THE ROLE OF THE THERMOSPHERIC WIND IN THE FORMATION OF THE SPATIAL STRUCTURE OF THE HIGH-LATITUDE F LAYER

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Abstract. The improved version of the mathematical model of the convecting high-latitude ionosphere, which includes both polar latitudes and subauroral ones, is applied to investigate how the horizontal thermospheric wind affects the spatial structure of the high-latitude F region. The applied model produces three-dimensional distributions of the electron density, positive ion velocity, electron and ion temperatures at the F-layer altitudes. Spatial distributions of zonal and meridional components of the neutral wind are the input parameters of the model. Simulations are performed for two distinct distributions of the neutral wind. The calculations are made for two seasons: equinox and summer. The results indicate that neutral wind distinctions ought to influence appreciably the spatial structure of the high-latitude ionosphere, in particular, on the heat regime of the F layer.

Introduction

It is generally understood now that the horizontal thermospheric wind arises due to irregular atmosphere heating by the solar radiation. The global neutral wind system at the F-layer altitudes contains mainly a motion of the neutral gas from the dayside, where the pressure is increased, to the nightside, where the pressure is dropped. On the other hand, the charged particles of the F-region ionosphere are strongly magnetized and may be considered to be attached to the magnetic field lines. The ionosphere plasma drift in the direction perpendicular to the magnetic field $\mathbf{B}$ is strongly affected by the electric field $\mathbf{E}$. It is known that the F-layer ionosphere plasma transport perpendicular to magnetic field lines follows $\mathbf{E} \times \mathbf{B}$ convection paths. The convection electric field is known to achieve considerable values at high latitudes. Thus, the flow situation, where differences between the neutral gas velocity and the ionosphere plasma drift velocity are not small in comparison with the species thermal speeds, is typical for the high-latitude upper atmosphere.

As a consequence of large drift velocity differences between neutral and ionized gases, achieved some hundreds m/s, frictional heating can rise in the F-region ionosphere due to elastic collisions between neutral particles and ions. It should be emphasized that frictional heating of ionospheric plasma can be produced by both neutral winds and electric fields. The effects of neutral winds on the temperature altitude profiles of the ionospheric plasma at one point of the earth's surface have been investigated by using mathematical models [*Stubbe and Chandra*, 1971; *Mingalev and Mingaleva*, 1982; *Mingaleva and Mingalev*, 1983]. It is of interest also to investigate how neutral winds affect the spatial distributions of charged particle temperatures in the whole high-latitude F-layer ionosphere. The purpose of this paper is to study the effect of neutral winds on the formation of the spatial structure of the high-latitude ionosphere, in particular, the electron and ion temperature distributions.

The mathematical model

Recently, we have developed the improved version of the mathematical model of the convecting high-latitude ionosphere [*Mingaleva and Mingalev*, 1998]. The improved version of the model is the generalization of the mathematical model of the convecting polar ionosphere developed earlier by *Mingalev et al.* [1988]. The primary improvement of the model consists in the model having acquired the capability to produce three-dimensional distributions of ionospheric quantities at the F-layer altitudes both at polar latitudes and at subauroral ones.

Our model produces three-dimensional distributions of the electron density, positive ion velocity, and ion and electron temperatures. It encompasses the ionosphere above 36^o magnetic latitude and at distances between 100 and 700 km from the earth along the magnetic field line for one complete day. In the model calculations a field tube of plasma is traced as it moves along a convection trajectory through the moving neutral atmosphere. The profiles against distance from the earth along the geomagnetic field line of ionospheric quantities are obtained by solving the appropriate system of transport equations of ionospheric plasma. By tracing many field tubes of plasma, we can construct three-dimensional steady distributions of ionospheric quantities.

The system of transport equations of ionospheric plasma in the reference frame convecting together with a field tube of plasma, whose axis h is directed upwards along the magnetic field line, may be written as follows:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial h}(N V_i) = q + q_e + q_p - l \,, \tag{1}$$

$$m_i N \left(\frac{\partial V_i}{\partial t} + V_i \frac{\partial V_i}{\partial h} \right) - \frac{4}{3} \frac{\partial}{\partial h} \left(\mu \frac{\partial V_i}{\partial h} \right) + \frac{\partial}{\partial h} \Big[N k \, (T_i + T_e) \Big] + m_i N g \sin I = m_i N \sum_{n=1}^{3} \frac{1}{\tau_{in}} (U_n - V_i) \,, \tag{2}$$

$$\frac{\partial T_i}{\partial t} = \frac{1}{M} \frac{\partial}{\partial h} \left(\lambda_i \frac{\partial T_i}{\partial h} \right) - V_i \frac{\partial T_i}{\partial h} + \frac{\gamma - 1}{N} \left(\frac{\partial N}{\partial t} + V_i \frac{\partial N}{\partial h} \right) T_i + \frac{1}{M} \left(P_{ie} + \sum_{n=1}^{3} P_{in} \right) \,, \tag{3}$$

$$\frac{\partial T_e}{\partial t} = \frac{1}{M}\frac{\partial}{\partial h}\left(\lambda_e \frac{\partial T_e}{\partial h}\right) - V_e \frac{\partial T_e}{\partial h} + \frac{\gamma - 1}{N}\left(\frac{\partial N}{\partial t} + V_e \frac{\partial N}{\partial h}\right) T_e$$
$$+ \frac{1}{M}\left(P_{ei} + \sum_{n=1}^{3} P_{en} + Q + Q_e + Q_p - L_r - L_v - L_e - L_f\right), \quad (4)$$

where N is the O^+ ion number density (which is assumed to be equal to the electron concentration at the F-layer altitudes); V_i is the parallel (to the magnetic field) component of the positive ion velocity; q is the photoionization rate; q_e is the production rate due to auroral electron bombardment; q_p is the production rate due to auroral proton bombardment; l is the positive ion loss rate (taking into account the chemical reactions $O^+ + O_2 \rightarrow O_2^+ + O$, $O^+ + N_2 \rightarrow NO^+ + N$, $O_2^+ + e \rightarrow O + O$, and $NO^+ + e \rightarrow N + O$); m_i is the positive ion mass; k is Boltzmann's constant; T_i and T_e are the ion and electron temperatures, respectively; q is the acceleration due to gravity; I is the magnetic field dip angle; $1/\tau_{in}$ is the collision frequency between ion and neutral particles of type n; U_n is the parallel component of velocity of neutral particles of type n; $M = \frac{3}{2} k N$; $\gamma = \frac{5}{3}$; V_e is the parallel component of electron velocity (which is determined from the equation for parallel current); μ is the ion viscosity coefficient; λ_i and λ_e are the ion and electron thermal conductivity coefficients, respectively; Q, Q_e and Q_p are the electron heat rates due to photoionization, auroral electron bombardment and auroral proton bombardment, respectively; L_r, L_v, L_e and L_f are the electron cooling rates due to rotational excitation of molecules O_2 and N_2, vibrational excitation of molecules O_2 and N_2, electronic excitation of atoms O, and fine structure excitation of atoms O, respectively. The quantities on the right-hand sides of equations (3) and (4), denoted by $P_{\alpha\beta}$, describe the type α particles energy change rates as a result of elastic collisions with particles of type β, with large drift velocity differences having been taken into account. Thus, the quantities $P_{\alpha\beta}$ contain frictional heating produced by thermospheric winds. To calculate spatial distributions of ionospheric quantities by using our mathematical model, several input parameters must be given, including a neutral atmosphere, soft electron and proton precipitation characteristics, plasma convection pattern and so forth. In particular, spatial distributions of zonal and meridional components of the neutral wind must be given, which are the input parameters too. The vertical component of the neutral wind is assumed to be zero.

The neutral atmosphere composition, expressions for the quantities, that appear in the system (1)–(4), some of the input parameters of the model, numerical method, boundary conditions, and other details were taken from our previous models [*Mingalev et al.*, 1988; *Mingaleva and Mingalev,* 1996].

Ionospheric simulation

The convection electric field is the important input parameter of the model. The results of calculations to be presented in this paper were obtained by using the plasma convection model which is the combination of the pattern A of the empirical convection models at polar latitudes of *Heppner* [1977] and the empirical model of ionospheric electric fields at middle latitudes, developed by *Richmond* [1976] and *Richmond et al.* [1980]. Our model can describe different combinations of the geomagnetic activity level, solar cycle and seasons. For this study, the calculations were performed for low geomagnetic activity ($K_p = 2$) and middle solar activity ($F_{10.7} = 150$) conditions, and for two distinct days: March 24 (equinox) and July 15 (summer).

To evaluate the role of the neutral wind in the formation of the spatial structure of the high-latitude ionosphere, we made calculation for two distinct cases in which the distributions of zonal and meridional components of the thermospheric wind were different. The first case corresponds to the flow situation where zonal and meridional components of the neutral wind are assumed to be zero at all points of the three-dimensional region under consideration, that is the thermospheric wind is assumed to be missing. The second case corresponds to the flow situation, in which the thermospheric wind is present.

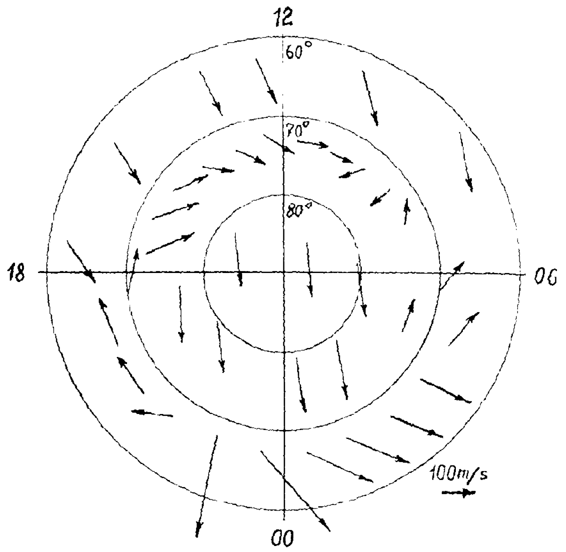

Fig. 1. The horizontal distribution of the neutral wind at 300 km. From *Meriwether et al.* [1973].

For the second case, spatial distributions of zonal and meridional components of the neutral wind are defined as follows. The thermospheric wind pattern is assumed to be a combination of theoretical and empirical models.

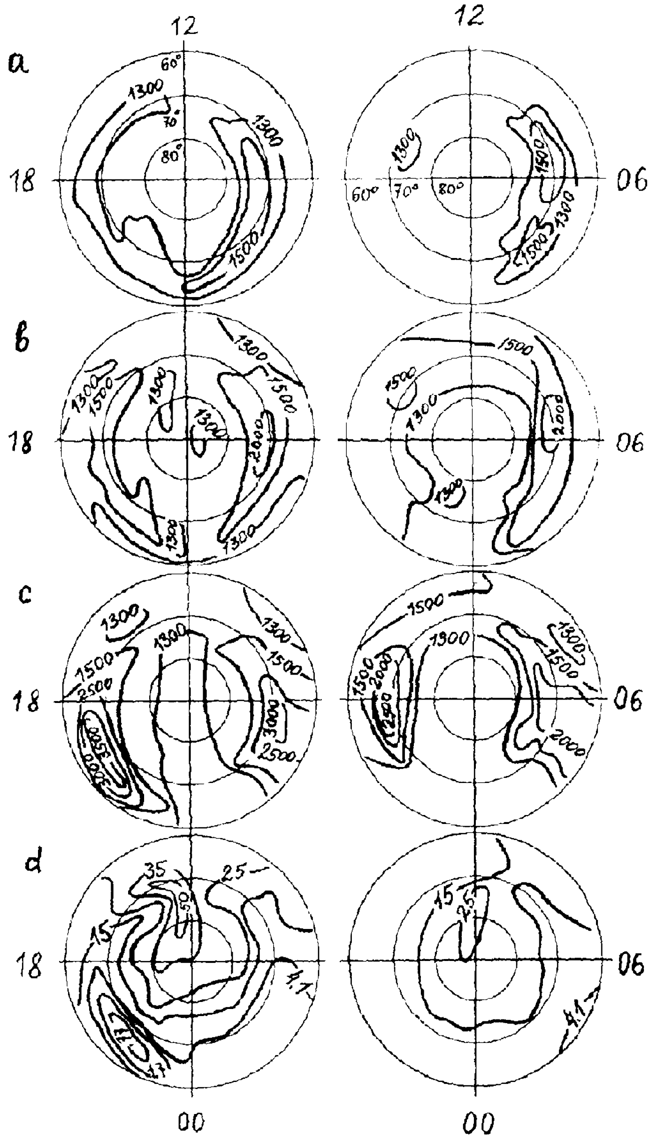

Fig. 2. The simulated distributions of ionospheric quantities in the absence (*left*) and presence (*right*) of the neutral wind: **a** T_i (in ^{o}K) at level $h = 300\,$km; **b** T_i (in ^{o}K) at level $h = 600\,$km; **c** T_e (in ^{o}K) at level $h = 300\,$km; **d** N (in units of $10^4\,\mathrm{cm}^{-3}$) at level $h = 600\,$km; the results are given for equinox.

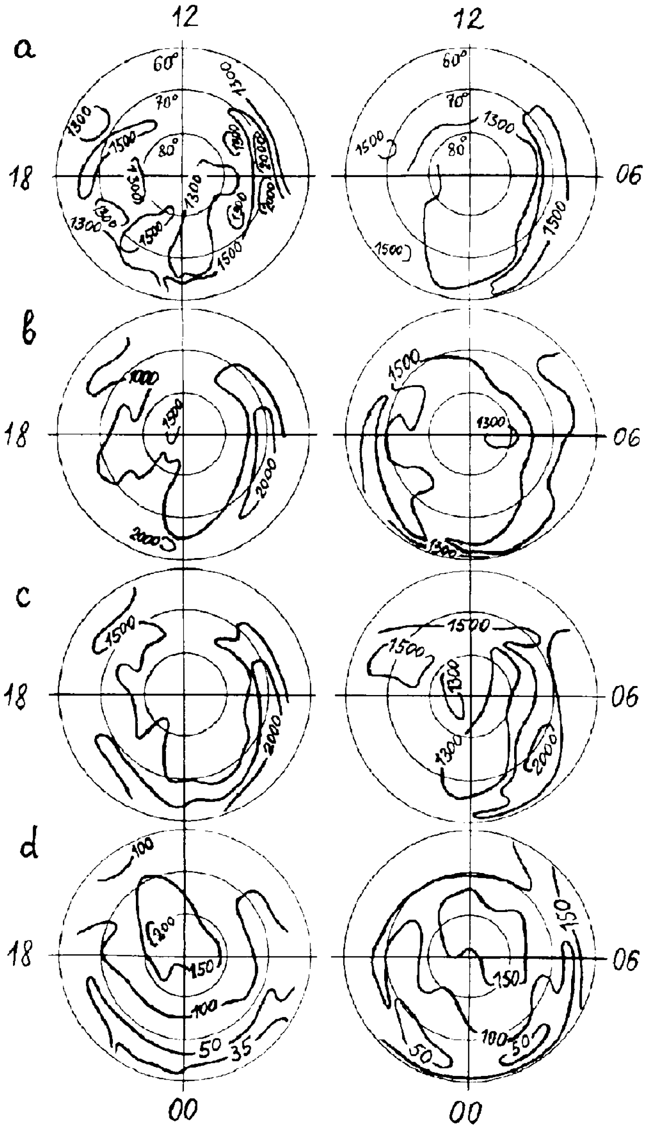

Fig. 3. The simulated distributions of ionospheric quantities in the absence (*left*) and presence (*right*) of the neutral wind: **a** T_i (in ^{o}K) at level $h = 300\,$km; **b** T_i (in ^{o}K) at level $h = 600\,$km; **c** T_e (in ^{o}K) at level $h = 300\,$km; **d** N (in units of $10^4\,\mathrm{cm}^{-3}$) at level $h = 300\,$km; the results are given for summer.

Altitudinal dependencies of zonal and meridional components of the neutral wind are derived from model simulations performed by *Mingalev* [1979]. These dependencies are approximated by analytical expressions which contain the magnitudes of zonal and meridional components of the neutral wind at fixed altitude. The latter two magnitudes as functions of latitude and longitude are taken from the empirical model of the neutral wind. The empirical, horizontal distribution of the neutral wind at 300 km used here is due to *Meriwether et al.* [1973]. This distribution is shown in Fig. 1.

The results of simulation of the spatial structure of the high-latitude F region, obtained for two distinct distributions of the neutral wind, described above, are shown in Figs. 2 and 3. The computed distributions of ionospheric quantities illustrate both common characteristic features of the high-latitude ionosphere and distinctions caused by the neutral wind. One of the prominent peculiarities of the high-latitude ionosphere is the existence of regions of increased ion temperature in morning and evening sectors. These ion temperature hot spots are originated from frictional heating of ionospheric plasma produced mainly by enhanced convection electric fields in the down and dusk sectors. From Figs. 2 and 3 we can see that the formation of the ion temperature hot spots is influenced by neutral winds too. The values of the ion temperature, calculated on condition of the absence of thermospheric wind, can differ from values of T_i, computed on condition of the presence of thermospheric wind, for more than $500\,^o$K. It can be seen that the effect of the neutral wind on the formation of ion temperature distributions must be greater in summer than in equinox.

The remarkable feature of the high-latitude ionosphere is the existence of electron temperature hot spots in the main ionospheric trough. The physical mechanism responsible for the formation of the electron temperature peaks in the dawn and dusk sectors of the main ionospheric trough, presented in Figs. 2c and 3c, was identified by *Mingaleva and Mingalev* [1996]. We can see from results presented that the thermospheric wind can affect the electron temperature hot spots formation. Inside of hot spots, maximum values of electron temperature,computed on condition that the neutral wind is absent, can differ from the maximum values of T_e, calculated under condition that the neutral wind is present, for more than $1000\,^o$K. It turns out that the effect of the thermospheric wind on the formation of electron temperature distributions must be more essential in equinox than in summer.

From simulation results presented, we can see that the electron concentration distributions, calculated under condition that the thermospheric wind is absent, can differ appreciably from the distributions of N, computed on condition that the thermospheric wind is present. In particular, conspicuous differences may take place in the main ionospheric trough. As it can be seen from Figs 2 and 3, the effect of neutral wind on the formation of electron concentration distributions must be more considerable in equinox than in summer.

Conclusions

The improved version of the mathematical model of the convecting high-latitude ionosphere, which enables us to calculate three-dimensional distributions of the electron density, positive ion velocity, electron and ion temperatures at the F-layer altitudes, was applied to investigate how the horizontal thermospheric wind affects the spatial structure of the high-latitude F region. The calculations were made for two seasons: equinox and summer. The simulation results indicated that the distributions of ionospheric quantities, calculated on condition that the thermospheric wind is absent, ought to differ appreciably from the ionospheric quantities distributions, computed on condition that the thermospheric wind is present. The differences of the ion temperatures can achieve values of more than $500\,^o$K in the F-region ionosphere. The differences of the electron temperatures may acquire the values of more than $1000\,^o$K at F-layer altitudes. The effect of the neutral wind on the formation of electron temperature and concentration distributions must be more essential in equinox than in summer. On the contrary, the role of the neutral wind in the formation of ion temperature distributions must be more conspicuous in summer than in equinox.

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