by a stylized image of a dial that marks local midnight.
Fig. 2. Same as Fig. 1, but for the "standard" summer (left panels) and spring (right panels) months.
Fig. 3. Same as Fig. 1, but for "standard" winter (left panels) and summer (right panels) months. The added solid lines with dots correspond to November (left panels) and May (right panels), respectively.
Fig. 4. March (solid line) and September (dashed line) $foF2_{(med)\ medians}$ for the Hobart (top panel) and Wakkanai (bottom panel) NSVZIs. The dashed vertical line marks the 04 UT time point, which corresponds to 13 LT for Wakkanai and 15 LT for Hobart st. Additional notations are the same as in Fig. 1.
Fig. 5. Values ofε in the "standard" winter (left) and spring (right) seasons for Hobart (top panels) and Wakkanai (bottom panel) NSVZIs. Additional notations are the same as in Fig. 1.
Fig. 6. Same as Fig. 5, but for "standard" summer (left) and fall (right) seasons.
Fig. 7. Changes during the annual interval (from 01.12.2007 to 30.11.2008, abscissa axis) of the Sun's zenith angle (χ) for 12 LT, left ordinate axes (open circles) and $_{median}$ values of $foF2_{med}$ (for the same local time), right ordinate axes (solid lines with shaded circles) for the Hobart (upper panel) and Wakkanai (lower panel) NSVZIs, respectively. Above the open circles, the day of the corresponding month is indicated in fractions for easy perception.

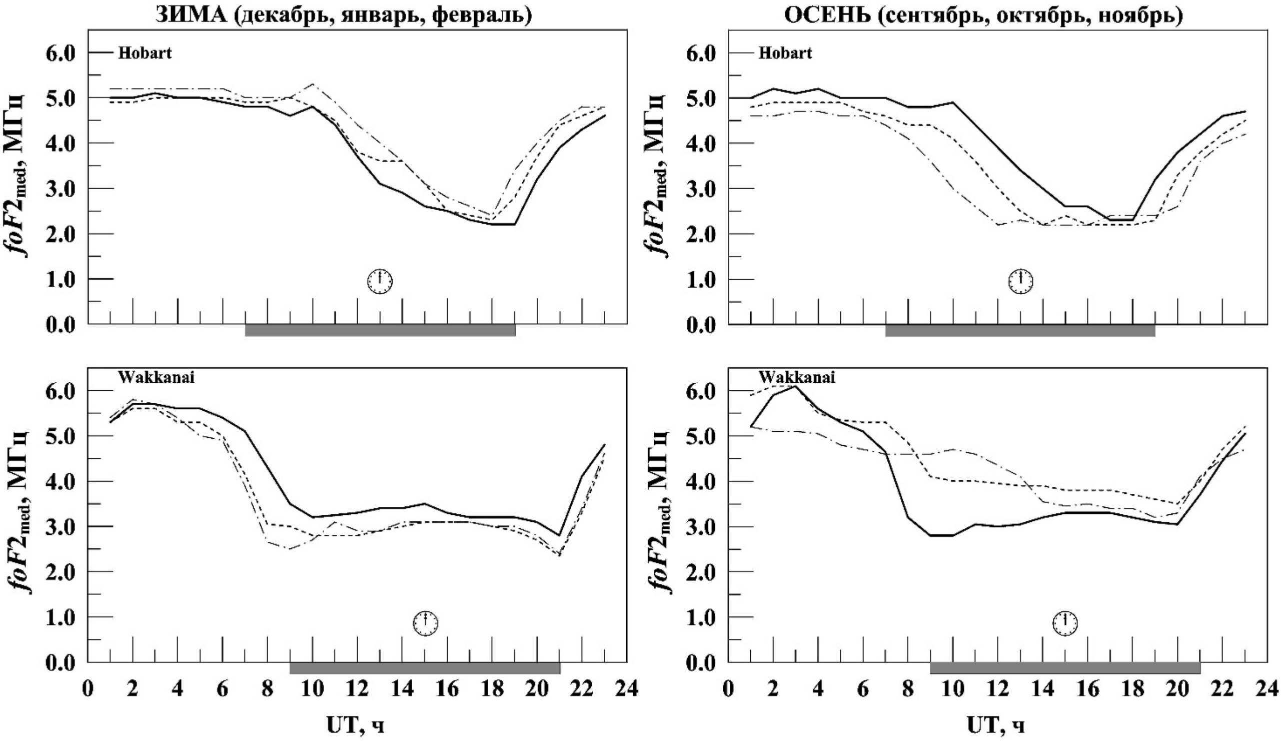

ЗИМА (декабрь, январь, февраль)
ОСЕНЬ (сентябрь, октябрь, ноябрь)
Hobart
Wakkanai
foF2med, МГц
UT, ч

Figure 1.

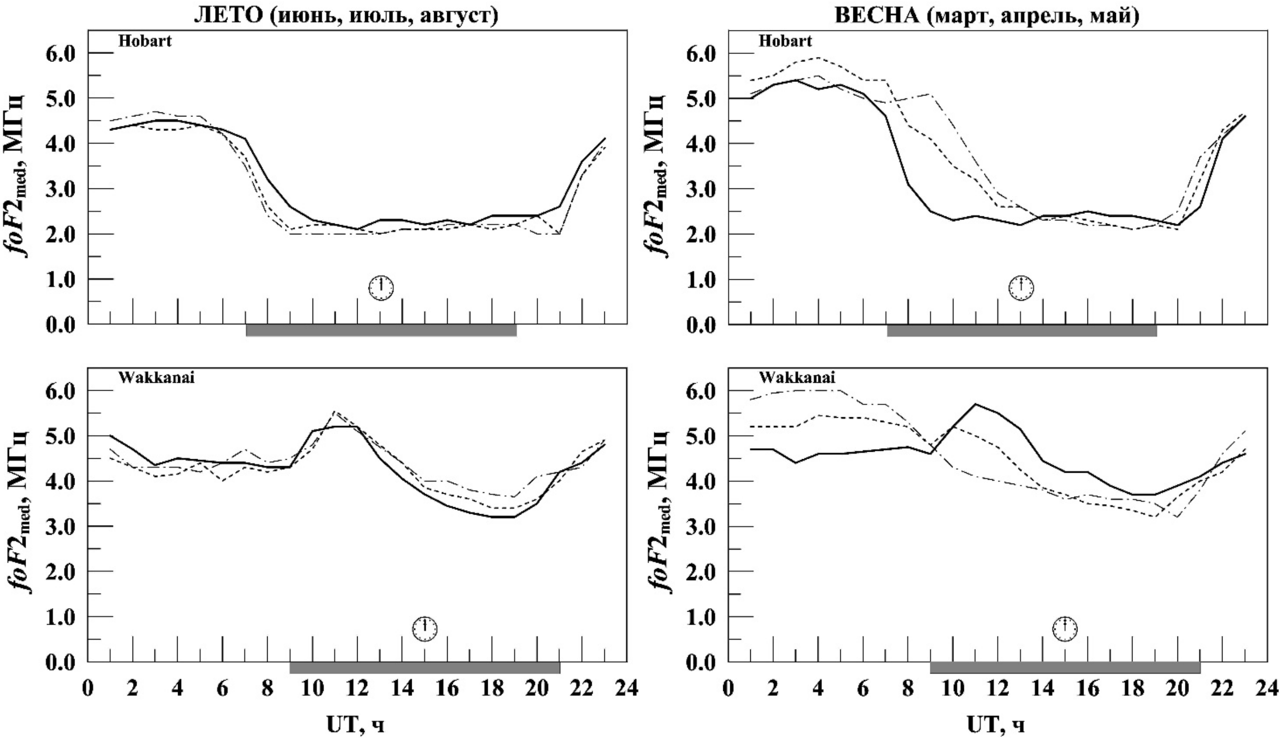

ЛЕТО (июнь, июль, август)
ВЕСНА (март, апрель, май)
Hobart
Wakkanai
foF2med, МГц
UT, ч

Figure 2.

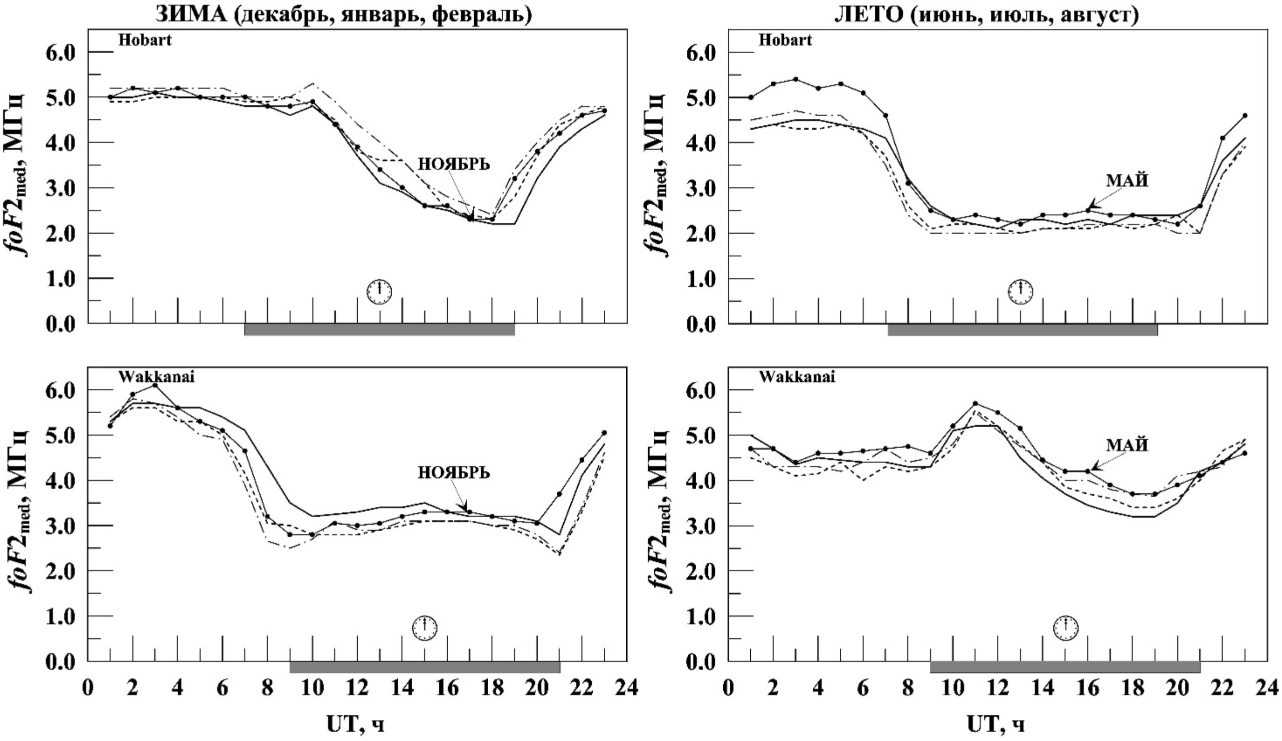
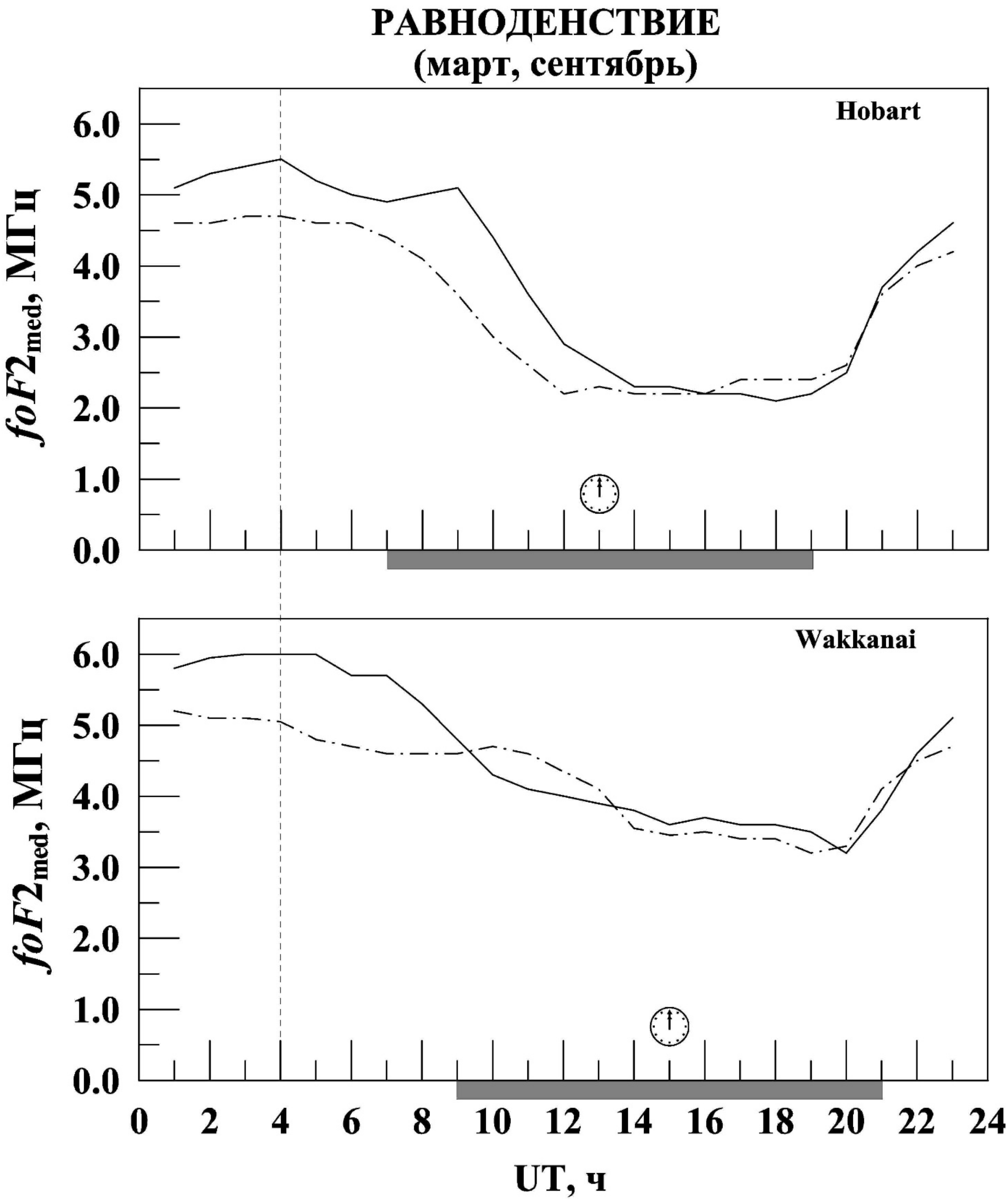


Figure 3.



РАВНОДЕНСТВИЕ
(март, сентябрь)
Hobart
Wakkanai
foF2med, МГц
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0 2 4 6 8 10 12 14 16 18 20 22 24
UT, ч

Figure 4.

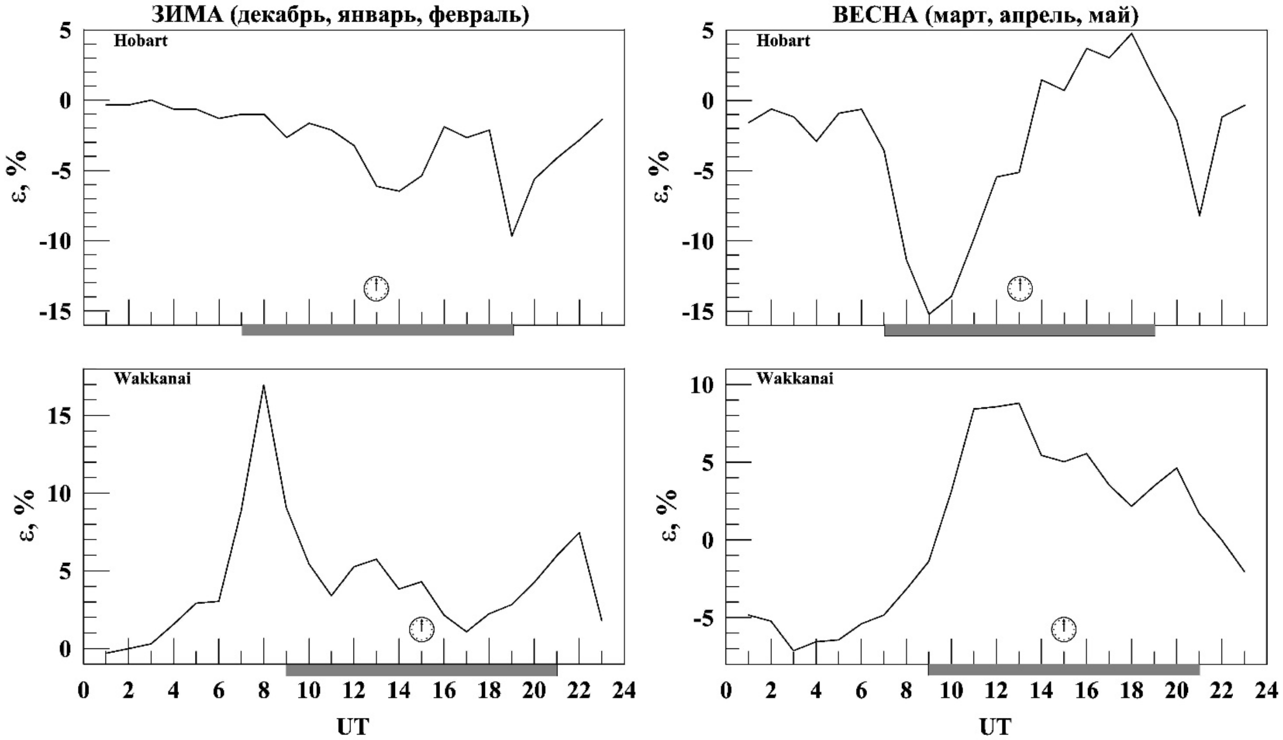


Figure 5.

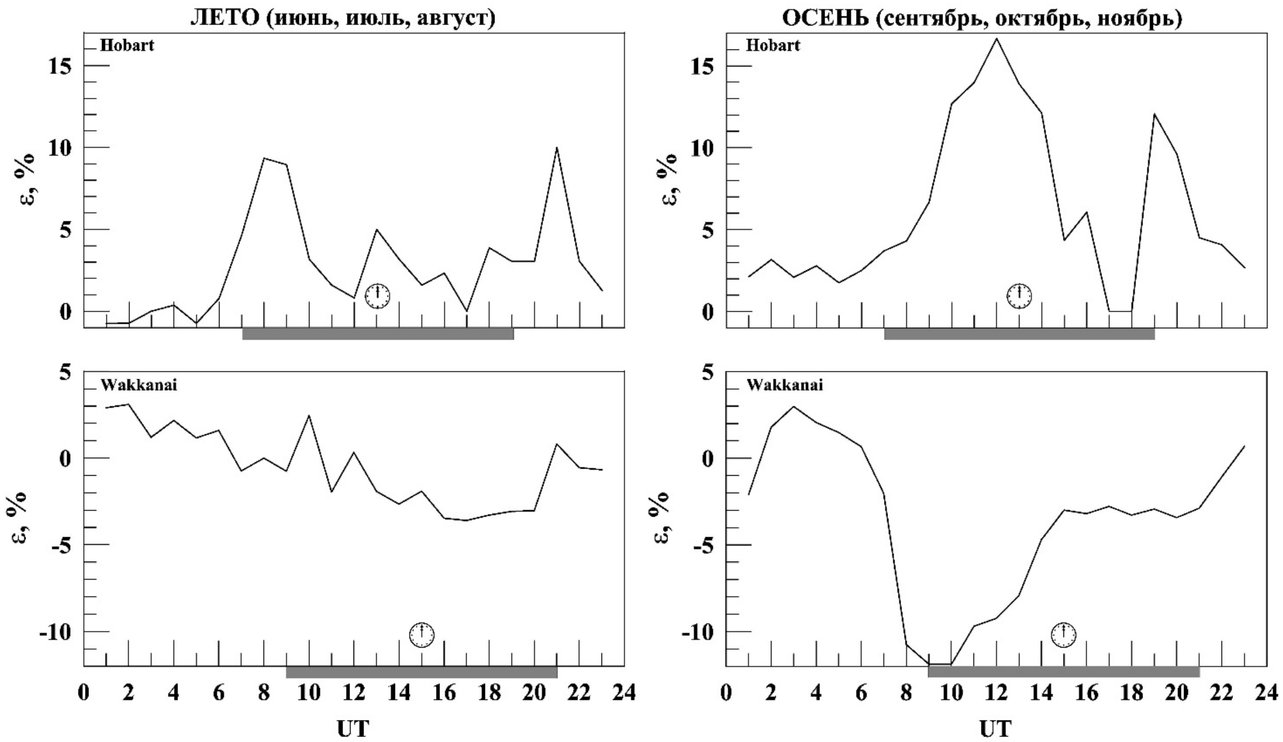
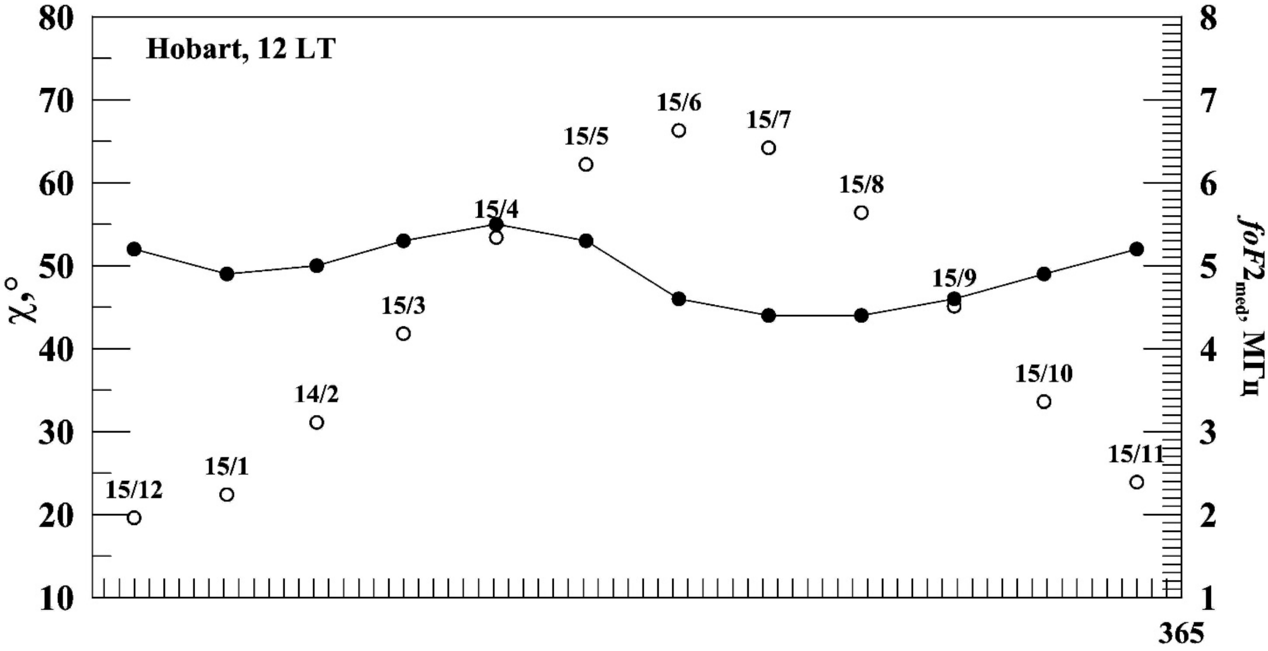


Figure 6.



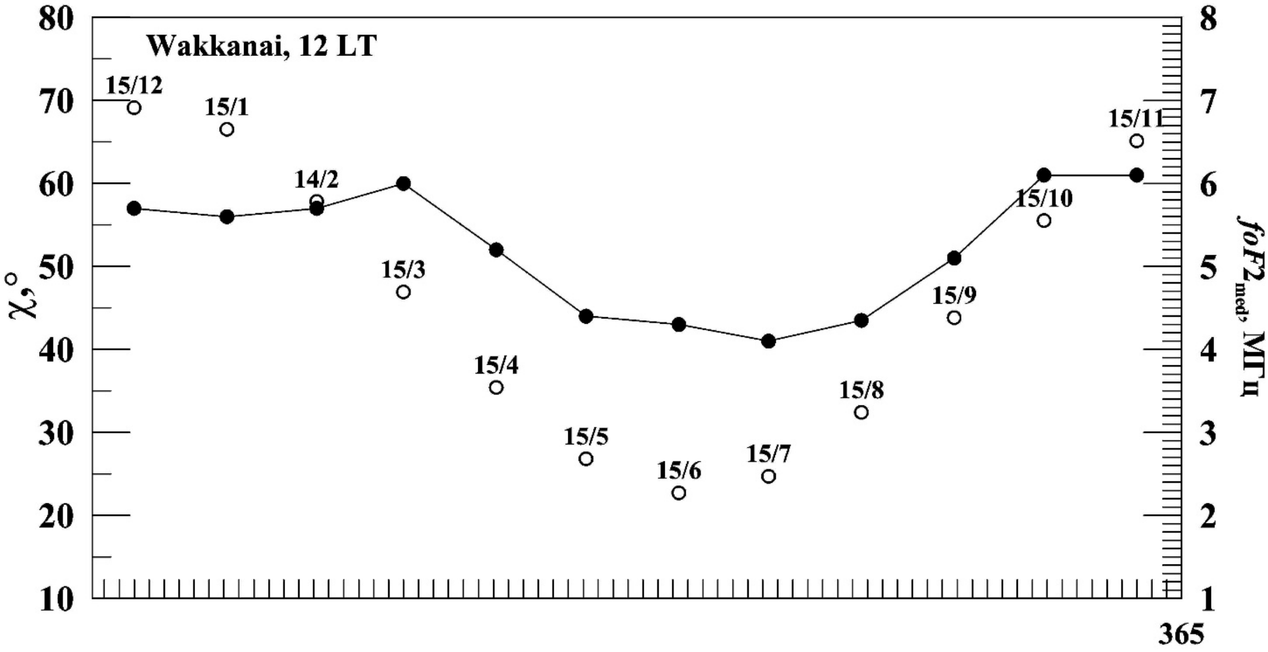


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Figure 7.