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ELECTRON DENSITY AT F1-LAYER HEIGHTS IN THE LAST SOLAR MINIMUM (2007–2009)

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Abstract. We present the results of the analysis of annual variations in daily electron density (*N*) at heights 140–160 km for the last solar minimum (2007–2009) obtained from digisonde measurements at the ionospheric station Irkutsk (52° N, 104° E). New coefficients of the known semi-empirical model (SEM) describing the connection between *N* and thermospheric characteristics are calculated to identify regularities of these variations. We have revealed that a characteristic feature of the annual *N* variations during the solar minimum is a change in their phase by 180° in a relatively narrow altitude interval (170–180 km). These results and the new SEM coefficients are original and important for atmospheric and ionospheric physics.

Keywords: semi-empirical model of electron density, annual variations, F1-layer heights.

INTRODUCTION

Parameters of the electron density profile *N*(*h*) at F1-layer heights (120–200 km) are rigidly associated with the state of the thermospheric neutral gas [Shchepkin, Klimov, 1980], therefore the electron density *N* at these heights should be controlled not only by the solar zenith angle, but also by concentrations of the main gas particles and their temperatures. At these heights, aeronomy characteristics change rapidly: there are large gradients of the neutral gas temperature and rapid changes in electron and ion temperatures. Features of this height interval are manifested themselves in the formation of the F1 layer, in peculiar time variations of the *N*(*h*) profile, and also in the dependence on solar and geomagnetic activity level. It is convenient to consider such *N* variations using calculations made with the semi-empirical model (SEM) developed by the authors [Shchepkin et al., 1997], which describes the electron density as a function of thermospheric conditions with easily identified seasonal and diurnal variations under different solar and magnetic activity levels.

The purpose of this work is to analyze annual variations in the electron density *N* at F1-layer heights (140–200 km) during the 2007–2009 solar minimum. We examine deviations of calculated *N* values from experimental ones in various months of these years and discuss their possible causes. Note that results of the calculations are valid for the neutral atmosphere model NRLMSISE-00 we adopt [Picone et al., 2002].

MODEL CALCULATIONS

At fixed F1-layer heights, *N* values can be described with the help of analytical relation [Shchepkin et al., 2005, 2007]:

$$N/N_{av}=x_1+x_2([O]/(5[O_2]+[N_2])^{1.5}+$$
$$+x_3([O]/[N_2])^{0.5}\cos(\chi)^{0.5}+ \quad (1)$$
$$+x_4\exp(-(T-600)/600)+x_5(E/E_0).$$

Here, N_{av} determines the average *N* value over the entire volume of data separately for each height, x_j are coefficients of equation (1). Concentrations of neutral particles [O], [O_2], and [N_2] and temperature *T* are calculated with the neutral atmosphere model NRLMSISE-00 [Picone et al., 2002], χ is the solar zenith angle, *E* is the integral intensity of ionizing radiation flux, E_0 corresponds to *E* in solar maximum. *E* values are computed with the model [Tobiska, Eparvier, 1998]. To obtain x_j of equation (1), we take an array of daily hourly values of *N* measured with the Irkutsk digisonde at 120, 130, ..., 190, 200 km in 2003–2009 from 7 to 18 LT. To calculate thermospheric characteristics and *E* values, we use daily *F*10.7 index and its values averaged over 81 days (three rotations of the Sun). The geomagnetic activity level is taken into account using daily 3-hour values of the A_p index [http://wdc.kugi.kyoto-u.ac.jp]. Hence we obtain coefficients of fitted equation (1) for the station Irkutsk at solar minimum, which contribute greatly to the current SEM version (Table 1).

Table 1

Coefficients in fitted equation (1)

h, km	$N_{av}\cdot 10^4 cm^{-3}$	x_1	x_2	x_3	x_4	x_5
120	9.35	–0.1387	–7.245	4.261	0.0000	0.8025
130	10.70	–0.2776	–7.167	4.505	0.1869	0.7202
140	12.47	–0.3066	–6.225	4.458	0.1925	0.6873
150	14.42	–0.3814	–4.803	4.160	0.3468	0.7123
160	16.55	–0.4446	–2.760	3.710	0.4833	0.7606
170	19.24	–0.5073	0.565	3.168	0.5719	0.7501
180	23.06	–0.5759	4.977	2.627	0.5941	0.6790
190	27.95	–0.6901	8.793	2.199	0.5940	0.7681
200	32.92	–0.8756	10.967	1.972	0.6136	1.1206

RESULTS

Typical shapes of calculated annual variations in noon N_{cal} at low and upper levels of the height interval 140–200 km are shown in Figure 1. Annual variations in N_{cal} for three years of the solar minimum (2007–

2009) are presented separately for heights of 150 and 190 km. We can say that the N_{cal} values corresponding to the same height are quite close to each other in all the three years. Maximum values are pronounced at low heights (in particular, at 150 km) in summer; and minimum values, in winter. Such shape of $N_{cal}(D)$ curves (D is the number of day in year) is typical for heights 140–170 km. At 190 and 200 km, maximum N_{cal} values occur generally in winter; and minimum annual variations, in summer.

$N_{cal}(D)$ curves of one type are transformed into curves of another type near 170 km. Near this height, annual N variations change its phase by 180°. Here, the lowest amplitude of annual variations is observed. These changes in the shape of the N_{cal} annual variations are caused by height variations in gas composition occurring against a change in the dependence of ionospheric charged particle neutralization rates on electron density.

Figure 2 shows annual variations (2007) in noon N_{cal} at 150, 170, and 190 km. By comparison, experimental N_{21} values are given at each height, i.e. N_{exp} averaged over 21 days across the entire data set (±10 days centered at a given point). At all the heights there is a good correspondence of the curves describing annual variations of the calculated and experimental N, both in magnitude and in shape. The similarity of the N_{21} variations with the N_{cal} variations lies in the fact that the summer maximum is observed at 150 km, whereas at 190 km N values are much larger in winter than in equinoxes and summer. Similar Figures representing annual variations of N_{cal} in 2008 and 2009 fall into the above pattern.

At 190 and 200 km, the minimum of the $N_{cal}(D)$ curve is stable in July. At the same time, the maximum usually occurs in winter, in November or December.

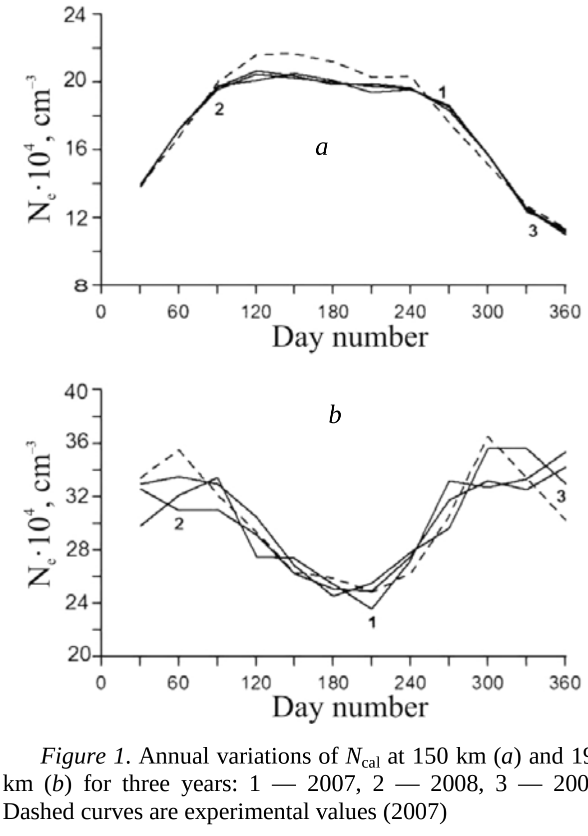

Figure 1. Annual variations of N_{cal} at 150 km (*a*) and 190 km (*b*) for three years: 1 — 2007, 2 — 2008, 3 — 2009. Dashed curves are experimental values (2007)

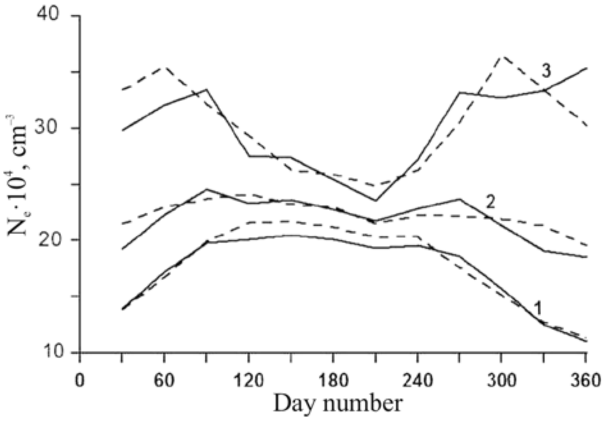

Figure 2. Annual variations in noon N_{cal} calculated in 2007 at 150 km (1), 170 km (2), and 190 km (3). Dashed curves are experimental N_{21} for each height

As derived from calculations, a slight decrease in N_{cal} occurs in December or January. In this case, a double-humped shape of the $N_{cal}(D)$ curve with peaks in March and October–November is typical for the solar minimum. Minimum values of N_{cal} are observed below 190 km in winter. In general, we can speak of a good degree of approximation of most experimental material. By comparison, we present Table of calculated values (daylight hours) N_{cal} and experimental N_{21} (April and June 2007–2009).

Data of Table 2 (a, b) suggest that there is quite reasonable agreement between the experimental and calculated N. Consider deviations of dN (obtained from monthly average N_{cal} by averaging daily values over each LT hour) from experimental values N_{exp}, using the formula

$$dN=(N_{cal}-N_{exp})/N_{exp}.$$

Deviations of dN at 150 and 190 km for some months of 2007 are shown in Table 3 (a, b).

Note the winter (February) excess of N_{cal} over $N_{\mathbf{exp}}$ in forenoon hours at 150 km, and also in morning hours at 190 km. These phenomena can be associated with calculation errors at >70° solar zenith angles and may be related to features of the deviation of gas composition from its model description [Shchepkin et al., 2008]. At low heights 140–160 km, the lack of data can be explained by the fact that at low solar activity with winter minimum N values they become small and unreliable.

CONCLUSION

SEM allows us to examine the behavior of the ionosphere at heights below 200 km, where the photochemical equilibrium condition holds in daytime.

The coefficients of the semi-empirical model regression equation we have obtained in this work correspond to the specific conditions of the last solar minimum (2007–2009) and are an important additional feature of this model. We have used these coefficients to calculate and analyze annual electron density N variations at F1-layer heights at the station Irkutsk.

Table 2, a

N_{cal} and N_{21} at 150 km (N·10^4, cm^{-3})

150 km	April							June					
year	LT	8	10	12	14	16	18	8	10	12	14	16	18
2007	N_{cal}	20	22	23	21	19	15	19	21	21	20	18	16
	N_{21}	14	19	21	19	14	7	15	20	21	21	17	11
2008	N_{cal}	20	22	22	21	19	15	19	21	21	20	18	15
	N_{21}	14	18	19	18	14	6	15	19	20	19	16	11
2009	N_{cal}	20	22	22	21	19	15	19	21	21	20	18	15
	N_{21}	14	19	20	19	14	7	15	20	21	20	17	10

Table 2, b

N_{cal} and N_{21} at 190 km (N·10^4, cm^{-3})

190 km	April							June					
year	LT	8	10	12	14	16	18	8	10	12	14	16	18
2007	N_{cal}	33	35	35	33	31	26	25	27	28	27	25	22
	N_{21}	22	27	31	29	26	18	21	25	27	25	22	19
2008	N_{cal}	33	35	34	33	30	26	25	27	27	27	25	22
	N_{21}	21	24	26	26	24	15	20	25	25	23	20	17
2009	N_{cal}	33	35	35	33	31	26	25	27	28	27	25	22
	N_{21}	22	25	28	27	23	16	22	26	26	24	21	15

Table 3, a

dN (%) in some months of 2007 at 150 km

LT	7	8	9	10	11	12	13	14	15	16	17	18
February	–	0	10	17	15	7	0	0	0	–	–	–
April	0	7	0	0	0	5	0	0	0	7	0	0
June	0	0	–5	–5	–5	–9	–5	–5	–5	–6	0	0
September	0	8	7	0	0	0	0	6	7	18	0	–
December	–	–	–	0	0	9	8	0	–	–	–	–

Table 3, b

dN (%) in some months of 2007 at 190 km

LT	7	8	9	10	11	12	13	14	15	16	17	18
February	60	19	0	0	3	3	3	0	7	5	–6	50
April	0	4	8	3	0	0	3	3	0	0	0	0
June	–10	0	-8	0	0	–3	4	0	4	0	0	5
September	0	4	0	4	3	0	3	0	–4	4	5	30
December	–	–	7	3	6	0	3	3	9	–	–	–

The most characteristic feature of the electron density variations during this period is a change in the phase of annual variations by 180° in a relatively narrow height interval (170–180 km) with the lowest annual variations of daytime *N*.

Further work with the accumulated experimental data will allow us to develop a more complete version of SEM for different solar activity levels. Such a model is important in particular for the estimation of thermospheric gas composition at F1-layer heights from ionospheric measurements.

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