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The Importance of Electric Field in Formation of Sporadic E (Es) at the Equatorial Region

Giorgi T. Dalakishvili, Goderdzi G. Didebulidze, Maya M. Todua, Lekso A. Toriashvili

Ilia State University, Space Research Center, G. Tsereteli str.3a, 0162 Tbilisi, Georgia.
didebulidze@iliauni.edu.ge

ABSTRACT

It has been shown analytically and by appropriate numerical methods that the formation and localization of sporadic E (Es) in the equatorial area can be determined by the height profiles of the ion vertical drift velocity and its divergence. In this case, the existence of a minimum negative value (maximum convergence rate) in the divergence profile, when ions converge vertically into the Es layer, is significantly determined by both the neutral wind velocity and the zonal and vertical components of the electric field.

In the equatorial region, with a constant westward electric field, the maximum vertical convergence rate of ions is in the region of the height where the ion-neutral collisional (ν_{in}) and ion cyclotron (Ω_i) frequencies are equal. In case of the constant upwards or downwards electric field, this rate is located at approximately 0.9H (where H is a neutral scale) above or below the region where $\nu_{in} = \Omega_i$, respectively. The vertical convergence of the ions developed in these regions and the formation of the Es layer can take place against the background of their upward or downward drift. It localizis in the node of this drift velocity, or in the regions where this velocity disappears. Such predicted formation and behavior of Es layers are demonstrated by numerical methods.

The effect of the zonal and vertical components of the electric field, as well as the wind velocity determined by the HWM14 data, on the processes of ion convergence/divergence development is shown. In these cases, the ion convergence/divergence process induced by the electric field can affect both the formation and disruption (depletion) of the Es layer formed by neutral wind, as well as can also form an additional layer.

Key words: *lower thermosphere, electric field, sporadic E (Es), ion vertical drift velocity, numerical methods.*

1. Introduction

Sporadic E(Es) are observed in the lower thermosphere of globe including the equatorial regions [1, 2]. The Es layers observed in equatorial regions are not always localized in the region of zonal neutral wind polarization change [3-5], as defined by the windshear theory [6-9]. This indicates that there is an additional mechanism of convergence of ions in the Es type layer in the equatorial region, which can be caused by the presence of an electric field [3, 10].

The vertical ion drift (EB drift) caused by the electric field of equatorial electrojet origin [11, 12] penetrate the equatorial ionosphere E and F regions is important for studying the behavior of ions/electrons in these regions of the ionosphere. Therefore, the electric field can influence the formation and localization of Es layers in the lower thermosphere [13, 14].

The presented studies will show that the electric field in the equatorial lower thermosphere can cause the existence of a minimum negative value in the divergence of ions vertical drift velocity necessary to develop ions vertical convergence [13, 14]. This condition can be fulfilled even when the electric field is constant and leads to the development of the process of vertical convergence of ion/electrons into a narrow layer (convergence instability) and thus the formation of a high density Es layer is possible [15, 16].

By theoretical and appropriate numerical methods, the formation and localization of Es layers in the height regions of about 90-150 km of the equatorial lower thermosphere will be shown. Along with the electric field, the presence of the neutral wind will be considered. The horizontal wind is determined by the HWM14 data [17, 18].

2. Theoretical background of sporadic E(Es) formation at the equatorial region.

The condition of ion vertical convergence into narrow thin layer and formation Es layer can be obtain by solving the continuity equation of ions in the analytical approach, which $N_i(z,t)$ in analogy Dalakishvili et al. [13] and Didebulidze et al. [15] has the following form:

$$N_i(z,t) \approx N_{om} \exp\left\{-\left(\frac{2D}{H_{ic}^2} + div\mathbf{w}_{i\mathrm{v}}\right)(t-t_o) - \left(\frac{z-[z_{om}+\mathrm{w}_{i\mathrm{v}}(t-t_o)]}{H_{ic}}\right)^2\right\} \quad (1)$$

Here the small variations of ions drift velocity $\mathbf{w}_{i\mathrm{v}}(0,0,\mathrm{w}_{i\mathrm{v}})$ and its vertical changes $\partial \mathrm{w}_{i\mathrm{v}}/\partial z$ during time $t-t_o << H_{ic}^2/2D$ are assumed. H_{ic} is the characteristic scale height of ions which at some initial time $t=t_o$ determines the main ion/electron layer thickness ($2H_{ic}$) and the height region $z-z_{om}=\pm H_{ic}$, where their density decreases e-times. $H_{ic}^2/2D$ is the characteristic time of the ion density decrease by their diffusion ($\propto D$).

Equation (1) of ion/electron $N_e(z,t)$ density (assuming quasineutrality $N_i = N_e$) describes the evolution of their Gaussian type distribution, which at the initial time $t=t_o$, has maximal density (peak density) N_{om} at height $z=z_{om}$ (initial peak height). The value of $(div\mathbf{w}_{i\mathrm{v}})\min<0$ (or $(-div\mathbf{w}_{i\mathrm{v}})\max>0$) is characteristic to ion/electron density increase rate and the value of $(div\mathbf{w}_{i\mathrm{v}})\max>0$ to its depletion rate.

In analogy with Dalakishvili et al. [13] and Didebulidze et al. [15], when occurs the conditions:

$$(div\mathbf{w}_{i\mathrm{v}})\min < -\frac{2D}{H_{ic}^2} \quad (2)$$

then the equation (1) shows a tendency of formation of high density Es type layer of ion/electron ($\frac{N_m(t>t_o)}{N_{om}}>1$). The peak height of this layer $z=z_{om}+\mathrm{w}_{i\mathrm{v}}(t-t_o)$ moves upward ($\mathrm{w}_{i\mathrm{v}}>0$) or downward ($\mathrm{w}_{i\mathrm{v}}<0$) by ions vertical drift velocity $\mathrm{w}_{i\mathrm{v}}$ and it could be localized at the height region with $\mathrm{w}_{i\mathrm{v}}=0$ or $\mathrm{w}_{i\mathrm{v}}\to 0$. According to the equation (2), at the region with maximal ion vertical drift velocity divergence $(div\mathbf{w}_{i\mathrm{v}})\max>0$ the ion/electron density depletion ($\frac{N_m(t>t_o)}{N_{om}}<1$) occurs.

We take a right-handed set of coordinates (*x, y, z*) with *x* directed to the magnetic north, y to the west and *z* vertically upward.

The effect of electric field $\mathbf{E}(E_x,E_y,E_z)$ and neutral wind velocity $\mathbf{V}_n(V_{xn},V_{yn},V_{zn})$ on ions motion is included in its vertical drift velocity $\mathrm{w}_{i\mathrm{v}}$, which at equatorial region (with *I*=0 and $E_x=0$), have the following form [13, 19]:

$$\mathrm{w}_i = \mathrm{w}_{i\mathrm{v}} - \frac{D_i}{N_i}\frac{\partial N_i}{\partial z}, \quad (3)$$

where

$$\mathrm{w}_{i\mathrm{v}} = -C_{\mathrm{v}} \frac{E_y}{B} - C_h \left(\mathrm{V}_y - \frac{E_z}{B} \right) \tag{4}$$

$$C_{\mathrm{v}} = \frac{1}{\kappa^2 + 1} \quad , \tag{5}$$

$$C_h = \frac{\kappa}{\kappa^2 + 1} \quad , \tag{6}$$

$$D_i = \frac{\kappa^2}{\kappa^2 + 1} \frac{k_B T_i}{m_i \nu_{in}} . \tag{7}$$

The quation (3) in case of absence of ions diffusion is the same as given by Abdu et al. [19]. This equation shows an importance of electric field zonal (E_y) and vertical (E_z) components in addition with zonal neutral wind (V_y) in ions vertical drift velocity. Here we assume that the ions diffusion also can influence on ions vertical drift and their layered structure in the lower thermosphere.

An analogy between the vertical drift velocities of ions at equatorial (I=0) and mid-latitudes (e.g., I>30$^{\mathrm{o}}$) described by equation (1) [13] shows that the conditions of their into Es-type layer vertical convergence $(-div\mathbf{w}_{i\mathrm{v}})\max > 0$ or initial layer divergence/desruption $(div\mathbf{w}_{i\mathrm{v}})\max > 0$ in accordance with equations (3-7) can be described by the following equation:

$$-div\mathbf{w}_{i\mathrm{v}} = C_{\mathrm{v}} \frac{1}{B} \frac{\partial E_y}{\partial z} + C_{\mathrm{v}}^{'} \frac{E_y}{B} + C_h \left(\frac{\partial V_y}{\partial z} - \frac{1}{B} \frac{\partial E_z}{\partial z} \right) + C_h^{'} \left(V_y - \frac{E_z}{B} \right) \quad , \tag{8}$$

where

$$C_{\mathrm{v}}^{'} = \frac{\partial C_{\mathrm{v}}}{\partial z} , \tag{9}$$

$$C_h^{'} = \frac{\partial C_h}{\partial z} . \tag{10}$$

Equation (8) shows that both in the equatorial area and at mid-latitudes [13,15] the conditions of vertical convergence ($(-div\mathbf{w}_{i\mathrm{v}})\max > 0$) and divergence ($(div\mathbf{w}_{i\mathrm{v}})\max > 0$) of ions are significantly determined by the height profiles of $C_{\mathrm{v}}(z)$ and $C_h(z)$ factors, equations (5) and (6), and their vertical change $C_{\mathrm{v}o}^{'}(z)$ and $C_{ho}^{'}(z)$, equations (9) and (10).

Thus, the factors $C_{\mathrm{v}0}(z)$, $C_{h0}(z)$, $C_{\mathrm{v}o}^{'}(z)$ and $C_{ho}^{'}(z)$ are important for studying the influence of the zonal wind velocity V_y, electric field (E_y, E_z) magnitude and direction, as well as their vertical change ($\frac{\partial V_y}{\partial z}$, $\frac{\partial E_y}{\partial z}$, $\frac{\partial E_z}{\partial z}$), on the process of convergence of ions/electrons into an Es-type layer in the equatorial region, equation (4). It is somewhat similar to studying the influence of the magnitude, direction and their vertical shear ($\frac{\partial V_x}{\partial z}$, $\frac{\partial V_y}{\partial z}$) of meridional V_x and zonal wind velocity V_y at mid-latitudes with factors $\sin I \cos I \cdot C_{\mathrm{v}}$, $\cos I \cdot C_h$, $\sin I \cos I \cdot C_{\mathrm{v}}^{'}$ and $\cos I \cdot C_h^{'}$ on the vertical convergence of ions/electrons into an Es-type layer [13, 15].

In Fig. 1 the height profiles of ion convergence/divergence rate $(-div\mathbf{w}_{i\mathrm{v}})\max > 0$ factors a) $C_{\mathrm{v}}(z)$ and $C_h(z)$, b) $C_{\mathrm{v}}^{'}(z)$ and $C_h^{'}(z)$ at equatorial regions (I=0), are given.

Fig. 1 shows that the factor $C'_{\mathrm{v}}(z)$ has a maximum value at an altitude of about 121 km, which corresponds to the region at equatorial and mid-latitudes, where $\kappa = 1$ ie $\nu_{in} = \Omega_i$. In the absence of equatorial zonal wind and vertical electric field ($\mathrm{V}_y = 0$, $E_z = 0$) in this height region, the condition $(div\mathrm{w}_{i\mathrm{v}})\min = (\frac{\partial \mathrm{w}_{i\mathrm{v}}}{\partial z})\min < 0$ of vertical convergence of ions occurs for the westward constant electric field ($E_y = constant > 0$), and the condition $(div\,\mathrm{w}_{i\mathrm{v}})\max = (\frac{\partial\,\mathrm{w}_{i\mathrm{v}}}{\partial z})\max > 0$ of their divergence takes place for the eastward electric field ($E_y < 0$), see equation (9) . In these cases, the formation of the Es layer and the depletion of ions are expected respectively, see equation (2).

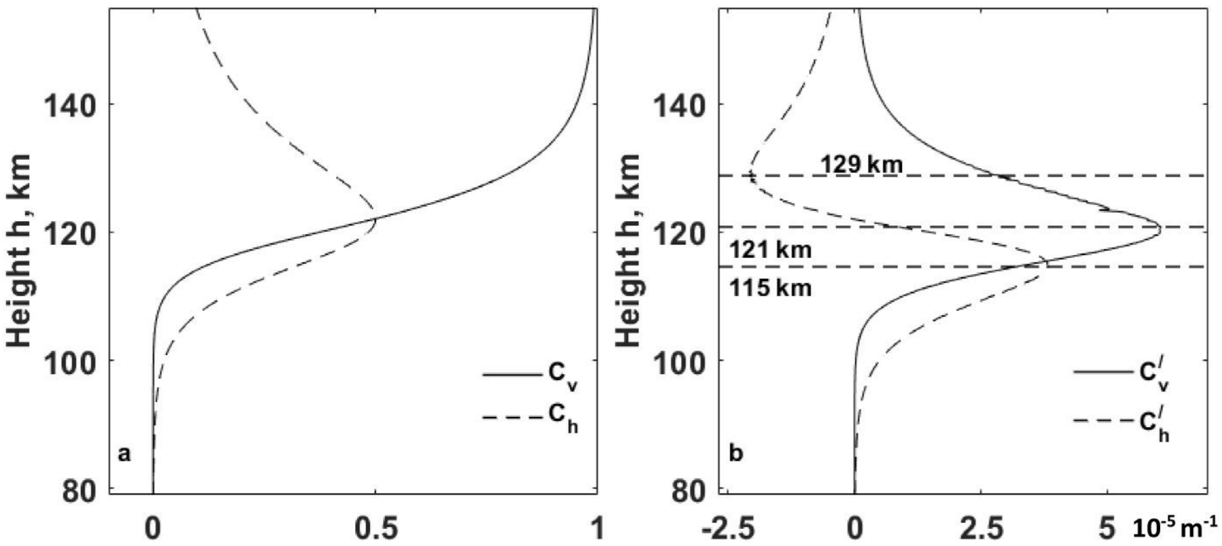

Fig. 1. The height profiles of ion convergence/divergence rate $-div\mathbf{w}_{i\mathrm{v}}$ factors a) $C_{\mathrm{v}}(z)$ and $C_0(z)$, b) $C'_{\mathrm{v}}(z)$ and $C'_h(z)$ at equatorial region (I=0).

Fig. 1 also shows that similarly the mid-latitude [15] factor has a maximum positive value approximately 0.9H below the altitude corresponding to the condition $\nu_{in} = \Omega_i$ (h=115km) and a minimum negative value above 0.9H (h= 129km).

In this case, on the vertical drift velocity of ions in the equatorial region, equation (4), the combined action ($\mathrm{V}_y - \frac{E_z}{B}$) of the zonal wind ($\mathrm{V}_y$) and the vertical electric field (E_z), it is possible to form an Es type layer even when the magnitude of $\mathrm{V}_y - \frac{E_z}{B}$ is constant. When $\mathrm{V}_y - \frac{E_z}{B} = \mathrm{constant} > 0$ and $E_y = 0$, then the convergence processes of ions develop against the background of drift below them, and the formation of the Es layer is expected in the lower height h<115 km regions. In this case ($\mathrm{V}_y - \frac{E_z}{B} = \mathrm{constant} > 0$) in the regions of upper heights around h = 129 km ($(div\mathrm{w}_{i\mathrm{v}})\max > 0$) the depletion of the ion/electrons is expected.

When $\mathrm{V}_y - \frac{E_z}{B} = \mathrm{constant} < 0$ and $E_y = 0$, then the inverse behavior of ions/electrons is expected: in the height regions of about h=129 km occurs $(div\mathrm{w}_{i\mathrm{v}})\min < 0$ and the formation of Es layer is expected, and in the lower heights about h=115 km where $(div\,\mathrm{w}_{i\mathrm{v}})\max > 0$ the charged particles depletion is expected.

Thus, the zonal E_y electric field can form the Es layer independently of the neutral wind, and that of the by the vertical electric field E_z, is possible in the case when the neutral wind is relatively weak ($\mathrm{V}_y << -\frac{E_z}{B}$).

We will demonstrate these and other cases of ion behavior and Es layer formation that can be predicted by the suggested theory numerically in the next section. Hereafter the vertical coordinate z represents the residual between some actual h and initial heights h_o ($z = h - h_o$).

3. Results and discussion

To investigate the behavior of the height profile of ion/electron density $N_e(z,t)$ (assuming quasi-neutrality $N_e = N_i(Fe^+)$) under the influence of the electric field $\mathbf{E}(0, E_y, E_z)$ and horizontal wind with velocity $\mathbf{V}_n(V_{xn}, V_{yn}, 0)$ we solve the continuity equation of ions numerically [15, 20-22], taking into account the ions vertical drift velocity w_i for equatorial, equations (3-7), region. We use the initial conditions of ion/electron distributions in accordance with the analytical approach, equation (1), of the solution of ions continuity equation.

In this stage of study, we consider the nighttime condition, and the ion/electron production and loss rates are neglected. In the presented simulation, the neutral particle densities of the lower thermosphere are used from the NRLMSISE-00 model [23], for the equatorial (7^o± 2°N, 45° ± 2° E; I=0± 2°) region. Further, we will consider the existence of the horizontal wind velocity $\mathbf{V}_n(V_{xn}, V_{yn}, 0)$, of which meridional V_{xn} and zonal V_{yn} components height profiles are determined by the HWM14 data [17,18].

To consider the importance of electric field $\mathbf{E}(0, E_y, E_z)$ in formation of a sporadic E we demonstrate the possibility of its formation even in case when zonal E_y or/and vertical E_z components of the electric field are homogeneous and the horizontal wind is absent. We will use the zonal and vertical electric field values $E_y = \pm 0.4 mV/m$ and $E_z = \pm 2 mV/m$, which are about those used by [5, 19]. For the initial ion/electron layer peak height (h_{om}), we consider the upper $h_{om} = 120\ km$ and the lower $h_{om} = 105\ km$ cases. The height of the upper peak is relatively close to the maximum/minimum regions of convergence $C'_{\mathrm{v}}(z)$ and $C'_h(z)$ factors (121 km, 115 km, 129 km), while the location of the lower peak $h_{om} = 105\ km$ is close to the regions of the often observed location of Es layers (about 102-104 km) [24, 25].

In Fig. 2 the behavior of ion/electron density $N_e(z,t)/N_{om}$ at equatorial region with I=0 (7^o N; 45^o E) for initial layer peak height (panels a,b,c,d) at $h_{om} = 120\,km$ and (panels e, f, g, h) $h_{om} = 105\,km$, under an influence (panels a and e) westward $E_y = 0.4 mV/m$, (b and f) eastward $E_y = -0.4 mV/m$, (c and g) upward $E_z = 2 mV/m$ and (d and h) downward $E_z = -2 mV/m$ electric field in case of absence horizontal wind ($\mathrm{V}_{yn} = 0$) are demonstrated.

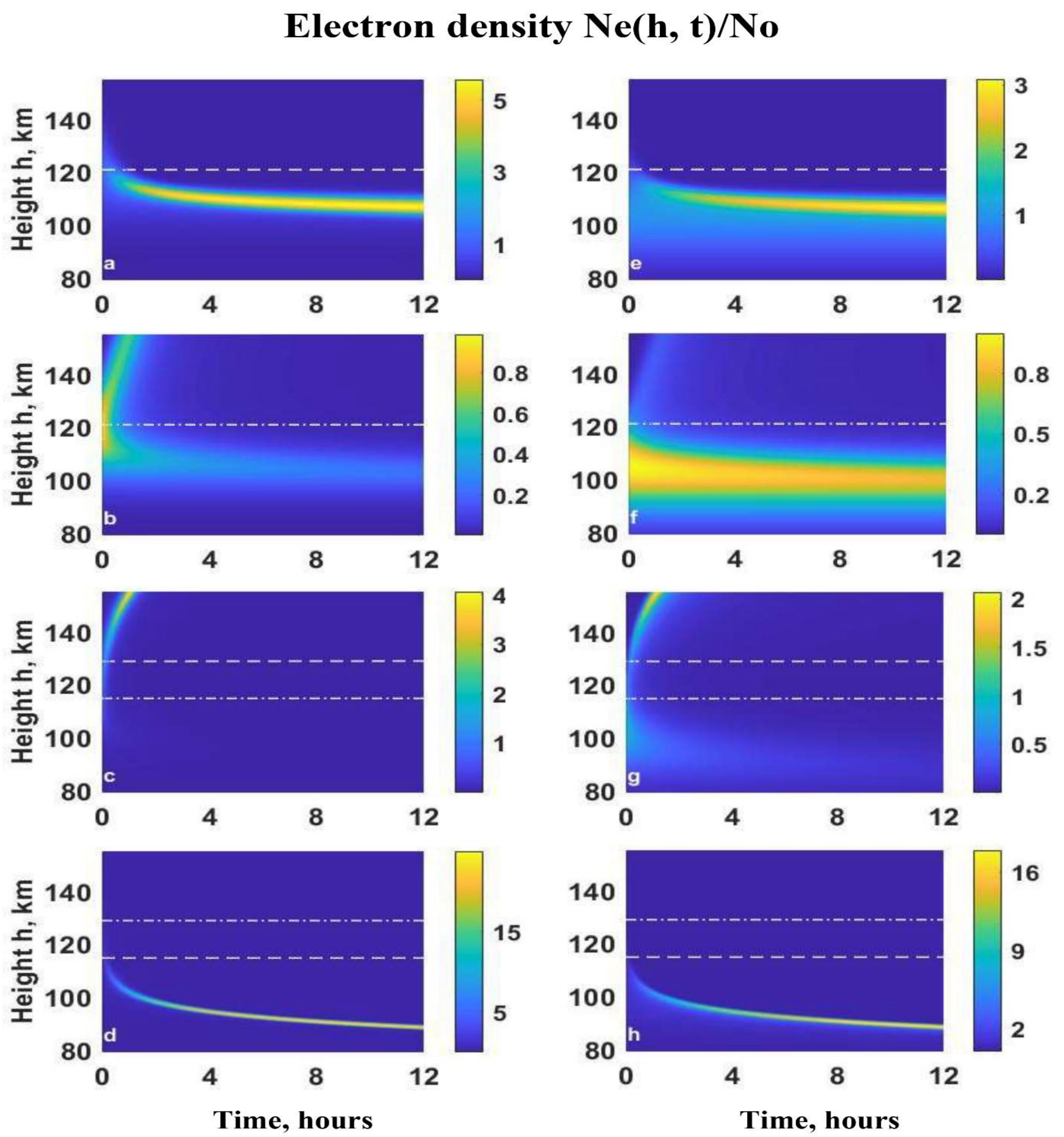

Fig. 2. The behavior of ion/electron density $N_e(z,t)/N_{om}$ at the equatorial region I=0 (7^o N; 45^o E) for the initial peak heights of the layer at $h_{om}=120\,km$ (panels a,b,c,d) and $h_{om}=105\,km$ (panels e, f, g, h), under an influence of westward $E_y=0.4\,mV/m$ (panels a and e), eastward $E_y=-0.4\,mV/m$ (b and f), upward $E_z=2\,mV/m$ (c and g) and downward $E_z=-2\,mV/m$ (d and h) electric fields, in case of absence of the horizontal wind ($V_{yn}=0$=0) . The dashed and dashed-dotted lines correspond to the heights of development of ion convergence ($(div\mathbf{w}_{iv})\min<0$) and divergence ($(div\mathbf{w}_{iv})\max>0$), respectively.

(Fig. 2a), $N_{em}/N_{om}>1.5$ (Fig. 2c) and $N_{em}/N_{om}>25$ (Fig. 2d) exceeds their magnitudes $N_{em}/N_{om}\geq 3$ (Fig. 2e), $N_{em}/N_{om}\approx 1$ (Fig. 2g) and $N_{em}/N_{om}>16$ (Fig. 2h) for the lower location $h_{om}=105\,km$ of the initial peak.

Fig. 2 shows that in the absence of wind $V_{yn} = 0$ the westward $E_y > 0$ (panels a and e), upward $E_z > 0$ (panels c, d) and downward $E_z < 0$ (panels g and h) electric fields can form a high density Es layer, even when it is homogeneous: $N_{em} / N_{om} > 5$ (Fig. 2a), $N_{em} / N_{om} > 1.5$ (Fig. 2c), $N_{em} / N_{om} > 25$ (Fig. 2d), $N_{em} / N_{om} \geq 3$ (Fig. 2e), $N_{em} / N_{om} \approx 1$ (Fig. 2g) and $N_{em} / N_{om} > 16$ (Fig. 2h). In these cases, the Es layer is formed in presence of conditions of vertical convergence of ions $(div\mathbf{w}_{i\mathrm{v}})\min < 0 \propto (C_{\mathrm{v}}^{'})\max > 0$ and $(div\mathbf{w}_{i\mathrm{v}})\min < 0 \propto (C_h^{'})\max > 0$, equations (4-10) (see Fig. 1b as well), at height about *h*=121 km (panels a and e), *h*=131 km (panels c and g) and *h*=115 km (panels d and h), respectively. Here, the Es type layer is formed during the downward $-C_{\mathrm{v}} \frac{E_y}{B} < 0$ (panels a and e), $-C_h \frac{E_z}{B} < 0$ (panels d and h) and upward $-C_h \frac{E_z}{B} > 0$ (panels c and g) drift of ions. They are respectively localized below (*h*<121km and *h*<115km) and above (*h*>129km) the height regions of ions convergence development where $w_{i\mathrm{v}} \to 0$.

The densities of the Es layer formed in these cases are higher when the peak height of the initial layer of ions is located near the region of its convergence development. For example, in the case of the westward electric field $E_y > 0$ (Figures 2a and 2e), as well as for $E_z > 0$ (Fig. 2d and 2h) at the upper location of the ion/electron peak $h_{om} = 120\ km$, their density $N_{em} / N_{om} > 5$

Fig. 2 also shows that for the eastward electric field $E_y < 0$ (panels b and f), at the height regions around 121 km a divergence condition $\left(-\frac{\partial w_{i\mathrm{v}}}{\partial z}\right)\max \propto (C_{\mathrm{v}}^{'})\max > 0$ occurs and accordingly the initial layer is depleted/destructed ($N_e / N_{om} << 1$). The role of the eastward electric field in the destruction of the observed Es layers is noted by [26].

Here it is also important to note that, in the case of a vertically downward field $E_z < 0$ (Fig. 2d and 2h), the divergence of ions developed in the 129 km height region increases their flow to the lower *h*<129 km regions. At the same time, the convergence developed at 115 km leads to the formation of a relatively high density Es layer with $N_{em} / N_{om} > 25$ and $N_{em} / N_{om} > 1.5$, than it was in the direction above the field $E_z > 0$ (Fig. 2c and 2g), as well as in its westward direction $E_y > 0$ (Fig. 2a and 2e). It is also important to note that the influence of ion diffusion on their convergence, equations (4)-(6), and therefore on the density of the Es layer, is noticeable for the upper heights of the lower thermosphere. In our case (see Fig. 2c and 2g) for the upward electric field $E_z > 0$ the Es layer formed at *h*>129 km is less dense and lasts for a shorter time (about $t - t_o < 2\,h$) than when it is formed in the lower regions (see Fig. 2 a, 2d, 2e and 2h).

Thus, in the equatorial lower thermosphere, the Es layer can be formed both westward $E_y > 0$ (Fig. 2a and 2e), and upward $E_z > 0$ (Fig. 2c and 2g) or downward $E_z < 0$ of the homogeneous electric field (Fig. 2d and 2h), which, according to equations (4), (5) and (6), is due to the presence of the minimum negative value of divergence of the vertical drift velocity $\mathbf{w}_{i\mathrm{v}}$ of ions $(div\mathbf{w}_{i\mathrm{v}})\min < 0$ (or $\left(-\frac{\partial w_{i\mathrm{v}}}{\partial z}\right)\max \propto (C_{\mathrm{v}}^{'})\max, (C_h^{'})\max > 0$) (see Fig. 1b), equation (10). In these cases ($E_y = 0$ or $E_z = 0$ and $V_{yn} = 0$) there is no ion drift velocity node $w_{i\mathrm{v}} = 0$, equation (4), and the formed Es type layer is localized in the regions where $w_{i\mathrm{v}} \to 0$.

The behavior of ions in the lower thermosphere is influenced by both the electric field and the neutral wind, equation (4). In order to distinguish the share/part of the influence of the electric field (see Fig. 2) together with its neutral wind in the vertical convergence of ions and, accordingly, in the formation of sporadic E, we consider its formation both in the case of wind only (**E**=0 and **V**≠0) and during their simultaneous presence (**V**≠0 and **E**≠0) at equatorial latitudes.

We estimate in ions qontituity equation the vertical ion drift velocity w_{iv} and its divergence $div\mathbf{w}_{ivo}$ for nighttime ($t-t_o \leq 12\,h$) height profiles in the lower thermosphere at equatorial *I*=0 (7^o N; 45^o E) regions, using neutral wind velocity HWM14 data.

Fig. 3a and 3b show that the vertical drift velocity of ions w_{iv}, caused by the zonal wind determined by HWM14 data, and its divergence $div\mathbf{w}_{iv}$ in certain regions of the lower thermosphere at 90-160 km height fulfill the condition of vertical convergence of ions $(div\mathbf{w}_{iv})\min < 0$, equation (2). The presence of this condition is noticeable for at least $t - t_o \leq 3h$, and accordingly the vertical convergence of ions develops and high-density Es layers are formed both at the top of the initial layer peak $h_{om} = 120\,km$ (panel c) and at the bottom $h_{om} = 105\,km$ location (panel d). In these cases, the Es layers are localized in the ion drift velocity nodes $w_{iv} = 0$ (for example, at *h*=140-150km altitudes), as well as towards the bottom of the lower thermosphere, where $w_{iv} \to 0$ (panels c and d). We estimate in ions qontituity equation the vertical ion drift velocity w_{iv} and its divergence $div\mathbf{w}_{iv}$ for nighttime ($t-t_o \leq 12\,h$) height profiles in the lower thermosphere at equatorial *I*=0 (7^o N; 45^o E) regions, using neutral wind velocity HWM14 data.

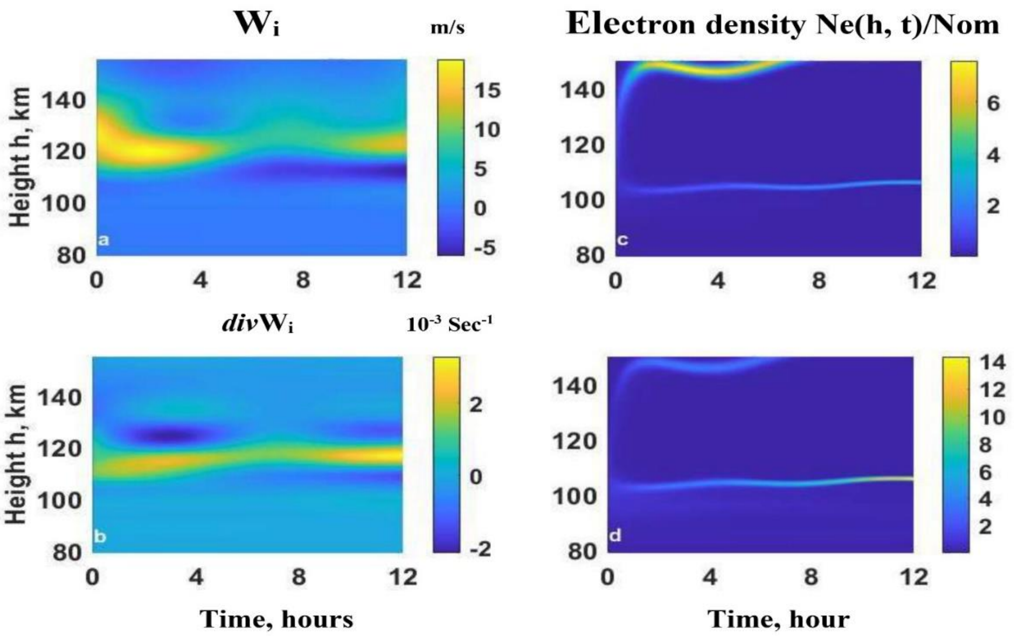

Fig. 3. The behavior of the ion/electron vertical drift velocity Wiv determined by the HWM14 data (day 102) of zonal wind velocity (panel a) and its divergence div Wiv (panel b) and correspondingly numerically estimated ion/electron density $N_e(z,t)/N_{om}$ at the equatorial region with *I*=0 (7^o N; 45^o E) for the initial peak height $h_{om} = 120\,km$ (panel c) and $h_{om} = 105\,km$ (panel d).

Fig. 3a and 3b show that the vertical drift velocity of ions w_{iv}, caused by the zonal wind determined by HWM14 data, and its divergence $div\mathbf{w}_{iv}$ in certain regions of the lower thermosphere at 90-160 km height fulfill the condition of vertical convergence of ions $(div\mathbf{w}_{iv})\min < 0$, equation (2). The presence of this condition is noticeable for at least $t - t_o \leq 3h$, and accordingly the vertical convergence of ions develops and high-density Es layers are formed both at the top of the initial layer peak $h_{om} = 120\,km$ (panel c) and at the bottom $h_{om} = 105\,km$ location (panel d). In these cases, the Es layers are localized in the ion drift velocity nodes $w_{iv} = 0$ (for example, at *h*=140-150km altitudes), as well as towards the bottom of the lower thermosphere, where $w_{iv} \to 0$ (panels c and d).

The formation of the lower Es layer takes place continuously from the convergence region (about 100-105 km) against the background of the drift of ions below (Fig. 3a) and for these times they are localizing in the vicinity of *h*=100 km (Fig. 3c and 3d). It is important to note that for the ion/electron initial layer peak height ($h_{om} = 105\,km$) is located below divergence height region (about 115 km) and close to the lower convergence region (around 110-100km), the upper layer is no longer formed and charge particles mainly accumulating in the lower Es layer ($N_{em} / N_{om} \geq 12$), where $w_{iv} \to 0$

Thus, with the presented theoretical model by use the HWM14 data, it is possible to form Es layers at the equatorial regions. In these cases (Fig. 3c and 3d), despite the different behavior of the formed Es layers than it was under the influence of the electric field (Fig. 2), the development of the vertical convergence of ions and the formation and localization of the Es layer can be determined by the profiles of the vertical drift of ions and its divergence, equations (2), (4) and (9).

We further show the significant influence of the electric field and the neutral wind combined effect on the ions drift velocity and their vertical convergence, by consideration the Es layers formation and behavior for the wind and field parameters discussed above (Fig. 2).

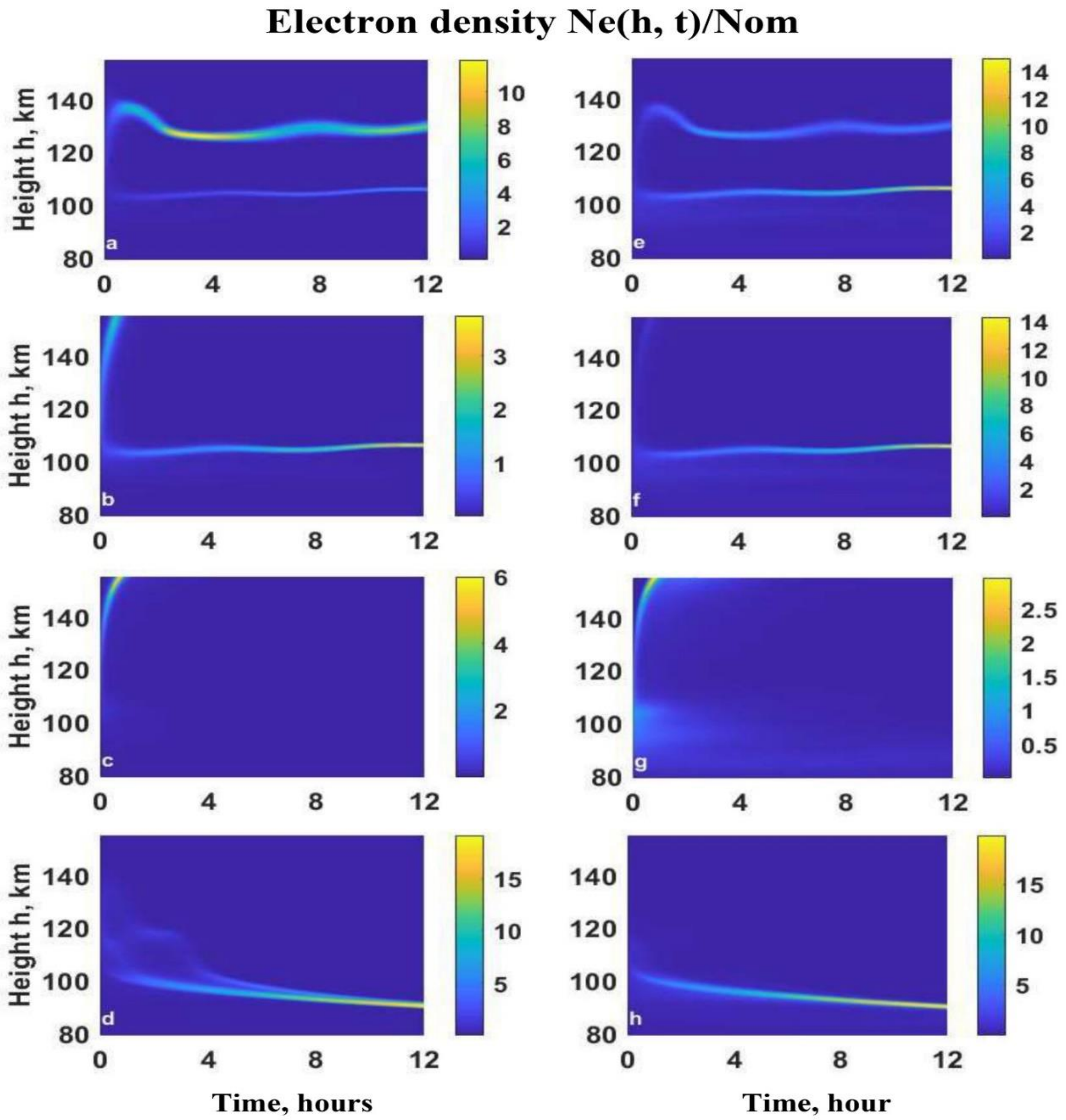

Fig. 4. That of the given in Fig. 2 in case of presence horizontal wind with velocity (V_{yn}) determined by the HWM14 used in Fig. 3.

Fig. 4 shows that sporadic E formation is possible due to the combined action of the electric field and neutral wind on the behavior of the ions, and it is possible both for the upper ($h_{om} = 120\ km$) (panels a-d) and lower ($h_{om} = 105\ km$) locations (panels e-h) of their initial layer peak. Here, sporadic E can be formed by two sub-Es layers, (e.g., see panels a, b, e and f), which were not formed only in zonal electric field (see Fig. 2a, 2b, 2e and 2f) or only in neutral wind (see Fig. 5a and 5b). Here, the behavior of the lower Es layer formed at about *h*=104 km corresponds to the behavior of the wind-induced Es layer (Figures 3c and 3d), while the upper one formed at about 130-140 km is determined by the combined action of both the westward electric field and the westward/eastward wind.

Fig. 4c, 4d, 4g and 4h also show that for the considered vertical electric field (2 mV/m) the neutral wind has little influence on the localization region of the upper (140-150 km altitude) and lower (about 90 km) Es layers formed during 1-3 hours (see Fig. 2, 4a and 4b). Here, the neutral wind somewhat changes the concentration of the formed Es layers.

Fig. 4 c and g also show that in the considered case, the Es layer (see Fig. 4c and 4d) formed by the zonal wind at about 104 km is destroyed when the ions drift upwards caused by the vertically directed electric field.

Thus, in the equatorial region, both the zonal and vertical components of the electric field together with the zonal component of the neutral wind have an impact on the vertical convergence of ions, equations (4) and (9), and therefore on the formation and behavior of Es layers. We consider the same in the simultaneous presence of the zonal and vertical components of the electric field and the neutral zonal wind in this region. In this case, the vertical drift of ions caused by the electric field (**E**) and the wind, equation (4), and therefore the convergence/divergence rate, equation (9), are determined by the total effect of these parameters and the development of the cases discussed above.

Thus, with the presented theoretical model, we have shown that under the influence of the horizontal neutral wind, homogeneous electric field, and also their combined action on the behavior of ions/electrons, it is possible to form sporadic E(Es) in the lower thermosphere of equatorial regions (see Figures 2-4). The obtained sporadic E multilayer structure, the influence of the electric field on it, the lowering and localization of Es layers towards the lower height *h*<110km regions, as well as the relatively low density of these layers towards the upper *h*>120-130km regions are observed phenomena [27-29].

4. Conclusions

The formation of sporadic E (Es) in the equatorial region by the electric field, zonal wind, as well as their joint action on the ions vertical convergence, was studied theoretically and by appropriate numerical methods.

1. It was shown that the formation and localization of sporadic E (Es) at the equatorial region, in analogy to the mid-latitudes [13], can be determined by the height profiles of the ion vertical drift velocity $\mathbf{w}_{iv}$ and its divergence $div\mathbf{w}_{iv} = \frac{\partial w_{iv}}{\partial z}$. In this case, the presence of a minimal negative value of $(div\mathbf{w}_{iv})\min < 0$ (maximal convergence rate $(-div\mathbf{w}_{iv})\max > 0$) in the divergence profile, during which the ions converge vertically into the Es layer, equations (1) and (2), is significantly determined by the zonal velocity of neutral wind V_{yn}, as well as by the zonal Ey and vertical Ez components of the electric field, equation (4).

The theoretically predicted formation and localization of Es layer in the regions with $w_{iv} = 0$ or $w_{iv} \to 0$, equation (1), as well as ion/electron depletion, when the condition $(div\mathbf{w}_{iv})\max > 0$ occurs, are demonstrated by numerical methods (see Fig. 2 and 3).

2. It is shown that when neutral wind is absent, then in the equatorial region the westward electric field Ey>0, as well as the upward $E_z > 0$ and downward Ez<0 fields can form an Es type layer

(see Fig. 2 and 3), even when the field is homogeneous. For the westward $E_y = constant > 0$ ($E_z = 0$) field, the region of convergence development with $(-div\mathbf{w}_{i\,vo})\max \propto (C'_{vo})\max > 0$, equation (2), corresponds to the height (about *h*=121km), where $\nu_{in} = \Omega_i$ (Fig. 1b). For the upward $E_z = constant > 0$ ($E_y = 0$) and downward electric field the region of development of ions vertical convergence with $(-div\mathbf{w}_{i\,vI})\max \propto (-C'_{ho})\max > 0$ is usually above or below by about 0.9H from the region where $\nu_{in} = \Omega_i$

In the same cases, an upward $E_z > 0$ or downward $E_z < 0$ Ez<0 electric fields can cause destruction/depletion of the layer at the heights which are 0.9H below (about *h*=115km) and above (about *h*=129 km), respectively, from the region with condition $\nu_{in} = \Omega_i$.

3. For the eastward $E_y = constant > 0$ ($E_z - 0$, $V_{yn} = 0$) electric field in the height region where $\nu_{in} = \Omega_i$ (*h*=121km, Fig. 1) the condition $(div\mathbf{w}_{i\,vo})\max > 0$ occurs, the divergence process develops and the initial layer is depleted (disrupted). A similar ion divergence condition occurs for downward electric field $E_z < 0$ in the area of about 129 km height, while for $E_z > 0$ the process of ion depletion develops at about 115 km height and the initial layer is disrupted.

4.In the equatorial region (e.g., *I*=0; 7^o N, 45^o E) only the zonal wind can form the Es layers. Accordingly, the regions of their formation development ($(div\mathbf{w}_{i\,vo})\min < 0$, $(div\mathbf{w}_{i\,vI})\min < 0$) and localization ($w_{i\,vo} = 0$ or $w_{i\,v0} \to 0$; $w_{i\,vI} = 0$ or $w_{i\,vI} \to 0$) (Fig. 4), are defined by the magnitude, direction and vertical shear of wind velocity, equations (8). This is demonstrated for the HWM14 typical data (Figure 4).

5. In the presence of an electric field (with E_y or/and E_z components) and zonal wind in the equatorial region (e.g., I=0, 7 ^{o} N, 45 ^{o} E), the ions drift velocity ($\mathbf{w}_{i\,vo}$) and their vertical convergence/divergence condition ($(div\mathbf{w}_{i\,vo})\min < 0 / (div\mathbf{w}_{i\,vo})\max > 0$) include both the field and the neutrals factors. Their total effect is manifested in convergence, as well as during the development of divergent processes. The expression of their joint action is the appearance of an additional Es layer, the changes in their localization regions ($w_{i\,vo} = 0$ or $w_{i\,v0} \to 0$) and densities, as well as their destruction (depletion) (see Fig. 2), unlike the case with only neutral wind (see Fig. 4).

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ელექტრული ველის მნიშვნელობა ეკვატორულ არეში სპორადული E (Es) ფენის ფორმირებაში

გ. დალაქიშვილი, გ. დიდებულიძე, მ. თოდუა, ლ, ტორიაშვილი

რეზიუმე

ანალიზურად და შესაბამისი რიცხვითი მეთოდებით ნაჩვენებია, რომ ეკვატორულ არეში სპორადული E (Es) ფორმირება და ლოკალიზაცია შესაძლებელია განისაზღვროს იონების ვერტიკალური დრეიფის სიჩქარის და მისი დივერგენციის სიმაღლის პროფილებით. ამ შემთხვევაში, დივერგენციის პროფილში მინიმალური უარყოფითი მნიშვნელობის (მაქსიმალური კონვერგენციის სისწრაფის) არსებობა, რომლის დროსაც იონები ვერტიკალურად კონვერგირდებიან Es ფენად, მნიშვნელოვნადაა განსაზღვრული, როგორც ნეიტრალური ქარით, ასევე ელექტრული ველის ზონალური და ვერტიკალური კომპონენტებით. ეკვატორულ არეში მუდმივი დასავლეთის ელექტრული ველისას იონების მაქსიმალური ვერტიკალური კონვერგენციის სისწრაფე იონ-ნეიტრალების დაჯახების (ν_{in}) და იონების ციკლოტრონული სიხშირის (Ω_i) ტოლობის სიმაღლის რეგიონშია. მხოლოდ ზემოთ ან ქვემოთ მიმართული მუდმივი ელექტრული ველის შემთხვევაში კი ის მდებარეობს $\nu_{in} = \Omega_i$ რეგიონიდან შესაბამისად დაახლოებით 0.9H ნეიტრალების შკალით ზემოთ ან ქვემოთ, შესაბამისად.ამ რეგიონებში განვითარებული იონების ვერტიკალური კონვერგენცია და Es-ტიპის ფენის ფორმირება შესაძლებელია მიმდინარეობდეს მათი ზემოთ ან ქვემოთ დრეიფის ფონზე. ის ლოკალიზდება ამ დრეიფის სიჩქარის ნოდაში, ან რეგიონებში სადაც ეს სიჩქარე ქრება. Es-ტიპის ფენების ამგვარი ნაწინასწარმეტყველევი ფორმირება და დინამიკა დემონსტრირებულია რიცხვითი მეთოდებით.

ნაჩვენებია, როგორც ელექტრული ველის ზონალური და ვერტიკალური კომპონენტების, ასევე HWM14 მონაცემებით განსაზღვრული ქარის სიჩქარის ეფექტი იონების კონვერგენცია/დივერგენციის განვითარების პროცესებზე. ამ შემთხვევებში ელექტრული ველით გამოწვეულ იონების კონვერგენცია/დივერგენციის პროცესს შეუძლია გავლენა იქონიოს ქარით Es-ტიპის ფენის როგორც ფორმირებასა და დაშლაზე (გამოფიტვაზე), ასევე შეუძლია წარმოქმნას დამატებითი ფენა.

საკვანძო სიტყვები: ქვედა თერმოსფერო, ელექტრული ველი, სპორადული E (Es), იონის ვერტიკალური დრიფტის სიჩქარე, რიცხვითი მეთოდები.

Значение электрического поля в формировании спорадических E (Es) в экваториальной области

Г. Далакишвили, Г. Дидебулидзе, М. Тодуа, Л. Ториашвили

Резюме

Аналитически и соответствующими численными методами показано, что образование и локализация спорадических E (Es) в экваториальной области может определяться высотными профилями скорости вертикального дрейфа ионов и ее дивергенцией. При этом существование минимального отрицательного значения (максимальной скорости сходимости) в профиле расходимости, когда ионы сходятся вертикально в слой Es, существенно определяется как скоростью нейтрального ветра, так и зональной и вертикальной составляющими электрического поля.

В экваториальной области при постоянном западном электрическом поле максимальная скорость вертикальной конвергенции ионов приходится на область высот, где ионно-нейтральная столкновительная (ν_{in}) и ионно-циклотронная (Ω_i) частоты равны. В случае постоянного восходящего или нисходящего электрического поля эта скорость находится примерно на 0.9H (где H – нейтральная шкала) выше или ниже области где $\nu_{in} = \Omega_i$, соответственно. Вертикальная конвергенция ионов, развивающихся в этих областях, и образование слоя Es могут происходить на фоне их дрейфа вверх или вниз. Она локализуется в узле этой скорости дрейфа или в областях исчезновения этой скорости. Такое предсказанное формирование и поведение слоев Es демонстрируется численными методами.

Показано влияние зональной и вертикальной составляющих электрического поля, а также скорости ветра, определенной по данным HWM14, на процессы развития конвергенции/расхождения ионов. В этих случаях процесс сближения/расхождения ионов, индуцированный электрическим полем, может влиять как на образование, так и на разрушение (истощение) слоя Es, образованного нейтральным ветром, а также может образовывать дополнительный слой.

Ключевые слова: нижняя термосфера, электрическое поле, спорадическое E (Es), скорость вертикального дрейфа ионов, численные методы.