

VARIATIONS OF IONOSPHERIC PARAMETERS OVER ALMATY (KAZAKHSTAN) IN 1999–2013

S.N. Mukasheva

*Institute of Ionosphere National Centre for Space Research
and Technology,
Almaty, Kazakhstan, snmukasheva@gmail.com*

V.I. Kapytin

*Institute of Ionosphere National Centre for Space Research
and Technology,
Almaty, Kazakhstan, kapytinsanct@mail.ru*

A.M. Malimbayev

*Institute of Ionosphere National Centre for Space Research
and Technology,
Almaty, Kazakhstan, nanozavr@mail.ru*

Abstract. The paper presents the results of a study of the behavior of ionospheric parameters of the total electron content, $I(t)$, and electron density in the maximum F2 layer, N_m , over Almaty (Kazakhstan) [43.25° N; 76.92° E] in 1999–2013. The time interval under study covers different solar activity levels. We have shown that at $F10.7 > 175$ in summer and at $F10.7 > 225$ in winter there is a saturation effect, i.e. with increasing solar activity level values of $I(t)$ do not increase. The observed nonlinear relationship between the total electron content of the ionosphere and the solar radiation flux $F10.7$ results from the nonlinear relationship between the solar ultraviolet radiation and the solar radiation flux.

The study of the variability of the mid-latitude ionosphere parameters during different solar and geomagnetic activity levels has shown that the standard deviation $\sigma(x)$ and average shift x_{ave} of $I(t)$ and N_m fluctuations relative to the quiet level weakly depend on solar activity, but greatly depend on geomagnetic activity when $F10.7 < 100$.

Keywords: total electron content, solar activity, ionosphere.

INTRODUCTION

Radio sounding of the ionosphere by global positioning system signals enables continuous monitoring of Earth's ionosphere [Afraimovich, Perevalova, 2006]. Global Ionospheric Maps (GIM), designed at several research centers (JPLG, US; CODE, Switzerland, etc.), are a powerful modern tool for monitoring and studying the global and local ionospheric structures [Mannucci et al., 1998; Schaer et al., 1998a, b]. These studies are essential for understanding dynamic processes in near-Earth space. They make it possible to understand how external factors, such as solar activity, affect Earth's dynamic structure, in particular near-Earth space. In recent years, the variability of ionospheric parameters depending on solar and geomagnetic activity has been extensively studied [Araujo-Pradere et al., 2005; Mandrikova et al., 2018; Shreedevi et al., 2018; Bolaji et al., 2019]. Spatial variability of the ionosphere depending on season is examined using modern statistical methods, e.g. wavelet analysis [Shi et al., 2014]. Works are underway on modification of solar activity indices in the International Reference Ionosphere (IRI) and IRI extended to the plasmasphere (IRI-Plas) [Gulyaeva, 2016]. To examine the ionospheric electron density variability, a local empirical model of electron density for conditions of low geomagnetic activity, which can be applied to any solar activity level, is proposed [Deminov et al., 2015].

The authors have examined the variability of ionospheric parameters — total electron content $I(t)$ (TEC) and electron density in the maximum F2 layer N_m — over Kazakhstan for a sufficiently long period covering different solar activity levels. Solar activity is characterized by the $F10.7$ index — solar radiation flux at a

wavelength of 10.7 cm. Geomagnetic activity is characterized using the A_p index. The purpose of this work is to identify the relationship between ionospheric parameters and variations of external factors such as solar radiation flux. We report the results of the analysis of variability of ionospheric parameters over Almaty (Kazakhstan) for two local times (midday and midnight), three seasons, low ($F10.7 < 100$) and high ($F10.7 > 170$) solar activity, undisturbed ($A_p < 9$) and disturbed ($A_p > 27$) geomagnetic conditions. The results obtained using modern satellite technologies, designed to work with GPS data on TEC, and also from measurements made at the Almaty vertical sounding station allow us to identify regional features of the mid-latitude ionosphere.

DATA

We have obtained TEC values $I(t)$ from IONEX maps in the GIM node [42.5° N; 75.0° E], closest to the coordinates of Almaty [43.25° N; 76.92° E]. We have used GIM [<ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex>] in IONEX format, calculated by the Center for Orbit Determination (CODE) in Europe, University of Berne, Switzerland from data gathered by more than 150 GPS receiving stations. Each IONEX-dat file contains vertical TEC values per day on the universal time scale (UT) with a temporal resolution of 2 hrs. Vertical TEC is calculated with respect to solar-geomagnetic conditions from spherical harmonic formulas [Afraimovich, Perevalova, 2006]. The universally accepted TEC unit is TECU (total electron content unit), equal to 10^{16} m^{-3} . The behavior of TEC is examined together with N_m variations, measured at the Almaty vertical sounding station [43.25° N; 76.92° E].

RESULTS AND DISCUSSION

Ionospheric parameters versus solar activity level

Consider variations of ionospheric parameters over the period 1999–2013, which covers different solar activity levels: high (1999–2002) when the solar radiation flux at a wavelength of 10.7 cm $F_{10.7} > 150$; moderate, $F_{10.7} = 100 \div 150$ (2003–2004 — the descending phase of solar activity and 2011–2013 — the ascending phase of solar activity and abnormally low solar maximum); low, $F_{10.7} < 100$ (2005–2010 with the deepest solar minimum over the past 100 years). The development of solar cycle 24 and its features are described in [Ishkov, 2012; Bruevich et al., 2018].

Figure 1, *a* shows variations of the daily $F_{10.7}$ index. Information has been obtained from the website of the Space Weather Prediction Center of National Oceanic and Atmospheric Administration (NOAA) [<http://www.swpc.noaa.gov>]. Variations of midday and midnight $I(t)$ for 1999–2013 are shown in Figure 1, *b* and *c* respectively. The solid thick curve indicates the running average with the 81-day time window, constructed to eliminate seasonal variations.

Annual averages of $F_{10.7}$, midday and midnight $I(t)$, and N_m are listed in Table 1. Midday $I(t)$ decreases ~5 times — from 63.1 TECU in solar maximum (1999) to 12.7 TECU in solar minimum (2009).

Midday N_m decreases ~4.3 times — from $175.6 \cdot 10^{10} \text{ m}^{-3}$ in solar maximum (2001) to $40.3 \cdot 10^{10} \text{ m}^{-3}$ in solar minimum (2008). Midnight $I(t)$ decreases ~3 times — from 18.3 TECU in solar maximum (2002) to 6.1 TECU in solar minimum (2008). Midnight N_m decreases ~2.6 times — from $41.7 \cdot 10^{10} \text{ m}^{-3}$ in solar maximum (2000) to $16.1 \cdot 10^{10} \text{ m}^{-3}$ in solar minimum (2008 and 2009).

The midnight values of both TEC and electron density at the maximum F2 layer during the years of solar maximum reach their midday values during the years of solar minimum: (15 ± 3) TECU and $(41 \pm 3) \cdot 10^{10} \text{ m}^{-3}$ respectively.

Regression dependences of midday winter (upper panel) and summer (lower panel) $I(t)$ on solar activity level for 1999–2013 are shown in Figure 2. The regression dependences were obtained from 1201 midday winter values (November, December, January, February) and 1260 midday summer values (May, June, July, August) of $I(t)$ for 1999–2013. When $F_{10.7} > 100$, the midday $I(t)$ in winter is higher than in summer, and this difference increases with increasing solar activity.

There is a positive correlation between midday winter $I(t)$ and solar activity at $F_{10.7} < 225$. The regression dependence can be represented as a linear function $y = b_1 x + b_0$, where $b_1 = 0.315$, $b_0 = -12.172$, a regression coefficient $R_{sq} = 0.85$. When $F_{10.7} > 225$ there is a saturation effect in winter, i.e. with increasing solar activity $I(t)$

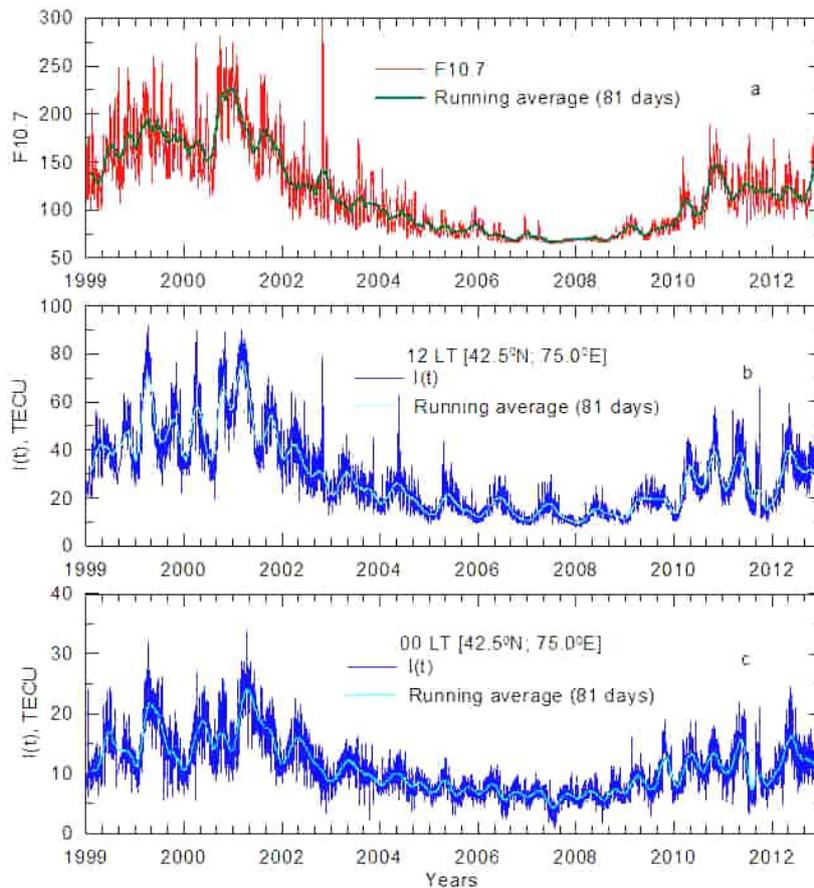


Figure 1. Variations in solar radiation flux at a wavelength of 10.7 cm $F_{10.7}$ (*a*), midday (*b*) and midnight (*c*) TEC values, obtained from IONEX maps in the GIM node [42.5° N; 75° E], for 1999–2013. The solid thick curve is the running average with the 81-day time window

Table 1

Annual average solar activity index $F10.7$, midday and midnight TEC $I(t)$ and electron density in the maximum F2 layer N_m

Years	Annual averages					Solar activity levels
	$F10.7$	$I(t)$, TECU		$N_m \cdot 10^{10} \text{m}^{-3}$		
		12 LT	00 LT	12 LT	00 LT	
1999	153.7	63.1	13.2	131.5	31.0	High $F10.7 > 150$
2000	179.5	50.6	15.9	147.3	41.7	
2001	181.5	50.1	15.4	175.6	29.8	
2002	179.5	56.3	18.3	–	–	
2003	128.8	33.2	12.7	104.9	26.2	Moderate (descending phase of solar activity) $F10.7 = 100 \div 150$
2004	106.5	24.4	10.3	83.4	26.2	
2005	91.7	20.1	8.7	67.9	20.8	Low (years with the deepest solar minimum over the past 100 years) $F10.7 < 100$
2006	80.0	16.1	7.5	54.0	18.9	
2007	73.1	15.2	6.9	47.7	17.0	
2008	69.0	13.2	6.1	40.3	16.1	
2009	70.6	12.7	6.5	41.7	16.1	
2010	80.1	17.9	9.2	57.3	19.8	
2011	113.4	27.9	11.3	83.4	25.1	Moderate (ascending phase and abnormally low solar maximum) $F10.7 = 100 \div 150$
2012	119.9	25.3	10.6	98.2	27.4	
2013	122.8	31.1	12.6	104.9	27.4	

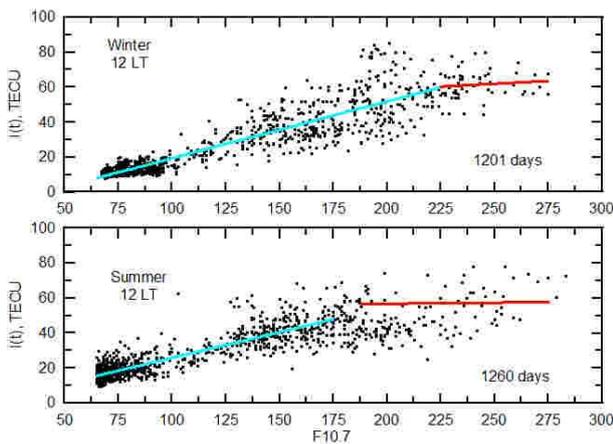


Figure 2. Regression dependence of midday winter (top) and summer (bottom) TEC values on solar activity level

no longer increases: $I(t) = (60 \pm 18)$ TECU. For summer conditions at $F10.7 < 175$, the regression dependence can be represented as a linear function with $b_1 = 0.293$, $b_0 = -3.477$ with a regression coefficient $R_{sq} = 0.80$. The saturation effect occurs in summer when $F10.7 > 175$: $I(t) = (55 \pm 18)$ TECU. We have revealed the tendency for saturation of the ionosphere at high values of $F10.7$ from data on the Faraday effect when receiving signals with a frequency $f = 136.112$ MHz from the geostationary satellite ETS-II for the period from September 1985 to December 1989 at the radio test site Orbita (Almaty, 43.2° N; 76.9° E) [Mukasheva, 1999].

A similar dependence of TEC on the solar radiation flux is discussed in [Balan et al., 1993]; the authors report results of the TEC analysis based on data from five stations in the Northern Hemisphere for the period from December 1980 to December 1985 when the solar radiation flux varied from 66 to 303 units. Balan et al. [1993] note that the observed nonlinear relationship between TEC and $F10.7$ is the result of the nonlinear relationship

between the solar ultraviolet radiation and the solar radiation flux at a wavelength of $\lambda = 10.7$ cm, which is confirmed by model calculations and satellite measurements [Titheridge, 1973; Tobiska, 1991; Shreedevi et al., 2018]. So, according to [Balan et al., 1993], variations of the entire solar ultraviolet radiation range show a linearly increasing relationship with $F10.7$ to $F10.7 < 200$. When $F10.7 > 200$, we can see the following:

- 1) the total solar ultraviolet flux (50–1050 Å) increases very slowly with $F10.7$;
- 2) solar ultraviolet radiation fluxes, which play a significant role in heating the thermosphere, in chromospheric lines He II (303.78 Å) and H Lyman-β (1025.72 Å) and 850–900 Å chromospheric emissions do not change with increasing $F10.7$;
- 3) solar ultraviolet radiation fluxes in the coronal lines Fe XV (284.15 Å) and 300–350 Å coronal emissions even decrease with increasing $F10.7$;
- 4) solar ultraviolet radiation fluxes in the Lyman-α (1216 Å), and He I (10.830 Å) lines measured by the Solar Mesosphere Explorer (SME) during solar cycle 21 also do not change with increasing $F10.7$.

Bruevich et al. [2018] by examining the hysteresis effect (which manifests itself in an ambiguous relationship between solar radiation fluxes during ascending and descending phases of solar activity) also show that daily values of the flux in the Lyman-α line (1216 Å) when $F10.7 > 180-200$ do not increase with $F10.7$.

Variability of the mid-latitude ionosphere at different solar and geomagnetic activity levels

The results of the analysis of variability of the ionospheric parameters $I(t)$ and N_m over Almaty (Kazakhstan) have been obtained for two local times (midday and midnight), three seasons (winter — November, December, January, February, equinox — March, April, September, October, summer — May, June, July,

August), for low ($F10.7 < 100$) and high ($F10.7 > 170$) solar activity; undisturbed ($A_p < 9$) and disturbed ($A_p > 27$) geomagnetic conditions (see Tables 2 and 3). As a background level of $I(t)_0$ and N_{m0} , we have selected mean values at low geomagnetic activity $A_p < 9$ depending on solar activity level ($F10.7 < 100$ and $F10.7 > 170$), time of day (LT=12 and LT=24), and season. The sample length n for $I(t)_0$ if $F10.7 < 100$ and $A_p < 9$ was 520 points for winter, 511 for equinox, 548 for summer; if $F10.7 > 170$ and $A_p < 9$ it was 258 for winter, 177 for equinox, 287 for summer. The length of each sample depending on season and solar activity $n > 450$. The selected averages were utilized to analyze properties of fluctuations of the ionospheric parameters from the

standard deviation $\sigma(x)$ and average shift x_{ave} [Deminov et al., 2015]:

$$x_{ave} = (1/n) \sum_i x_i; \sigma^2(x) = (1/n) \sum_i (x_i - x_{ave})^2.$$

Here, $x_i = (I(t)_i / I(t)_0 - 1) \cdot 100\%$ or

$$x_i = (N_m(i) / N_{m0} - 1) \cdot 100\%,$$

depending on the chosen ionospheric parameter. Σ_i denotes summation over the index i from 1 to n , where n is the number of values of this sample.

The standard deviation $\sigma(x)$ of the ionospheric parameters considered, as seen from Table 2, weakly depends not only on solar activity, but also on season: on average $\sigma(x)$ varies between 27–30 % in all the seasons

Table 2

Standard deviation $\sigma(x)$ and average shift x_{ave} of $I(t)$ and N_m fluctuations relative to the quiet level above the station Almaty in the midday (LT=12) and midnight (LT=24) for three seasons (winter, equinox, summer) at low ($F10.7 < 100$) and high ($F10.7 > 170$) solar activity

Season	LT=12				LT=00			
	$F10.7 < 100$		$F10.7 > 170$		$F10.7 < 100$		$F10.7 > 170$	
	$\sigma(x), \%$	$x_{ave}, \%$						
$I(t)$								
Winter	25.9	4.5	33.9	3.7	24.9	0.2	26.7	4.1
Equinox	29.4	4.2	24.5	0.8	25.7	-0.7	30.4	0.1
Summer	27.8	3.7	22.4	-0.4	32.7	4.8	23.5	-1.0
N_m								
Winter	33.8	5.3	25.3	4.7	29.1	0.9	32.0	5.4
Equinox	31.9	3.3	23.3	-3.1	29.4	1.0	36.1	-2.3
Summer	30.6	4.1	22.8	-0.01	32.4	2.1	23.5	-3.2

Table 3

Standard deviation $\sigma(x)$ and average shift x_{ave} of $I(t)$ and N_m fluctuations relative to the quiet level above the station Almaty in the midday (LT=12) and midnight (LT=24) for three seasons (winter, equinox, summer) under quiet ($A_p < 9$) and disturbed ($A_p > 27$) geomagnetic conditions depending on solar activity level

Season	LT=12				LT=00			
	$A_p < 9$		$A_p > 27$		$A_p < 9$		$A_p > 27$	
	$\sigma(x), \%$	$x_{ave}, \%$						
$I(t), F10.7 < 100$								
Winter	21.7	0.034	46.4	60.0	25.4	0.015	24.6	12.8
Equinox	27.0	-0.001	42.5	38.3	26.5	0.027	23.6	-4.6
Summer	23.9	0.001	60.9	47.9	31.5	0.000	19.6	21.7
$I(t), F10.7 > 170$								
Winter	33.9	0.001	32.7	14.5	24.5	0.015	32.7	13.4
Equinox	22.3	0.001	23.3	1.2	30.2	0.003	26.3	-6.5
Summer	21.1	0.001	28.9	3.0	22.3	0.002	28.9	-4.5
$N_m, F10.7 < 100$								
Winter	29.6	0.007	45.3	37.2	28.0	0.005	24.9	-1.3
Equinox	29.6	0.009	45.8	29.1	28.6	0.003	31.4	10.3
Summer	26.7	0.011	56.4	46.0	31.6	-0.006	35.0	23.8
$N_m, F10.7 > 170$								
Winter	23.5	0.001	28.1	13.2	26.2	-0.008	34.2	13.8
Equinox	19.4	0.002	23.2	-4.4	33.6	-0.008	27.4	-12.3
Summer	21.1	0.004	26.3	0.0	21.7	0.005	24.5	-9.2

at any solar activity level. At any solar activity level and for both midday and midnight values of $I(t)$ and N_m , the condition $\sigma^2(x) \gg x_{ave}^2$ holds.

We can see (Table 3) that in all the seasons in the midday at $F10.7 < 100$ and high geomagnetic activity ($A_p > 27$) the standard deviation $\sigma(x)$ is greater ~1.5–2.5 times than that at low geomagnetic activity ($A_p < 9$).

Since $I(t)_0$ and N_{m0} were calculated for $A_p < 9$ depending on season and solar activity level, it is natural that x_{ave} is close to zero when $A_p < 9$ (see Table 3). At $F10.7 < 100$ and high geomagnetic activity, the condition $x_{ave}^2 \geq \sigma^2(x)$ holds, i.e. the average shift of $I(t)$ and N_m fluctuations relative to the quiet level exceeds the standard deviation of these fluctuations in absolute magnitude. When

$F10.7 > 170$, the variability depending on geomagnetic activity is less pronounced for both midday and midnight values of the standard deviation $\sigma(x)$ of $I(t)$ and N_m . The variability of the ionosphere under quiet conditions is determined by internal atmospheric processes, electron density fluctuations at night determine diffuse ionospheric plasma flows between conjugate ionospheric regions, plasmaspheric fluxes, effects of magnetic substorms, thermospheric wind [Essex, Klobuchar, 1980; Shi et al., 2014; Deminov et al., 2011, 2015; Shreedevi et al., 2018].

CONCLUSION

Using modern GIM technologies and vertical sounding data from the Almaty station [43.25° N; 76.92° E], we have examined the behavior of ionospheric parameters $I(t)$ and N_m for the period from 1999 to 2013 over Kazakhstan. The period of interest covers different levels of solar activity. We have shown that the midday $I(t)$ in winter is higher than in summer if $F10.7 > 100$, and this difference increases with increasing solar activity. There is a positive correlation between midday winter $I(t)$ and $F10.7$ at $F10.7 < 225$. The regression dependence can be expressed as a linear function with the regression coefficient $R_{sq} = 0.85$. When $F10.7 > 175$ in summer and $F10.7 > 225$ in winter there is a saturation effect, i.e. with increasing solar activity level $I(t)$ remains unchanged. The observed nonlinear relationship between the total electron content of the ionosphere and the solar radiation flux at a wavelength of 10.7 cm is the result of the nonlinear relationship between the solar ultraviolet radiation flux and the solar radiation flux, which is confirmed by model calculations and satellite measurements [Titheridge, 1973; Tobiska, 1991; Balan et al., 1993; Shreedevi et al., 2018].

The study of variability of the mid-latitude ionosphere parameters at different solar and geomagnetic activity levels has shown that the standard deviation $\sigma(x)$ and the average shift x_{ave} of $I(t)$ and N_m fluctuations relative to the quiet level over the Almaty station [43.25° N; 76.9° E] weakly depend on solar activity level, and strongly depend on geomagnetic activity. At low solar activity ($F10.7 < 100$) and high geomagnetic activity, x_{ave} is of the same order with $\sigma(x)$. At high solar activity ($F10.7 > 170$) the dependence on geomagnetic activity is less pronounced for midday and midnight values for both $\sigma(x)$ and $I(t)$ and N_m .

There is no principal difference between $I(t)$ and N_m in terms of solar and geomagnetic activity level, TEC variability are largely determined by electron density variability in the maximum F2 layer. The latter allows us to use $I(t)$, derived from GIM, to monitor conditions of the mid-latitude ionosphere to solve problems of reliable operation of satellite navigation and mobile communication systems, which is important for Kazakhstan having an area of 2 725 000 km² and the only vertical sounding station in Almaty.

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