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TRENDS IN THE F2-LAYER CRITICAL FREQUENCY FROM DATA OBTAINED AT THE IONOSPHERIC STATION YAKUTSK DURING THE PERIOD FROM 1956 TO 2017

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Abstract. A statistical analysis of vertical ionospheric sounding data from the Yakutsk station (62.01° N, 129.43° E, 57.12° MLAT) for the period from 1956 to 2017 encompassing six solar cycles has been carried out to identify long-term changes in the F2 layer of the subauroral ionosphere and their relationship with solar and geomagnetic activity. We examined variations in one of the main parameters of the ionospheric F2 layer, the critical frequency. A high correlation was found between the F2-layer critical frequency and the solar activity index *F*10.7. It is shown that during six solar cycles (cycles 19–24) there were negative trends in annual average F2-layer critical frequencies both at midday and at midnight. It has been revealed that f_oF2 trends depend on the season and time of day. Absolute values of the trends are higher in equinoctial and summer seasons. Peak negative trends are observed at midday during equinoctial months, reaching approximately –11 kHz/year.

Keywords: long-term trends, solar activity, subauroral ionosphere, F2-layer critical frequencies.

INTRODUCTION

It is known that the upper atmosphere experiences long-term variations due to the climate change caused by an increase in the amount of greenhouse gases in the atmosphere (see, e.g., [Laštovička et al., 2012; Rezac et al., 2018]). The F2-layer critical frequency f_oF2 is one of the key parameters determining the efficiency of propagation of radio waves of various ranges.

Long-term trends in ionospheric parameters have been studied for more than 35 years, starting with [Roble, Dickinson, 1989; Rishbeth, 1990], in which theoretical calculations revealed that carbon dioxide CO_2 doubling in the atmosphere leads to a change in the F2-layer peak height h_mF2 by 15–20 km. On the basis of long-term observations at different ionospheric stations, a lot of studies into trends in various ionospheric parameters, such as the F2-layer critical frequency, the F2-layer peak height, the E-layer critical frequency, have been carried out [Bremer, 1998; Mikhailov, Marin, 2000; Bremer et al., 2004; Laštovička, 2005, 2017, 2022; Laštovička et al., 2006; Laštovička, Jelínek, 2019; Rishbeth, 1997; Danilov, 2008, 2009, 2017; Danilov, Konstantinova, 2013, 2014; Kolesnik, etc., 2019; Danilov, Konstrantinova, 2020; Sivakandan et al., 2023; Jakowski et al., 2024; Danilov et al., 2024; Zherebtsov, etc., 2024]. Laštovička et al. [2006], using data from the Juluisruh station for the period 1976–1996, have detected the presence of a small negative trend in f_oF2. In [Bremer et al., 2012; Mielich, Bremer, 2013], the trends in f_oF2 and h_mF2 have been analyzed from data collected by 124 stations around the world and it has been shown that steady global trends in h_mF2 and f_oF2 are –0.138 km/yr and –0.0038 MHz/yr. Danilov [2017] observes that there are discrepancies between trends calculated in different papers, which may be attributed to the fact that daily and seasonal variations were ignored in the trend calculations, as well as data sets of different lengths were analyzed.

Cooling and subsidence of Earth's middle and upper atmosphere is currently considered to be the most widely accepted mechanism of negative trends in f_oF2 [Laštovička et al., 2008a]. Danilov [2008] using data from 12 mid-latitude stations has shown that the trend sign can be related to the sign of magnetic declination and inclination of a station, which suggests that there is a relationship between f_oF2 trends and the trend of the zonal thermospheric wind. Danilov and Konstantinova [2013] have revealed a tendency for negative trends in f_oF2 to grow in winter as compared to summer. The works cited above generally employ data from mid-latitude and low-latitude stations. However, Danilov and Konstantinova [2014] note that the trends for stations varying in latitude and longitude differ from each other. Thus, it is also necessary to examine trends in the critical frequency f_oF2 at subauroral and auroral stations. Continuous measurements at the subauroral station Yakutsk (62.01° N, 129.43° E, 57.12° MLAT) have been performed from February 1956 to the present day, providing long-term data on variations of ionospheric parameters.

This paper presents the results of the analysis of long-term (six solar cycles) variations in the F2-layer critical frequency from vertical ionospheric sounding data obtained at the Yakutsk station from 1956 to 2017. The analysis was carried out to identify trends in the F2-layer critical frequency of the subauroral ionosphere at midday and midnight of local time with allowance for solar and geomagnetic activity.

1. EQUIPMENT AND DATA

At the ionospheric station Yakutsk from February 1956 to November 2002, ionospheric parameters were recorded by a panoramic automatic ionospheric station AIS. These stations were commissioned in the Soviet Union during the International Geophysical Year (IGY). Each station was equipped with an AIS-type ionosonde, an antenna system, a set of measuring instruments, and an autonomous power plant. The pulsed power of a transmitter is at least 10 kW at low and 5 kW at high operating frequencies. The pulse duration is 50–70 μs. The repetition frequency is 50 pulses per second with AC mains locking [Vasiliev et al., 1961]. The data was processed according to the international rules for interpreting ionograms obtained by ground-based vertical sounding [URSI Guide..., 1977].

From November 2002 to the present, ionospheric parameters have been measured at the Yakutsk station with the digisonde DPS-4 [Reinisch, 2007]. The DPS-4 system has a low-power transmitter (300 W versus 5–10 kW for previous systems) and includes special signal processing methods for determining the direction of radio signal arrival, phase, polarization, and other characteristics.

The trends in f_oF2 are known to depend on time of day [Danilov, 2015]. With this in mind, we examine data on F2-layer critical frequencies for noon and midnight (LT) in this paper. In the absence of f_oF2 caused by radio signal absorption, shielding of overlying layer by underlying layer, technical failure, etc., we use data for an hour before or after 12 and 00 LT. The initial data set contains about 42 thousand values of f_oF2 for the noon and midnight hours, obtained throughout the observation period.

Figure 1, *a*, *b* illustrates f_oF2 variations during midnight and noon hours (LT) according to data from the Yakutsk ionospheric station for the period from 1956 to 2017. In Figure 1, *c*, *d*, the same data is presented as a function of year and day of the year. Figure 1 clearly shows 11-year variations due to solar activity, as well as the seasonal dependence of f_oF2. The f_oF2 distributions at midnight and noon are seen to differ: at 00 LT, f_oF2 is higher in summer; and at 12 LT, on the contrary, in winter (winter anomaly) (Figure 1, *c*, *d*).

Figure 2, *a*, *b* depicts monthly and annual average variations in the geomagnetic and solar activity indices A_p and F10.7 taken from [https://wdc.kugi.kyoto-u.ac.jp/; http://www.wdcb.ru/stp/data/solar.act/flux10.7/]; Figure 2, *b* presents median monthly and annual average f_oF2 for 00 and 12 LT. It is obvious that minimum annual average f_oF2 is observed during solar minimum and is ~2.5 MHz for midnight and ~5.0 MHz for midday conditions. The upper limit values of f_oF2 correspond to solar maxima and are ~6.0 MHz for midnight and ~10.0 MHz for midday conditions throughout the period in question. Average f_oF2 for the six solar cycles was 3.96 MHz and 6.84 MHz for night and day conditions respectively.

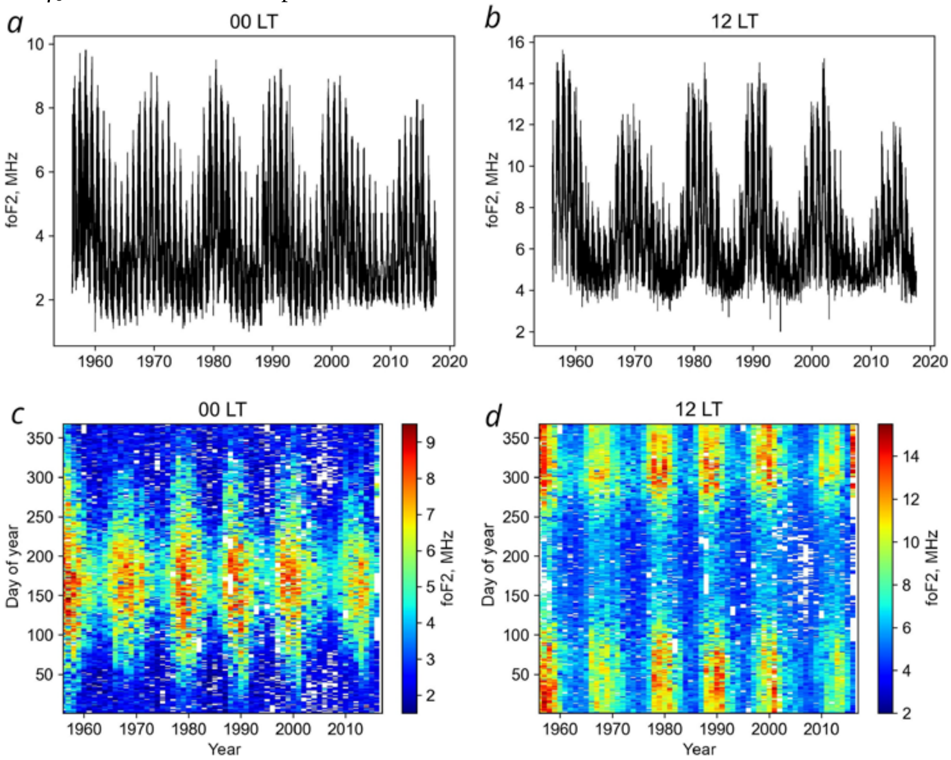

Figure 1. Variations in daily critical frequency f_oF2 (*a*, *b*) and f_oF2 as a function of year and day of the year (*c*, *d*) during midnight (*a*, *c*) and midday (*b*, *d*) hours (LT) according to data from the Yakutsk ionospheric station for the period 1956–2017

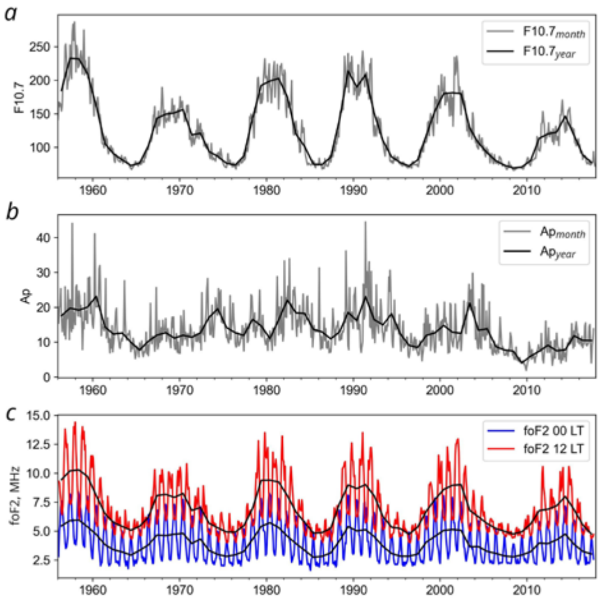

Figure 2. Variations in monthly (gray) and annual average (black) *F*10.7 [10^{-22}W m^{-2} Hz^{-1}] (*a*) and A_p (*b*); median monthly (blue, red) and annual average (black) f_oF2 (*c*) during midnight and midday hours (LT) according to data from the Yakutsk station for the period 1956–2017

2. DATA ANALYSIS TECHNIQUE

Ionospheric disturbances are associated with many processes of solar, geomagnetic, and wave origin (see, e.g., [Brunelli, Namgaladze, 1988; Galperin et al., 1990]). At the latitude of Yakutsk, variations in ionospheric parameters during disturbances may also depend on the dynamics of the main ionospheric trough. To study the effect of geomagnetic activity on f_oF2 trends, we analyze two data sets in this paper: 1) a complete data set; 2) a data set from which the days with daily K_p>24 are excluded [Brunelli, Namgaladze, 1988].

The method for identifying long-term f_oF2 trends is based on eliminating variations, related to solar (and geomagnetic) activity, through regression analysis. The calculated trends depend on the choice of the regression model, so we analyze several models in this paper:

1) simple linear regression with one independent variable *F*10.7 [Bremer et al., 2004]:

$$f_o\text{F2}_{\text{model}} = A + BF10.7; \quad (1)$$

2) a quadratic regression model of dependence of f_oF2 on *F*10.7 and *F*10.7^2 [Bremer et al., 2004; Laštovička et al., 2006]:

$$f_o\text{F2}_{\text{model}} = A + BF10.7 + C\left(F10.7\right)^2; \quad (2)$$

3) multiple linear regression of f_oF2 with two independent variables *F*10.7 and A_p [Bremer et al., 2004], which permits considering the geomagnetic activity effect:

$$f_o\text{F2}_{\text{model}} = A + BF10.7 + CA_p, \quad (3)$$

where *A*, *B*, and *C* are constants.

After calculating $f_o\text{F2}_{\text{model}}$, we find the difference between experimental and model f_oF2 values to eliminate the dependence of f_oF2 variation on solar and geomagnetic activity:

$$\Delta f_o\text{F2} = f_o\text{F2}_{\text{эксп}} - f_o\text{F2}_{\text{модель}}. \quad (4)$$

Next, the trend *T* [kHz/yr] is calculated using linear regression

$$\Delta f_o\text{F2} = D + T \cdot \text{год}, \quad (5)$$

where *D* is a constant.

3. RESULTS AND DISCUSSION

Figure 3 illustrates the dependences of f_oF2 on *F*10.7 and A_p, derived after applying the regression models. Regression functions and coefficients of determination are shown in panels. All the models are seen to give sufficiently high coefficients of determination R^2, which indicates a high statistical significance. Moreover, the largest R^2 values are observed for the multiple regression model that takes into account both solar and geomagnetic activity. Figure 4 displays calculated Δf_oF2 and regression trend lines (*T*). Both at 12 LT and at 00 LT, there is a negative trend for all the models.

However, the obtained trends vary. *T* is the highest in multiple linear regression (–3.595 kHz/yr for 00 LT and –4.097 kHz/yr for 12 LT), which is almost three times higher than in simple linear regression (–1.381 kHz/yr for 00 LT and –1.341 kHz/yr for 12 LT). These differences may be related to the influence of geomagnetic activity; therefore, we have made similar calculations for data with excluded disturbed days, i.e. only for days with daily K_p no more than 24 ($\Sigma K_p \leq 24$). The results are presented in Figure 5 and summarized in Table 1.

The exclusion of magnetically disturbed days generally leads to an increase in the coefficient of determination R^2 and an increase in the absolute trend (Table 1). In this case, the largest R^2 values are observed in quadratic linear regression. Comparing Figures 4 and 5 shows that the calculated trends for linear and quadratic regressions grow almost twofold. So, when taking into account all days for linear regression, *T*=–1.341 kHz/yr at 12 LT (Figure 4, *b*); when excluding disturbed days, *T*=–2.571 kHz/yr (see Figure 5, *b*).

The trends we have calculated agree with the global trends obtained in [Bremer et al., 2012; Mielich, Bremer, 2013], where, using data from 106 and 124 stations, it has been shown that the average global trend in f_oF2 is –1.8 kHz/yr and –3.8 kHz/yr respectively. Alfonsi et al. [2002] have calculated trends for the stations Lycksele (64.6° N, 18.8° E, 62.6 MLAT), Slough (51.5° N, 359.5° E, 54 MLAT), Rome (41.8, 12.5, 42.3 MLAT), and Mawson (67.6° S, 62.9° E, 73.3 MLAT) for ~36 years. For magnetically quiet days (A_p<7 nT), the trends are –2.8 kHz/yr, –2.7 kHz/yr, –6.8 kHz/yr, and –5.5 kHz/yr respectively. Sivakandan et al. [2023] with data from the Juliusruh station (54.6° N, 13.4° E) and the LSP (Lomb-Scargle periodogram) method have computed that trends in f_oF2 during midday and midnight hours are –4.44 kHz/yr and –4.13 kHz/yr respectively. Zherebtsov et al. [2024] have found a negative trend in N_mF2 ~ –0.0049·10^5 cm^{-3}/yr during the day and ~ –0.0026·10^5 cm^{-3}/yr at night at the Irkutsk station (52° N, 104° E), whose longitude is close to the longitude of

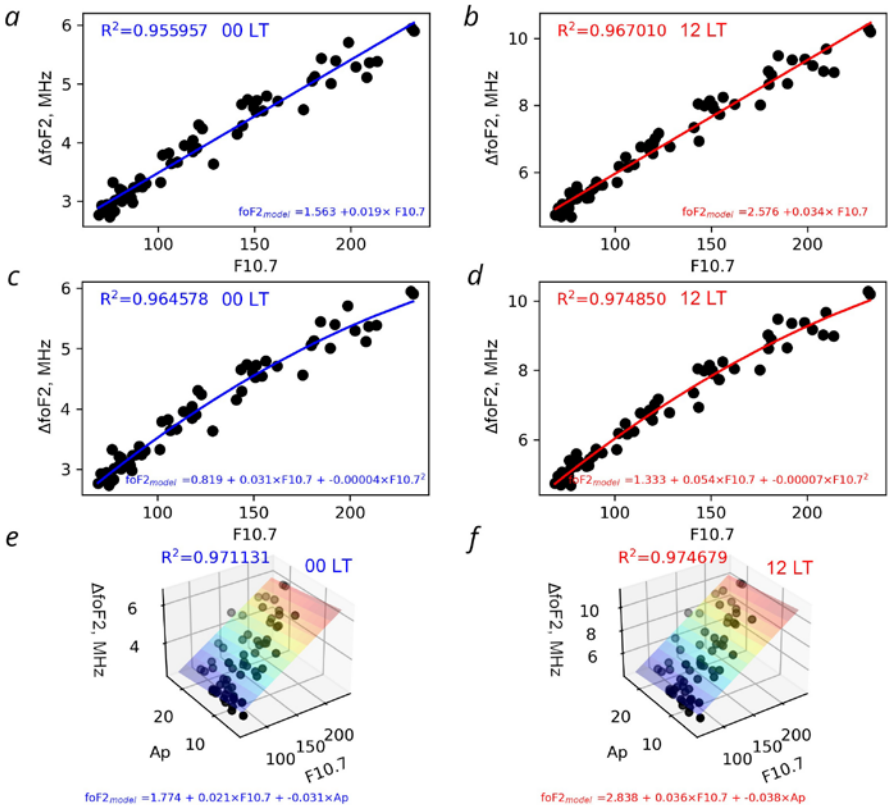

Figure 3. Dependence of the critical frequency f_oF2 for midnight (*a*,*c*, *e*) and midday (*b*,*d*, *f*) hours on the solar activity index *F*10.7 (black dots), as well as on the geomagnetic activity index A_p (*e*, *f*) according to data from the Yakutsk stations for the period 1956–2017; approximation of this dependence by three regression models (solid lines and plane): linear (*a*, *b*); quadratic (*c*, *d*); multiple (*e*, *f*)

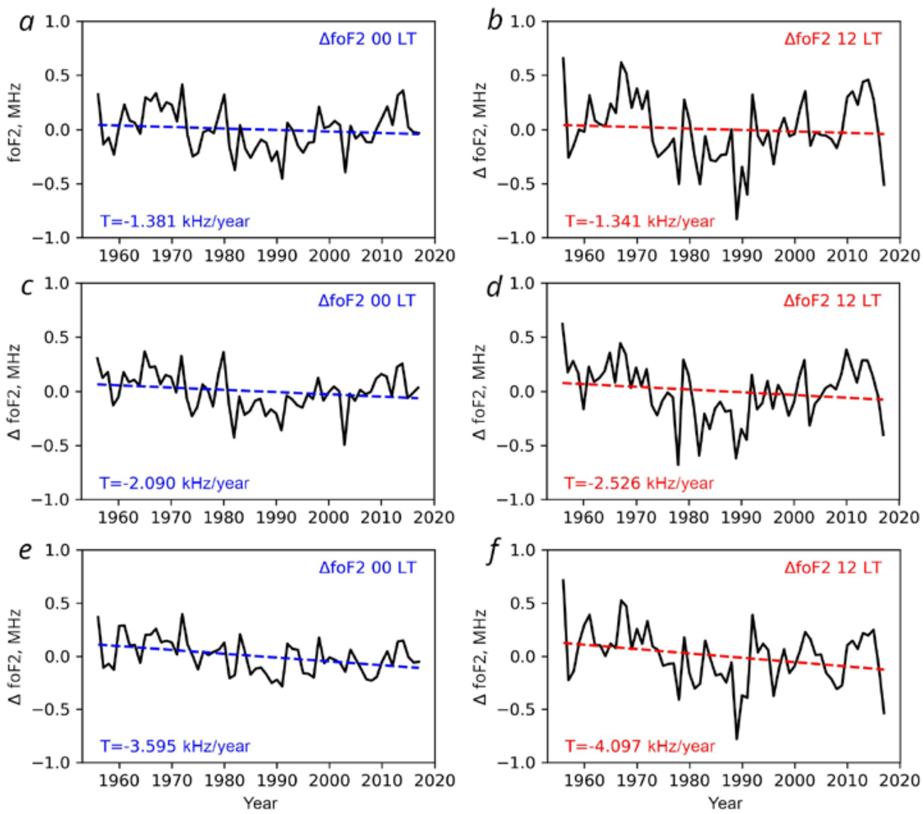

Figure 4. Calculated Δf_oF2 variations (black solid curves) and their linear regressions (dashed lines) from 1956 to 2017 for different regression models of dependence of f_oF2 on solar and geomagnetic activity: linear (*a*, *b*); quadratic (*c*, *d*); multiple (*e*, *f*)

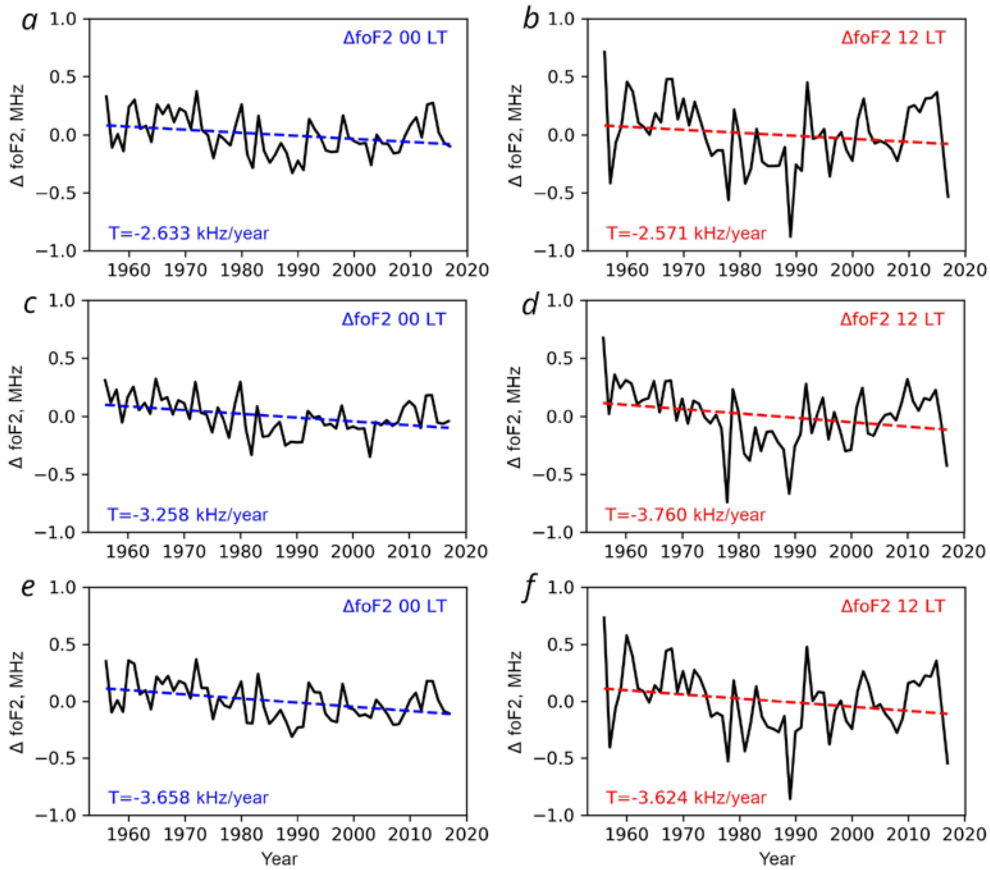

Figure 5. The same as in Figure 4, but for magnetically quiet days (ΣK_p<24)

Table 1

Annual trends in f_oF2 at 00 and 12 LT and coefficients of determination (R^2) for different regression models

Data sample	Model	Trend, kHz/year		Coefficient of determination with model R^2	
		00 LT	12 LT	00 LT	12 LT
All days	Linear model	–1.381	–1.341	0.956	0.967
	Quadratic model	–2.090	–2.526	0.965	0.975
	Multiple model	**–3.595**	**–4.097**	**0.971**	**0.975**
Quiet days ($\Sigma K_p \le 24$)	Linear model	–2.633	–2.571	0.968	0.972
	Quadratic model	**–3.258**	**–3.760**	**0.975**	**0.979**
	Multiple model	–3.566	–3.624	0.971	0.973

the Yakutsk station. Given the quadratic dependence of N_mF2 and f_oF2, these trends are –2.6 kHz/yr during the day and –0.23 kHz/yr at night, which also agrees with our results. Meanwhile, a number of studies [Bremer et al., 2012; Cnossen, Franzke, 2014; Danilov, Mikhailov, 1999] have shown that negative trends in f_oF2 for different stations can be both much lower than –0.2 kHz/yr and much higher than our values and can reach –20÷–30 kHz/yr. These differences may stem from the choice of different time intervals and from different location of stations for analysis, as well as seasonal features (see below).

Note that Zherebtsov et al. [2024] have concluded from the Irkutsk station data that taking geomagnetic activity into account almost does not affect the regression error, which contradicts our results. This may be due to the fact that the Irkutsk station is much more equatorial than the Yakutsk station located in the subauroral zone. Hence there is a need for additional studies involving higher-latitude ionosonde data from the Zhigansk complex geophysical station (66.8° N, 123.4° E) and the Polar Geocosmophysical Observatory (Tixie Bay, 71.5° N, 128.5° E) in order to correctly assess the contribution of geomagnetic activity.

In [Danilov, 2015; Laštovička, 2022], based on data from the mid-latitude stations Slough (51.5° N, 1.3° W), Juliusruh (54.6° N, 13.4° W), and Rome (41.8° N, 12.5°E), it has been established that the trends in f_oF2 depend not only on local time, but also on season. To explore the seasonal dependence of trends, monthly and seasonal trends (winter, spring, summer, and fall) for magnetically quiet days ($\Sigma K_p \le 24$) were calculated using data from the Yakutsk station and different regression models. Seasonal trends are median monthly average values for three months. The results are presented in Figure 6. At 00 LT for all models there is a negative trend (~–7 kHz/yr) in summer and a weak positive trend (~0.5–1.5 kHz/yr) in winter, whereas in February the positive trend grows to ~4 kHz/yr. There are two negative trend peaks at 12 LT: in March and October (to ~–11 kHz/yr). Similar peaks of negative trends during midday hours (10–14 LT) in the equinoctial months were also noticed in [Laštovička et al., 2008b; Danilov, Konstantinova, 2015], which indicates the adequacy of the results. In summer, the trend is ~–4 kHz/yr and it is lower in absolute value than at the equinox. It has also been found that predominantly negative trends are observed in all seasons. At both 00 LT and 12 LT, negative trends are greater in summer and equinoctial months than in winter, which is consistent with the results obtained in [Danilov, 2015]. The small absolute values of trends in winter during midday hours are, however, at variance with [Danilov, 2015], where it has been found that for the Juliusruh station at noon (10–16 LT) the trend in winter (November–February) in 1985–2009 ran to ~–33 kHz/yr, far exceeding that for multiple regression, ~ –2 kHz/yr, in Yakutsk, according to our calculations. This might have been due to the different time intervals chosen for analysis and the differences in the location of the Yakutsk and Juliusruh stations. Thus, at the latitudes of the Yakutsk station there is a seasonal dependence of the trend in f_oF2 both at midday and at midnight. The calculated trends and coefficients of determination for the quadratic regression model are listed in Table 2.

The results of statistical analysis of vertical ionospheric sounding data for the period from 1956 to 2017 from the Yakutsk subauroral station, located at a considerable distance in longitude from other subauroral ionospheric stations, extend the knowledge of long-term trends in ionospheric parameters in the Northern Hemisphere.

CONCLUSION

We have analyzed long-term variations in the critical frequency f_oF2, using data sets from the Yakutsk subauroral station for 62 years including six solar cycles. Our findings allow the following conclusions:

1. The correlation coefficients between annual average F10.7 and f_oF2 during midday and midnight hours reveal a statistically significant relationship between F2-layer critical frequency variations and solar activity.

2. We have found negative trends in F2-layer critical frequencies at midday and midnight for the period from 1956 to 2017. The trends for the full data set were –1.38 kHz/yr, –2.09 kHz/yr, and –3.63 kHz/yr at 00 LT and –1.26 kHz/yr, –2.526 kHz/yr, and –3.71 kHz/yr at 12 LT according to the linear, quadratic, and multiple regression models.

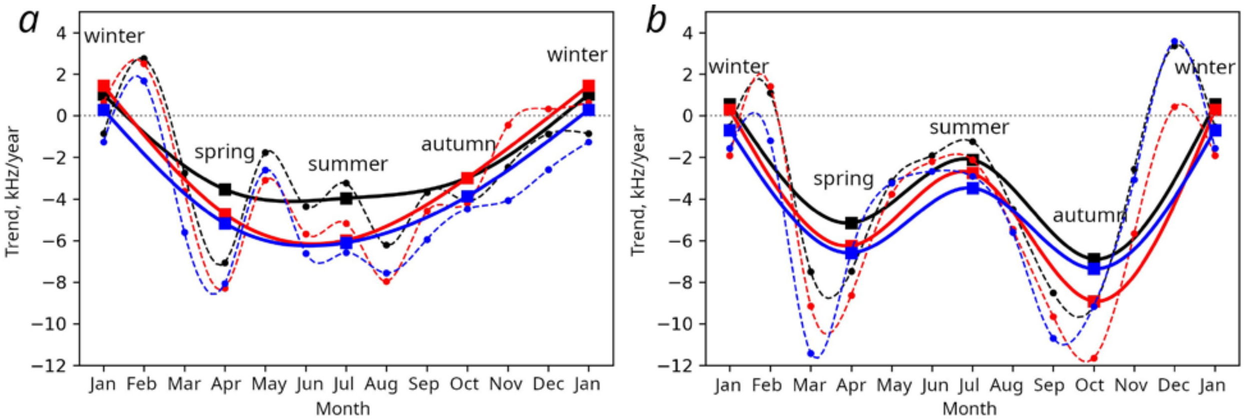

Figure 6. Seasonal variations of trends in f_oF2 at 00 (*a*) and 12 (*b*) LT according to data on magnetically quiet days ($K_p \leq 24$) for different models: linear regression (black), quadratic regression (red), multiple regression (blue). Trend variations in annual average f_oF2 are indicated by solid lines; median monthly, by dashed lines

Table 2

Trends in annual average f_oF2 and coefficients of determination R^2 for the quadratic regression model in different seasons at 00 and 12 LT

Data sample	Season	Trend, kHz/year		Coefficient of determination with model R^2	
		00 LT	12 LT	00 LT	12 LT
All days	winter	1.834	0.720	0.915	0.960
	spring	–1.898	–3.623	0.918	0.918
	summer	–4.872	–1.706	0.907	0.864
	fall	–2.476	–7.874	0.934	0.954
Quiet days ($\Sigma K_p \leq 24$)	winter	1.449	0.291	0.923	0.958
	spring	–4.718	–6.246	0.937	0.936
	summer	–5.980	–2.752	0.930	0.905
	fall	–2.985	–8.911	0.952	0.965

3. Exclusion of magnetically disturbed days from the data set leads to an increase in absolute trends in f_oF2 according to the linear and quadratic models and to a decrease in the difference between trends according to different models, which suggests that geomagnetic activity has an effect on long-term variations in f_oF2 over the Yakutsk subauroral station.

4. Seasonal dependence of the trend in f_oF2 has been found. The smallest absolute trend values are observed in winter. At midnight, the absolute negative trend is larger in summer. During midday hours, negative trends peak in the equinoctial months (September, October, March), reaching –11 kHz/year.

We are grateful to the World Data Center (WDC) in Russia [http://www.wdcb.ru/stp/data/solar.act/flux10.7/] for data on the solar activity index *F*10.7, as well as to the World Data Center for Geomagnetism in Kyoto [https://wdc.kugi.kyoto-u.ac.jp/] for data on geomagnetic activity indices.

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