Journal of the Georgian Geophysical Society, ISSN: 1512-1127
Physics of Solid Earth, Atmosphere, Ocean and Space Plasma, v. 23(1), 2020, pp. 27 -45

Formation of Sporadic E (Es) Layer by Homogeneous Horizontal Wind

Giorgi T. Dalakishvili, Goderdzi G. Didebulidze, Maya M. Todua

Abastumani Astrophysical Observatory of Ilia State University, Kakutsa Cholokashvili ave. 3/5, Tbilisi 0162, Georgia.

ABSTRACT

Theoretically and by corresponding numerical simulations it is shown that the formation and localization of sporadic E (Es) layer at its mainly observable mid-latitude lower thermosphere heights can be determined by homogeneous horizontal wind velocity direction and value. In the suggested theory, differently from 'windshear' theory, the wind direction and value, in addition to geomagnetic field and vertically changing ion-neutral collision frequency, determine the minimal negative value of the divergence of heavy metallic ions drift velocity, which in turn causes ion convergence into Es type horizontal thin layer. Here, in the upper heights of the lower thermosphere, the Es layer peak density and thickness are also controlled by ion ambipolar diffusion.

In the lower thermosphere of the northern hemisphere, the Es layer caused by horizontal homogeneous wind can be located at height regions where (1) the ions vertical drift velocity is zero and its divergence is negative (east-northward wind), (2) the ions drift downward (northward and westward wind), which occurs more frequently, or (3) the ions drift upward (eastward wind) and their negative divergences vanish and (4) in the case of dominance of southward wind the divergence of ion drift velocity is positive, consequently ion density divergence occurs and Es type layer formation is not expectable. The Es layer density increase and its vertical motion to its expectable location are faster for greater values of the horizontal wind velocity. The possibility of development of the suggested theory for vertically inhomogeneous wind is noted.

Key words: *sporadic e (es) layer, homogeneous horizontal wind*

1. Introduction

The knowledge of physical mechanisms of sporadic E (Es) layer formation could give a possibility to predict its possible location, which is very important for modern radio communications. The search for physical mechanisms of Es layer formation had started in early 1960-ies [1,2]. The 'windshear' theory is considered to be the main one explaining of sporadic E formation [3,4]. According to this theory, in the lower thermosphere the eastward wind at lower heights changes to the westward one at upper heights or southward wind to northward which causes the accumulation of the heavy metallic ions into the horizontal thin layer in the regions close to wind polarisation changes [5]. The observations show that the Es layers do not always form in the regions of changes of horizontal wind polarisation [6,7,8], which shows the necessity of modification of this theory.

In the presented study, the formation of sporadic E by horizontal homogeneous wind in its main observable region of 95-150km is shown using theoretical and corresponding numerical methods. According to the suggested theory the ion vertical drift velocity, caused by horizontal wind in the lower thermosphere, already has minimal negative or/and maximal positive values in its divergence, which is determined by geomagnetic field, vertically changing ion-neutral collision frequency, and also direction and value of wind velocity. In the framework of this theory, in the lower thermosphere, for the known dominant ions distribution and wind field the formation and possible location of the Es layer can be predicted.

In this case, the east-northward wind can form Es type layers at about middle height of these regions where ions drift velocity is zero and its divergence is negative. Relatively frequent formation of Es layer and its location at the bottom side of the lower thermosphere, where ions downward drift velocity and its negative divergence vanishes, occur during dominance of northward and westward components of wind velocity. For the upper heights of the lower thermosphere (about 135-150km) Es layer formation occurs during dominance of eastward wind where ions upward drift and their negative divergence vanishes. Here the Es layer density also is controlled by ions ambipolar diffusion. The Es type layer formation is faster for greater horizontal wind velocity. According to the suggested theory, an ion/electron divergence also occurs in case of dominance of southward component of the horizontal wind, where ions upward drift velocity divergence is positive.

Considering the influence of horizontal wind direction and values on the ion /electron behavior and taking into account their ambipolar diffusion, it is important to create a realistic model of sporadic E formation and predict its possible location [9]. The presented mechanism does not exclude the additional effect of influence of wind shear caused by tidal motion [10] or atmospheric waves and instabilities, as well as wind and electric field directions on the Es formation and behavior [11,12,13,14,15], which can be developed by suggested theory.

2. Theory of sporadic E formation under the influence of homogeneous horizontal wind

The horizontal wind influences on ion vertical drift velocity via combined action of the Lorentz forcing and ion-neutral collision. The dependence of ions motion on the meridional V_x and zonal V_y components of background horizontal wind velocity of neutral particles $\mathbf{V}(V_x, V_y, 0)$, taking into account their ambipolar diffusion, can be described by the equation of ions vertical drift velocity $\mathrm{w_i}$ [14,16,17]:

$$\mathrm{w}_i = -C_x(z)V_x - C_y(z)V_y - D_a(z)\frac{1}{N_i}\frac{\partial N_i}{\partial z} \ , \qquad (1)$$

where

$$C_x(z) = \frac{1}{1+\kappa^2(z)}\sin I \cos I \ , \qquad (2)$$

$$C_y(z) = \frac{\kappa(z)}{1+\kappa^2(z)}\cos I \ , \qquad (3)$$

$$D_a(z) = \frac{\kappa^2(z)+\sin^2 I}{1+\kappa^2(z)}\frac{2kT}{M_i \nu_{in}(z)} \ , \qquad (4)$$

Here $\kappa(z) = \nu_{in}(z)/\omega_i$, $\nu_{in}(z)$ is ion-neutral collision frequency, $\omega_i = eB/M$ is the ion gyrofrequency ($\omega_i = 80 s^{-1}$), $\mathbf{B}(B\cos I, 0, -B\sin I)$ is the Earth's magnetic field vector, *I* is the magnetic dip angle, M_i is the ion mass, $D_a(z)$ is ambipolar diffusion coefficient, $T = (T_e + T_i)/2$ is mean plasma temperature, T_e and T_i are ions and electrons temperatures, respectively, k_B is Boltzmann constant. 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 upwards. The $C_x(z)$ and $C_y(z)$ coefficients determine an influence of the meridioznal ($V_x = V\cos\varphi$) and zonal ($V_y = V\sin\varphi$) components of horizontal wind velocity $\mathbf{V}$ on ions vertical drift velocity. These coefficients significantly change in the lower thermosphere in the region between 100 km and 140 km height. This change is mainly caused by $\nu_{in}(z)$, which is determined by vertical distribution of neutral particle densities ([N2], [O2] and [O]) which are dominant in this region [18]:

$$\nu_{in}(z) = \left(2.62\,[N_2](z) + 2.61[O_2](z) + 1.43[O](z)\right)\cdot 10^{-10}\,s^{-1} \qquad (5)$$

To investigate the behavior of height profile of electron density $N_e(z,t)$, assuming quasi-neutrality $N_e = N_i$, we use continuity equation, taking into account the presence of background horizontal wind with meridional $V_x = V\cos\varphi$ and zonal $V_y = V\sin\varphi$ components ($V = |\mathbf{V}|$), in the expressions of ions vertical drift velocity, equations (1)-(4), which has the following form:

$$\frac{\partial N_i}{\partial t} = C'(z)VN_i + C(z)V\frac{\partial N_i}{\partial z} + C(z)N_i\frac{\partial V}{\partial z} + \frac{\partial}{\partial z}[D_a(z)\frac{\partial N_i}{\partial z}], \qquad (6)$$

where

$$C(z,\varphi) \equiv C_x(z)\cos\varphi + C_y(z)\sin\varphi = \frac{\cos\varphi\sin I + \kappa(z)\sin\varphi}{1+\kappa^2(z)}\cos I\,, \qquad (7)$$

$$C'(z,\varphi) \equiv \cos\varphi\frac{\partial C_x}{\partial z} + \sin\varphi\frac{\partial C_y}{\partial z} = \frac{\sin\varphi - 2\kappa(z)\cos\varphi\sin I - \kappa^2(z)\sin\varphi}{[1+\kappa^2(z)]^2}\cos I\,\frac{\partial\kappa}{\partial z}\,, \qquad (8)$$

$\varphi = \angle\hat{\mathbf{xV}}$ $(0 \le \varphi < 360^o)$ is angle between horizontal wind and x axes direction -wind orientation angle. Euation (6) shows that the behavior of the $N_e(z,t)$ in the lower thermosphere is determined by vertical changes in vertical flux of ion/electron ($\partial(\mathrm{N_e w}_i)/\partial z$), where it can be influenced by an ambipolar diffusion ($\propto D_a$), horizontal background wind value ($V = |\mathbf{V}|$) and shear ($\frac{\partial V}{\partial z}$), as well as by the height profile of the $C(z,\varphi)$ and $C'(z,\varphi)$ coefficients, equations (7) and (8). The latter coefficients are important in the current investigation. In turn, the height profile of the $C(z,\varphi)$ and $C'(z,\varphi)$ coefficients, equations (7) and (8), are determined by the beckground horizontal wind direction (φ), geomagnetic field ($\mathbf{B}$), ion-neutrals collision frequency $\nu_{in}(z)$ and its vertical changes ($\frac{\partial\kappa}{\partial z} \propto \frac{\partial\nu_{in}}{\partial z}$), see equations (2), (3), (7) and (8).

Equation (1) shows that when vertical drift velocity caused by horizontal wind exceeds their diffusive displacement characteristic velocity $CV >> \frac{D_a}{N_e}\frac{\partial N_e}{\partial z}$, then their vertical flux

$N_i\,\mathrm{w}_i \approx -N_iVC(z)$ is proportional to ion vertical drift factor *C(z)*. In this case, in a certain region of the lower thermosphere, where $\partial\,\mathrm{w}_i/\partial z \approx -VC'(z) - C(z)\frac{\partial V}{\partial z} > 0$, the ion/electron density can be increased ($\frac{\partial N_e}{\partial t} > 0$) and where $\partial\,\mathrm{w}_i/\partial z \approx -VC'(z) - C(z)\frac{\partial V}{\partial z} < 0$, it can be decreased (equation (6)). The windshear theory does not take into account the influence of C' factor on vertical changes in ions drift velocity (equation (8)) and, thus on sporadic E formation. According to this theory, when $-C(z)\frac{\partial V}{\partial z} > 0$, in the region where horizontal wind velocity ($\mathbf{V}$) changes its polarisation, and where $\mathrm{w}_i \approx -C(z)V = 0$, the ion/electron may converge into a thin layer and form the Es layer. Here, the condition $-C(z)\frac{\partial V}{\partial z} > 0$ depends on the wind shear and it can be met for any direction. In the present consideration, an increase in the ion/electron density ($\frac{\partial N_e}{\partial t} \propto -\frac{\partial\,\mathrm{w}_i}{\partial z} \approx C'(z)V > 0$) is possible under the influence of the particular direction of the homogeneous horizontal wind ($\frac{\partial V}{\partial z} = 0, \frac{\partial \mathrm{w}_i}{\partial z} \approx -C'(z)V$), when $C'>0$. In this case in the region where the factor C' is maximal, the vertical change of ions drift velocity is minimal $(\partial \mathrm{w}_i / \partial z)\min < 0$, so their convergence into a thin layer and formation Es is also possible.

In the case of homogeneous horizontal wind the C' factor determines both increase (e.g., $C'>0$) and decrease (e.g., $C'<0$) tendencies of ion/electron density, so it will be referred as an ion convergence/divergence factor. The points $z = z_c$ or $z = z_d$, where C' is maximal, $C'(z = z_c) = C'_{\max} > 0$ ($(\partial \mathrm{w}_i / \partial z)\min < 0$), and minimal $C'(z = z_d) = C'_{\min} < 0$

($(\partial \mathrm{w}_i / \partial z)\max > 0$), determine the regions with maximal tendency of ion/electron density convergence or their divergence and will be reffered as ion convergence driving point (ICDP) $z = z_c$ and ion divergence driving point (IDDP) $z = z_d$.

Let us note that when wind's direction changes to opposite ($\mathbf{V} \to -\mathbf{V}$), $C'(z)$ also changes the sign i.e. $C'(z,\varphi) \to -C'(z,\varphi + 180^o)$, see equation (8), therefore the ICDP z_c and IDDP z_d also exchange places - $z_c(\varphi) = z_d(\varphi + 180^o)$.

The approximated analytic solution of equation (6),

$$N_e(z,t) \approx N_{om} \exp\left\{ \left[-\frac{2D_a}{H_{ic}^2} + C'(z)V \right](t - t_o) - \left(\frac{z - [z_{om} - C(z)V(t - t_o)]}{H_{ic}} \right)^2 \right\}, \qquad (9)$$

shows the possibility of sporadic E formation in the case of presence of homogeneous horizontal wind, with behavior significantly determined by ions vertical drift factor C and their convergence/divergence C' factors. This solution is valid for small time of $t - t_o << H_{ic}^2 / 2D_a$ and heights $(z - z_{om}) << H_{ic}^2$. The equation (9) at the initial time of $t = t_o$ correspond to the ion/electron Gaussian type distribution layer with maximal density N_{om} (peak density) at corresponding $z = z_{om}$ height (peak height), which in the case of absence of wind ($C, C'=0$) decreases due to ambipolar diffusion $\propto N_{om} \exp[-\frac{2D_a}{H_{ic}^2}(t - t_o)]$. H_{ic} is characteristic scale height of ions, which at some initial time $t=to$ determines ion/electron main layer thickness ($2H_{ic}$) and height region $z - z_{om} = \pm H_{ic}$, where their density decreases e-times. Despite the fact that $N_e(z,t)$ described by equation (9) does not take into account the time dependence of parameters N_{om} and H_{ic}, which will be considered in numerical simulations in the next chapter, it still describes a tendency of sporadic E formation under the influence of homogeneous horizontal wind taking into account ions vertical drift and their ambipolar diffusion.

The $N_e(z,t)$ of equation (9) shows that, when

$$C'_{\max} V > \frac{2D_a}{H_{ic}^2} \qquad (10)$$

then its increase ($N_e / N_{om} > 1$) is possible. In this case when $C=0$, then at ICDP z_c the maximal increase in electron density occurs (developing convergence instability), equation (9), and the Es type high density narrow layer formation is possible around this point. Such convergence instability, continuing increase in electron density and decrease in its thickness around z_c in case of $C=0$ should be balanced by their ambipolar diffusive displacement ($\propto \frac{2D_a}{H_{ic}^2}$), which increases with decrease of this layer thickness.

According to equation (9), the development of ion/electron convergence processes ($\frac{\partial N_e}{\partial t} \propto C'(z)V > 0$ or *C'>0*) , are also possible during the downward (*VC>0* or *C>0*) or upward (*VC<0* or *C<0*) drift of peak height $z_m = z_{om} - VC(t - t_o)$ by velocity *VC*. These processes should be faster for greater values of the horizonal wind velocity V. So, for various directions of the horizontal homogeneous wind, the height profiles of the factors *C(z)* and *C'(z)* determine the regions, where, under its influence, the ion/electron convergence into dense thin layer and correspondingly sporadic E formation is possible. The *C(z)* and *C'(z)* factors also determine the regions of ion/electron density divergence (*C'<0*). For example, when *C=0* and $-C'_{\min}V >> \frac{2D_a}{H_{ic}^2}$, then maximal decrease of the ion/electron density will occur in the IDDP z_d ($C'_{\min}$<0).

Figure 1 depicts (**a**) the ions vertical drift $C(z,\varphi)$ and (**b**) convergence/divergence $C'(z,\varphi)$ factors height profiles for various horizontal wind (**V**) direction angle $\varphi = \angle \hat{\mathbf{xV}}$ $(0 \le \varphi < 360^o)$ at north hemisphere mid-latitude regions (45°±2° N, 45°±2° E) with geomagnetic declination $I=61^o$ ±2°. Blue and yellow lines correspond to the heights where ions vertical drift factor *C=0* at their divergence region (*C'*<0) for wind direction angles $\varphi_{b,W-S} = 90^o + \arctan g(\kappa / \sin I)$ and at their convergence region (*C'*>0) for $\varphi_{b,E-N} = 270^o + \arctan g(\kappa / \sin I)$, respectively. The arrows express the ions drift velocity direction at given height and horizontal wind direction angle φ determined by drift factor $C(z,\varphi)$, equation (7). The lower height arrows correspond to the height regions with comparatively smaller values of ion drift velocity ($C \approx 0.02 C_{\max}$). $z = h - h_o$ is the difference between an actual and some initial height h_o . Here and hereafter for simplicity $z = h$ ($h_o = 0$).

Figure 1 shows that, in the height region of the Es layers formation (100-140 km), the ion convergence/divergence factor $C'(z,\varphi)$ always exists and has maximal positive (*C'>0*) or/and minimal negative (*C'<0*) values. Therefore, in the framework of proposed mechanism, the convergence ($N_{em} / N_{om} > 1$) or divergence ($N_{em} / N_{om} < 1$) of ion/electron density under the influence of horizontal wind could occur.

In the upper atmosphere, at $z > 140 - 145 km$ and $z < 95 - 100 km$ the ion vertical drift factor *C(z)* changes slightly ($C \to \text{constant}$), and the ions convergence/divergence factor *C'* vanishes ($C' \to 0$) . Therefore, according to the proposed mechanism, formation of Es layer under the influence of the homogeneous wind ($\frac{\partial V}{\partial z} = 0$) horizontal components ($V_x, V_y \neq 0$) are less expected.

Figure 1b shows that, in case of northward wind ($\varphi = 0$) , the ICDP z_{cN} ($C'(z = z_{cN}) = C'_{\max} > 0$) and, in case of southward wind ($\varphi = 180^o$), the IDDP z_{dS} ($C'(z = z_{dS}) = C'_{\min} < 0$) are at about 121km height. For non-meridional directions of wind both - the ICDP z_c and IDDP z_d exist. During westward ($\varphi = 90^o$) and eastward ($\varphi = 270^o$) winds, $z_{cW} = z_{dE} \approx 116 km$ and $z_{cE} = z_{dW} \approx 131 km$.

Here and hereafter the lower thermosphere parameters in equations (1-6) are used in accordance with NRLMMSISE-00 model [19]. $z_{c,d}, z_m = h_m, H_{ic}$ and normalized electron density N_e / N_{om} will be given with 0.5km, 0.05km and 0.05 accuracy, respectively.

If we assume that neutral particles in the lower thermosphere have barometric distribution, then $\nu_{in}, \kappa \propto \exp(-z / H)$, and from equation (8) the maximal value of $C'(z, \varphi = 0) = C'_x(z)$

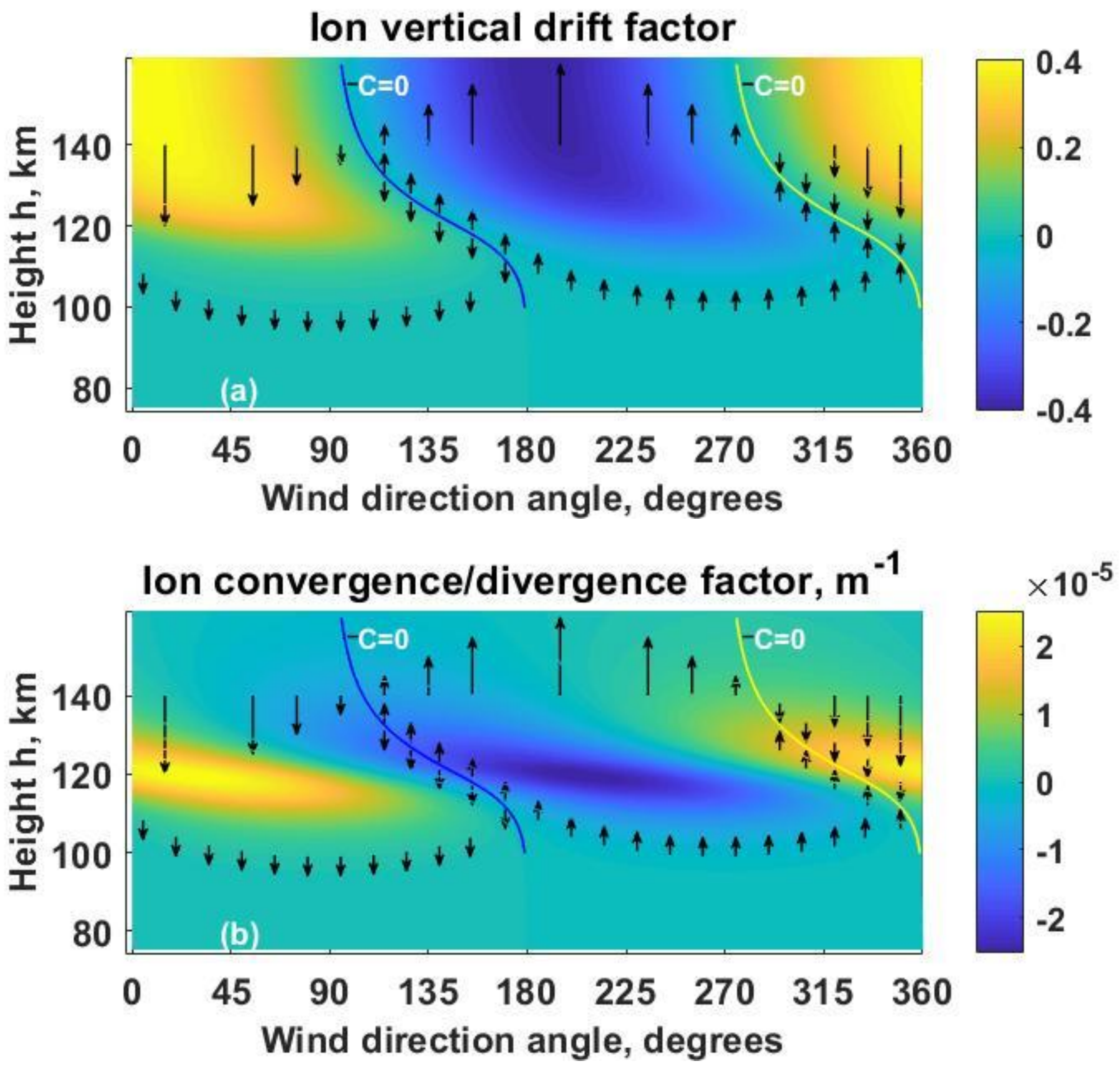

Figure 1. (**a**) The ion vertical drift $C(z,\varphi)$ and (**b**) convergence/divergence $C'(z,\varphi)$ factors height profiles for various horizontal wind (**V**) direction angle $\varphi = \angle \hat{\mathbf{x}}\mathbf{V}$ $(0 \le \varphi < 360^o)$ at north hemisphere mid-latitude regions (45°±2° N, 45°±2° E) with geomagnetic declination $I=61^o$ ±2°. Blue and yellow lines correspond to the heights where ions vertical drift factor $C=0$ at their divergence region (C'<0) for wind direction angles $\varphi_{b,W-S} = 90^o + \arctan g(\kappa / \sin I)$ and at their convergence region (C'>0) for $\varphi_{b,E-N} = 270^o + \arctan g(\kappa / \sin I)$, respectively. The arrows express the ion drift velocity direction at given height and horizontal wind direction angle φ determined by drift factor $C(z,\varphi)$, equation (7). The lower height arrows correspond to the height regions with expectably, comparatively smaller values of ion drift velocity ($C \approx 0.02 C_{\max}$).

can be obtained:

$$C'_{x\max}(\varphi = 0) = \frac{1}{2H} \sin I \cos I \ , \qquad (11)$$

which corresponds to $\kappa = 1$ ($\nu_{in} = \Omega_i$). H is the atmospheric scale. So, for the northward wind the ICDP z_{cN} corresponds to the height where $\nu_{in} = \Omega_i$ and for heavy metallic ions (Fe+) it is located at about

$z_{cN} \approx 121km$. In case of southward wind ($\varphi = 180^o$) $C'_{x\min}(\varphi = 180^o) = -C'_{x\max} = -(1/2H)\sin I \cos I$ and the IDDP $z_{dS} = z_{cN} \approx 121km$. For the mid-latitude regions ($\sin I \cos I \neq 0$), in case of presence of the meridional wind ($\varphi = 0$ or $\varphi = 180^o$) the ICDP z_{cN} ($(\partial \mathrm{w}_i / \partial z)\min < 0$) and IDDP z_{dS} already exist (Figure 1b) and they vanish at equatorial ($I \to 0$) and polar ($I \to 90^o$) regions.

For the barometric atmosphere, in case of westward wind $C'(z, \varphi = 90^o) = C'_v(z)$, estward wind $C'(z, \varphi = 270^o) = -C'_v(z)$, the ICDP $z_c(\varphi = 90^o) \equiv z_{cW}$ and $z_c(\varphi = 270^o) \equiv z_{cE}$ are located at about 0.9H ($z_{cW} - z_{cN} = -0.5H\ln(3 + \sqrt{8})$) below and above ($z_{cE} - z_{cN} = -0.5H\ln(3 - \sqrt{8})$) the point $z_{cN,dE} \approx 121km$, where:

$$C'_{v\max} = \frac{1}{4H}\cos I . \qquad (12)$$

In this case, the IDDP $z_d(\varphi = 90^o) \equiv z_{dW}$ and $z_d(\varphi = 270^o) \equiv z_{dE}$ are located at about *0.9H* above and below $z_{cN,dS} \approx 121km$, where $C'_{y\min} = -(1/4H)\cos I$.

Figure 1 shows that in case of meridional ($\varphi = 0$ or $\varphi = 180^o$) and zonal winds ($\varphi = 90^o$ or $\varphi = 270^o$), the location of convergence/divergence points and the values of C' at these points are close to those estimated for barometric atmosphere by equations (11) and (12), for the atmospheric scale heights *H*=8-10km. So, for northward wind there is only the ICDP (*C'*>0), while for southward wind - the IDDP (*C'*<0). Thus, according to equation (9), the development of electron convergence or divergence processes at $z_{cN} = z_{dS} \approx 121km$ are only expectable. For westward and eastward winds there are both convergence and divergence points and, correspondingly, the electron density behavior, equation (9), is determined by convergence and divergence processes developed in this region. For any other directions of the horizontal wind, *C* and *C'* factors are determined by their sums for meridional and zonal winds ($C_x(z)\cos\varphi$, $C'_x(z)\cos\varphi$, $C_y(z)\sin\varphi$ and $C'_y(z)\sin\varphi$), equations (7) and (8), the ICDP and IDDP locations are different.

Figure 1 shows that depending on wind direction (φ) the ICDP z_c ($C'(z = z_c) = C'_{\max} > 0$) and IDDP z_d ($C'(z = z_d) = C'_{\min} < 0$) can be located between 100km and 140km heights. In these regions of height the ion vertical drift factor *C(z)* is different (*C=0, C>0, C<0*). Therefore, according to equation (9), various scenarios of electron/ion convergence into a thin layer and formation of sporadic E can be developed.

We consider the possible scenario of Es type layer formation (*C'>0*) when ion vertical drift caused by horizontal wind: **(1)** *VC=0*, ***(2)*** *VC>0* is downward, **(3)** *VC<0* is upward, and also when **(4)** ion divergence occurs (*C'<0*).

(1) The condition of $VC(z = z_b) = 0$ (*C=0*) occurs at midlatitude lower thermosphere during east-northward and west-southward winds. $z = z_b$ is height where ion upstream and downstream flux caused by horizontal wind is balanced and $\mathrm{w}_i(z = z_b) = 0$ (see Figure 1 and equation (1)). In case of smaller influence of ion ambipolar diffusion on its vertical motion, $|CV| >> \left|\frac{D_a}{N_e}\frac{\partial N_e}{\partial z}\right|$, the value of $\mathrm{w}_i(z = z_b) \approx 0$, equation (1). In the considered midlatitude region the ions vertical drift balance points exist at 100-140km for the east-northward $285^o < \varphi < 360^o$ and its opposite west-southward $105^o < \varphi < 180^o$ winds, equations (1) and (7). Here $C(z = 140km, \varphi \approx 105^o; 285^o) = 0$.

For east-northward wind the condition of $C(z=z_b)=0$ $(-C_xV\cos\varphi - C_yV\sin\varphi = 0)$ occurs in the ion convergence (C'>0) region (see Figure 1), where the ion upward drift $-C_yV\sin\varphi$>0 (z<zb), caused by horizontal wind velocity east component ($U_y = V\sin\varphi < 0$), is balanced by their downward drift $-C_xV\cos\varphi < 0$ (z>zb), caused by the northward component ($U_x = V\cos\varphi > 0$). In this case the horizontal wind direction angle is $\varphi = 270^o + \arctan g(C_y / C_x) \equiv \varphi_{bE-N}$. When $\varphi_{bE-W} = 307^o$, ICDP $z_c \approx 127km$ and $\mathrm{w}_i(z=z_b)=0$ ($z_c \approx z_b$). In this case, from equation (9) the convergence layer and correspondingly, sporadic E formation are expected at height $z_c = z_b$.

When ion vertical drift velocity $VC(z=z_c)=0$, then according to equation (9), in the ICDP z_c, region ion convergence into a thin layer (convergence instability), caused by horizontal wind, can be balanced by their ambipolar diffusion and $C'V = \frac{2D_a}{H_{ic}^2}$. In this case the formation of sporadic E type thin layer with minimal thickness $H_{ic} = 1-3km$ at 120-130km heights is possible for the horizontal wind velocity about 50-150m/s or greater ($H_{ic} \propto 1/\sqrt{V}$). In case of small changes in the total electron content (TEC) in lower thermosphere, the Es type layer peak density N_{em}/N_{om} ($N_{em} \propto 1/H_{ic}$) can be increased by order of magnitude (for $H_{ic}(t=t_o)=10km$).

During west-southward wind the condition of $C(z=z_b)=0$ occurs in ion divergence (C'<0) region (see Figure 1), where the ions upward drift velocity $-C_yV\sin\varphi$>0 ($z > z_b$), caused by the wind velocity west component $U_y = V\sin\varphi > 0$, is equal to their downward drift $-C_xV\cos\varphi > 0$ ($z < z_b$), caused by the wind southward component $U_x = V\cos\varphi < 0$. In this case wind direction angle is $\varphi_b = 90^o + \arctan g(C_y / C_x) \equiv \varphi_{bW-S}$. For the horizontal wind west-east direction with $\varphi = 127^o$ at the IDDP $z_d(\varphi = 127^o) \approx 127km$ and $C(z=z_d)=0$. In this case, different from wind opposite east-north direction $\varphi = 307^o$ ($z_c(\varphi = 307^o) \approx 127km$), at the height of about 127km the ion/electron density divergence occurs, equation (9), and their upstream and downstream flow from this region increases. When ICDP is $z_c \approx 112km$ the electron convergence in the thin dense layer is possible during the downstream flow (*C>0*), shown by equation (10), and the formed Es type layer can be localized below ICDP regions with $C'(z)V \to +0$, $C(z)V \to +0$, ($\mathrm{w}_i \to -0$). Here $+0$ and -0 denote negligibly small positive and negative values, respectively. The condition $C' \to 0$, $C \to 0$ means that, for given direction of the wind, the values of $(C'/C'_{\max}) << 1$, $C << 1$ are decreased.

The ion/electron wind induced upstream flow ($z > 127km$) from region with $C(z=z_d)=0$ (see Figure 1) makes their diffusive displacement to the upper height quicker than in case of absence of wind.

(2) The ion downward drift (*VC>0*) at ICDP, caused by horizontal wind ($VC_x\cos\varphi + VC_y\sin\varphi > 0$), in addition to its west-southward direction, also occurs for northward ($\varphi = 0$), north-west and westward winds (see Figure1). In these cases the ion convergence into a thin layer and correspondingly sporadic E formation, descending towards lower regions identified by $C'(z)V \to +0$, $C(z)V \to +0$, are expected. For different directions of horizontal wind, when $307^o < \varphi < 360^o$ ($270^o + \arctan g(\kappa(z=z_{cb})/\sin I) < \varphi < 360^o$, $z_{cb} \equiv z_c = z_b$), the ICDP z_c is located above the point where *C=0* ($z_c > z_b$) and correspondingly the convergence layer should descent and locate at z_b height region, equation (9).

(3) When $285^o < \varphi < 307^o$ $(285^o < \varphi < 270^o + \arctan g(\kappa(z = z_{cb}) / \sin I))$, then ICDPs are located below the region with *C=0* (127km<z<140km) and the convergence layer should have a tendency of upwelling to this region ($w_i = 0$). Here for $\varphi = 285^o$ the condition *C=0* occurs at about 140km, where ion diffusive displacement for $H_{ic} < 5km$ exceeds their convergence caused by wind with velocities 50-150m/s and formation of high density ($N_{em} / N_{om} > 1$) thin ($H_{ic} < 5km$) layer during ions upward flux (*C<0*) is expectable to about 140 km. For horizontal wind direction $260^o < \varphi < 285^o$, the region with condition *C=0* located at z>140km, where $C'(z)V \to +0$, $C(z)V \to -0$ for 140-150km heights, the formation of convergence layer with smaller density is expected, compared to the wind direction with $285^o < \varphi < 307^o$. Note, that in these cases (*CV*<0), with increase of wind velocity, significant increase in the convergence layer is not expected, therefore the increase of upward drift of this layer to the region with $C'(z)V \to +0$, $C(z)V \to -0$ $(w_i \to +0)$ occurs.

(4) During southward wind ($\varphi = 180^o$) the divergence factor *C'<0*, equation (7), and in the region of heights 100-140km divergence processes of electron density are expected, equation (9). If the influence of southward component of wind velocity $V \cos\varphi < 0$ on ions upward drift is dominant, ($90^o + \arctan g(\kappa(z) / \sin I) < \varphi < 270^o$ i.e $(-VC_x \cos\varphi - VC_y \sin\varphi > 0)$, then formation of their high density convergence layer ($N_{em} / N_{om} > 1$) is less expected. Here it is important to note, that the development of above mentioned ion convergence or/and divergence processes also depend on its initial layer location with respect to the points z_c, z_d and z_b.

The winds with directions $\varphi = 105^o, 127^o, 285^o, 307^o$, for which $C(\varphi = 105^o, 285^o; z \approx 140km) = 0$ and $C(\varphi = 127^o, 307^o; z \approx 127km) = 0$, correspond to the considered regions (45°±2° N, 45°±2° E; *I=61°* ±2°) and can be estimated similarly by equations (2, 3) and (7) for the other midlatitude regions.

The details of the above described possibility of the electron density height profile behavior $N_e(z,t)$ under the influence of horizontal homogeneous wind, Es type dense thin layer formation for its relatively main directions and the development of divergence processes will be shown using numerical solution of equation (6) [20, 21, 22].

3. Results and discussion

By numerical solution of equation (6) we will demonstrate the normalized electron density height profile $N_e(h,t) / N_{om}$ behavior at lower thermosphere 90-150km height regions. For predominantly main directions of the horizontal wind for which we theoretically show a possibility of Es layer formation (equation (9)) at fixed height (with *C=0*), its downward and upward motions to the region with *C=0* or those where ion convergence positive factor (*C' >0*) vanishes. Considering wind direction for which ions drift factor $C(z = z_{c,d}) = 0$ and additional eight directions (north, north-west, ..., east-north), their influence on development of ion/electron divergence processes (when *C'<0*) is also seen.

At the first step, when $C(z = z_{c,d}) = 0$, we show that the influence of homogeneous horizontal wind on $N_e(h,t) / N_{om}$ behavior and Es layer formation is important at V=50m/s. In this case we assume relatively wide layer of heavy metalic ions at initial time $H_{ic}(t = t_o) = 16km$ when small changes in electron/ion density are expected due to their ambipolar diffusion at the absence of wind. For the lower thermosphere with dominant Fe+ ions the values of $H_{ic} = 8 - 16km$, which is used in suggested simulations, is close to the value of $k(T_i + T_e) / Mg$ [19]. Note, that for some midlatitude lower thermosphere regions the horizontal wind velocity of about 50m/s corresponds to the maximal values of mean seasonal meridional and zonal winds, because its high value is 100m/s or even higher [23,24,25].

Figure 2 presents the behavior of the normalized height profile of electron density $N_e(h,t)/N_{om}$ in the mid-latitude lower thermosphere in case of absence of wind (**V**=0) for its initial distribution peak height (**a**) $z_{om}=142km$, (**b**) $z_{om}=127km$, (**c**) $z_{om}=112km$ and (**d**) $z_{om}=97km$, and during presence of horizontal wind with V=50m/s directed (**a n-w), (b n-w**), (**c n-w**), (**d n-w**) to east-northward ($\varphi=307^o$, $z_{cE-N}=z_b$) and (**a w-s**), (**b w-s**), (**c w-s**), (**d w-s**) to west-southward ($\varphi=127^o$, $z_{dW-S}=z_b$), respectively.

Figure 2 shows the possibility of electron convergence into a dense thin layer, $N_{em}/N_{om}>1$ and $H_{ic}(t>t_o)<H_{ic}(t=t_o)$, (Figures 2a e-n, 2b e-n, 2c e-n, 2b w-e and 2c w-e). It also shows that their density divergence ($N_{em}/N_{om}<1$) dominates (Figure 2a w-s) and development of these processes is negligible (Figures 2d e-n and 2d w-s) under the influence of horizontal homogeneous wind, for various locations of the initial electron density $N_e(z,t=t_o)$ peak height ($z_{om}=142km$, $z_{om}=127km$, $z_{om}=112km$ and $z_{om}=97km$- Figures 2a-2d) at 90-150km height regions of the lower thermosphere. Here we demonstrate the electron convergence/divergence processes under the influence of the east-north directed $\varphi=307^o$ wind (middle panels), $C(\varphi=307^o,z=z_c\approx127km)=0$ and $z_d\approx112km$ (see Figure 1), as well as its opposite west-south directed wind $\varphi=127^o$ (right panels), $C(\varphi=127^o,z=z_d\approx127km)=0$ and $z_c\approx112km$ (see Figure 1). In case of absence of wind (**V**=0), for *t-t*$_o$*<0.4h*, changes in electron density $N_e(z,t)/N_{om}$ are smaller due to ambipolar diffusion of ions (Figures 2b, 2c and 2d), while they are noticeable (Figure 2a) only at upper location of its layer ($z_{om}=142km$). When $z_{om}=z_c=z_b\approx127km$ (where *C=0,C'>0* and $w_i=0$), electrons converge into higher density ($N_{em}/N_{om}>1$) thin layer (convergence instability), under the influence of east-north directed $\varphi=307^o$ wind, occurring at $z\approx127km$ (Figure 2b e-n), which is expected from equation (9). When peak height of the initial electron density z_{om} is located above 127 km (*z*$_{om}$*=142km*), where *C (z>127km) <0*, their convergence layer descends to $z_c=z_b\approx127km$ (*C=0*). When z_{om} is located at IDDP $z_d\approx112km$ (Figure 2c), then the electron convergence layer for *z>112km* moves upward (*C*<0) to the height region of $z_c=z_b\approx127km$. However, when z_{om} is located below $z_d\approx112km$ ($z_{om}=97km$, Figure 2d), then their downward flux from divergence region and smaller values in ion ambipolar diffusion do not change its density significantly (Figure 2d e-n).

Divergence and convergence processes developed during the west-south directed wind, $\varphi=127^o$ at the IDDP $z_d(\varphi=127^o)=z_c(\varphi=307^o)\approx127km$ (*C=0* and *C'<0*) and ICDP $z_c(\varphi=127^o)=z_d(\varphi=307^o)\approx112km$ (*C>0* and *C'>0*) (see Figure 1) influence electron density behavior (Figure 2, right panels). In this case when z$_{om}$>127km (z$_{om}$=142km -Figure 2a), the electron upstream flow is dominant, $C(\varphi=127^o,z>127km)<0$ (see Figure 1), and its density decreases ($N_{em}/N_{om}<1$, Figure 2a w-s). When z$_{om}$=127 km (Figure 2b), a part of electron density initial layer (z>127km) vanishes by their upstream flow, $C(\varphi=127^o,z>127km)<0$, and ion ambipolar diffusion increses, but downward moving electrons for height of z<127km is converged ($N_{em}/N_{om}>1$) at $z_c\approx112km$ and below (Figure 2b w-s). The development of electron convergence into thin dense layer ($N_{em}/N_{om}>1$), which probably move downward (*C >0*) to the region with $C\to+0,C'\to+0$, is more noticeable ($N_{em}/N_{om}>1.5$) for $z_{om}=112km$. The development of electrons convergence at $z_c\approx112km$ for its initial layer lower location of $z_{om}=97km$ is less noticeable ($N_{em}/N_{om}\approx1$) in this case of *V*=50m/s.

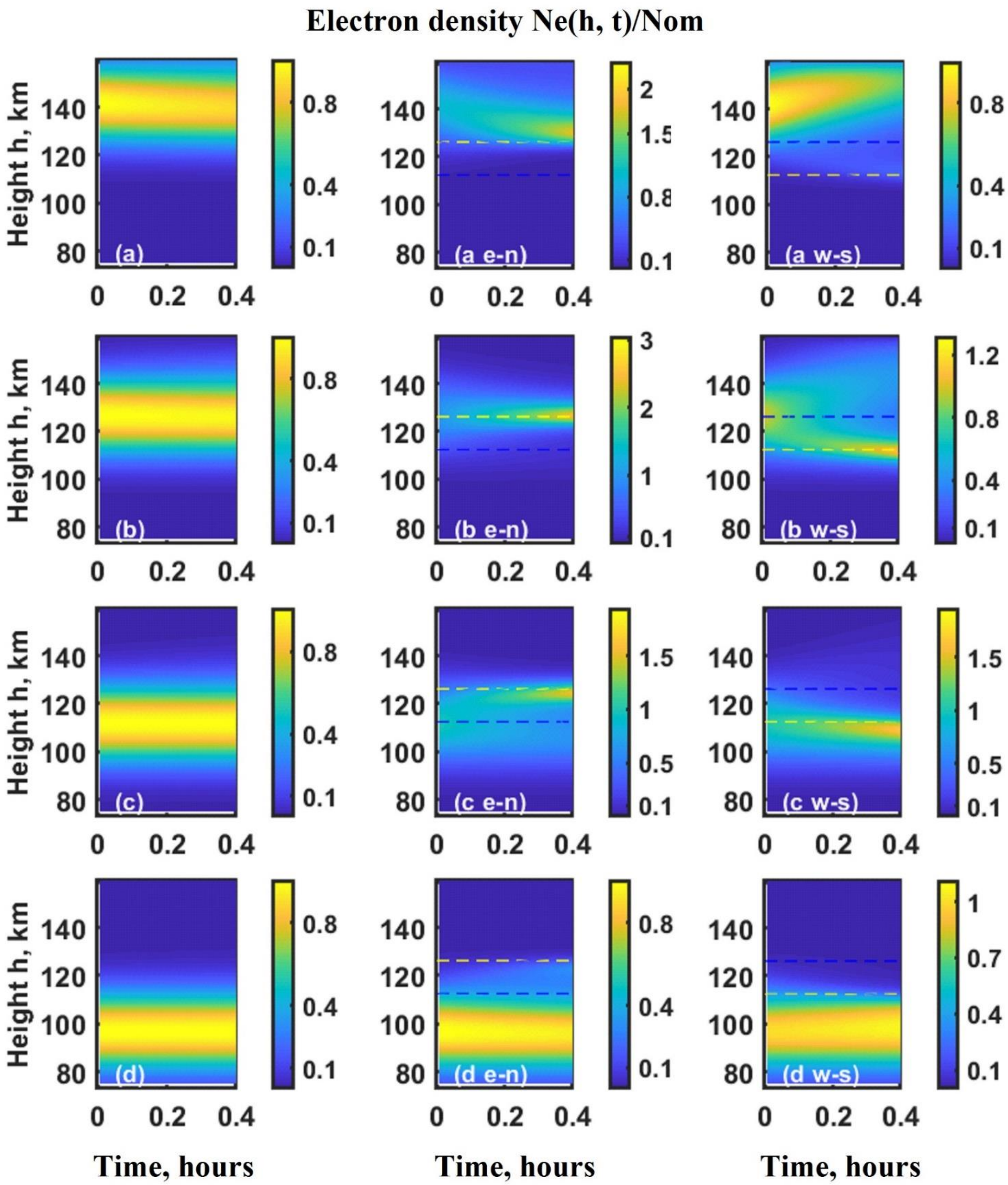

Figure 2. The behavior of the normalized height profile of electron density $N_e(h,t)/N_{om}$ in the mid-latitude lower thermosphere in case of absence of wind (**V**=0) for its initial distribution peak height (**a**) $z_{om} = 142km$, (**b**) $z_{om} = 127km$, (**c**) $z_{om} = 112km$ and (**d**) $z_{om} = 97km$, and during presence of horizontal wind with V=50m/s directed (**a n-w), (b n-w**), (**c n-w**), (**d n-w**) to east-northward ($\varphi = 307^o$, $z_{cE-N} = z_b$) and (**a w-s**), (**b w-s**), (**c w-s**), (**d w-s**) to west-southward ($\varphi = 127^o$, $z_{dW-S} = z_b$), respectively. Yellow and blue dashed lines correspond to the heights of ICDPs: $z_{cE-N}(\varphi = 307^o) \approx 127km$ and $z_{cW-S}(\varphi = 127^o) \approx 112km$ and IDDPs: $z_{dE-N}(\varphi = 307^o) \approx 112km$ and $z_{dW-S}(\varphi = 127^o) \approx 127km$, respectively.

Figure 2 also shows the possibility of Es type layer formation and development of divergence processes of electrons density as well as in the lower thermosphere, under the influence of considered horizontal wind (V=50m/s) for $t\text{-}t_o<0.4h$, which agrees with its behavior described by equation (9). Relatively quick formation ($\frac{\partial N_e}{\partial t} \propto C'V$) of high density Es type layer, its vertical motion ($\frac{\partial z_m}{\partial t} \propto -CVa$) and tendency to saturation in its location, where $C=0$ and $C'>0$ or $VC \to 0, VC' \to +0$, should be more noticeable for greater values of the horizontal wind velocity.

We will consider electron density $Ne(z,t)$ behavior for eight main directions of the horizontal wind (**V**): north ($\varphi = 0, z_c \approx 121km$) north-west ($\varphi = 45^o, z_c \approx 118km, z_d \approx 140km$), west ($\varphi = 90^o$, $z_c \approx 116km$, $z_d \approx 131km$), west-south ($\varphi = 135^o, z_c \approx 112km, z_d \approx 126km$), south ($\varphi = 180^o, z_d \approx 121km$), south-east ($\varphi = 225^o, z_c \approx 140km, z_d \approx 118km$), east ($\varphi = 270^o, z_d \approx 116km, z_c \approx 131km$) and east-north ($\varphi = 315^o, z_c \approx 126km, z_d \approx 112km$). For brevity the initial peak height of electron density is assumed at z_{om}=120km. For this case the most charachtristics of the Es type layer formation and also its motion/localization to regions with $C=0$ and $C'>0$ or $VC \to 0, VC' \to +0$, should be revealed. In order to have more profound diffusive effect in formation of sporadic E, relatively narrow initial electron density layer with $H_{ic} = 8km$ will be considered.

Figure 3 presents **t**he behavior of the normalized electron density height profile $N_e(h,t)/N_{om}$ in the mid-latitude lower thermosphere in case of horizontal wind with V=100 m/s directed to (**n**) north - φ=0, (n-w) north-west - $\varphi=45^o$, (w) west - $\varphi=90^o$, (w-s) west-south - $\varphi=135^o$, (s) south - $\varphi=180^o$, (s-e) south-east - $\varphi=225^o$, (e), east - $\varphi=270^o$, (e-n) east-north - $\varphi=315^o$. The ion distribution characteristic scale at initial time, equation (9), is $H_{ic}(t = t_o) = 8km$. Here for the Es type layers the peak densities (at $z = z_m$ or $h = h_m$) and thicknesses at $t\text{-}to=1.5h$ are: $N_e(z_m \approx 108km,\ \varphi = 0)/N_{om} \approx 5, H_{ic} \approx 1.58km$;

$N_e(z_m \approx 99km_m,\ \varphi = 45^o)/N_{om} \approx 6.2, H_{ic} \approx 1.26km$;

$N_e(z_m \approx 98km,\ \varphi = 90^o)/N_{om} \approx 6.5, H_{ic} \approx 1.25km$;

$N_e(z_m \approx 100km,\ \varphi = 135^o)/N_{om} \approx 3.7, H_{ic} \approx 1.6km$;

$N_e(z_m \approx 137km, t - t_o = 0.7h, \varphi = 270^o)/N_{om} = 1.2, H_{ic} = 5.6km$;

$N_e(z_m \approx 124km,\ \varphi = 315^o)/N_{om} \approx 4.3,\ H_{ic} \approx 1.5km$.

Figure 3 shows that the formation of Es type dense ($N_{me}(z, t - t_o = 1.5h)/N_{om} \approx 1.2 - 6{,}5$) thin ($H_{ic} \approx 1.2 - 5.6km$) layer occurs under the influence of horizontal wind with velocity 100m/s for its north (panel n), north-west (panel n-w), west (panel w), west-south (panel w-s) and east-north (panel e-n) directions. In cases of wind directions with $\varphi = 0$, $\varphi = 45^o$, $\varphi = 90^o$ and $\varphi = 135^o$, the Es type layer descend ($C>0$) to the regions with $VC \to +0, VC' \to +0$ (Figure 1), where $z_m(\varphi = 0) \approx 108km$, $z_m(\varphi = 45^o) \approx 99km$, $z_m(\varphi = 90^o) \approx 98km$ and $z_m(\varphi = 135^o) \approx 100km$ (Figures 3n, 3n-w, 3w and 3w-s), while for east-north directed ($\varphi = 315^o$) wind it is formed at

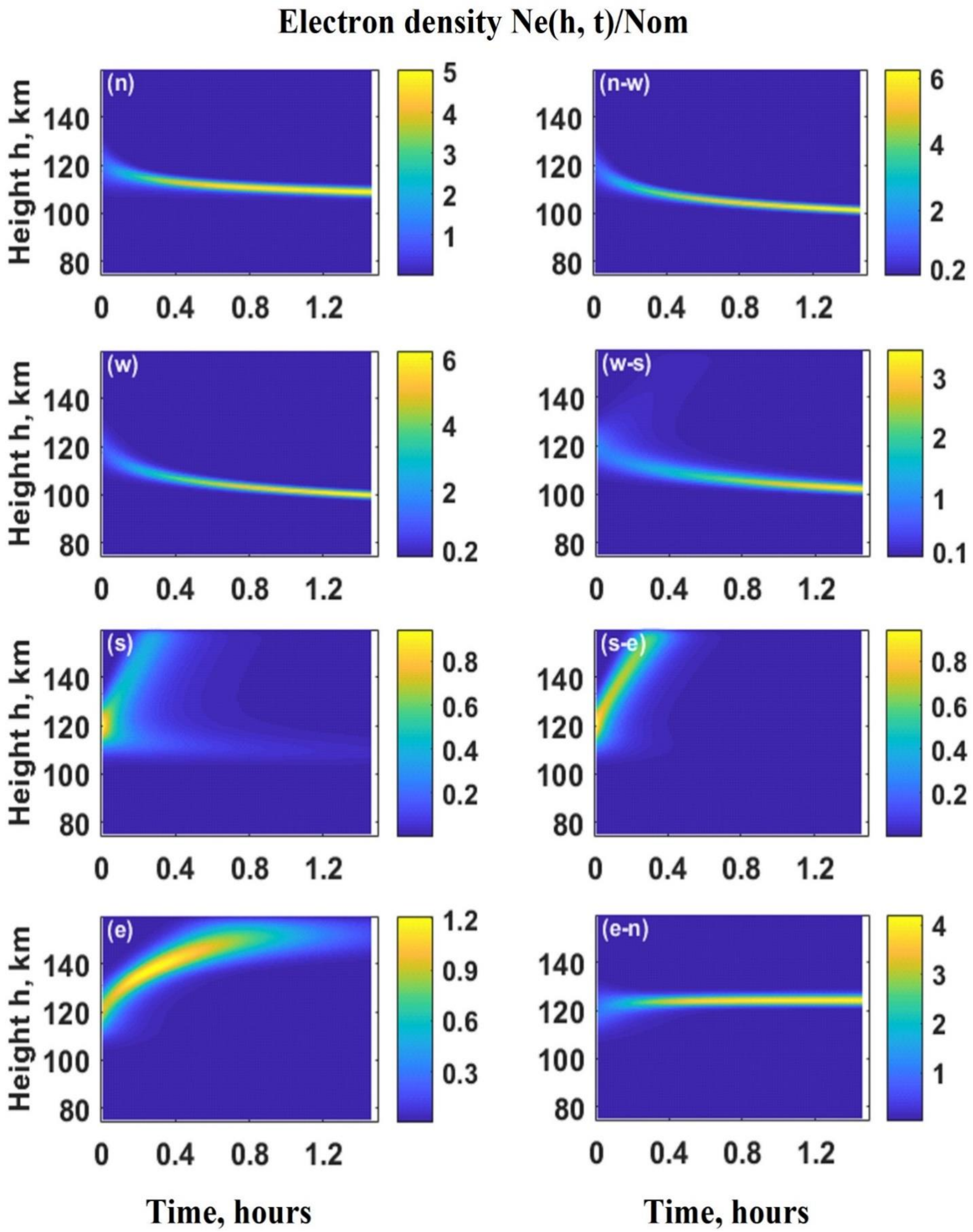

Figure 3. The behavior of the normalized electron density height profile $N_e(h,t)/N_{om}$ in the mid-latitude lower thermosphere in case of horizontal wind with *V*=100 m/s directed to (**n**) north - φ=0, (**n-w**) north-west - φ=45^o, (**w**) west - φ=90^o , (**w-s**) west-south - φ=135^o, (**s**) south - φ=180^o, (**s-e**) south-east - φ=225^o, (**e**), east - φ=270^o, (**e-n**) east-north - φ=315^o.

$z_b(\varphi = 315^o) = z_m \approx 124km$, $C(z = z_b) = 0$. Here the lower location of the peak heights of Es type layer corresponds to the regions with $C \to +0\,(\mathrm{w}_i \to -0), C' \to +0$ which occur at the lowest heights for westward wind (see Figure 1).

During the east-northward wind $\varphi = 315^o$ the upward motion of Es type layer is also noticeable to its location at $z_b \approx 124km$ (Figure 3e-n) for *t-t$_o$<1h* (similar to the one shown in Figure 2c e-n). In this case the ion characteristic scale $H_{ic}(t - t_o = 1h) \approx 1.3km$ corresponds to the minimal thickness of the Es layer, which is balanced by ambipolar diffusion of ions at $z_b \approx 124km$ region,with about $H_{ic} = \left(2D_a / VC'\right)^{1/2}$.

Figure 3e shows that during eastward wind ($\varphi = 270^o$) with velocity V=100m/s the ions/electrons drift upward (*CV<0*) and the convergence layer $N_e(z = z_m, t - t_o = 0.7h, \varphi = 270^o) / N_{om} = 1.2, H_{ic} = 5.6km)$ formed in upper heights ($z_m \approx 137km$) is comparatively wider than the one in cases of other directions of wind noted above (Figures 3n, 3n-w, 3w and 3w-s) where their drift was downward (*CV>0*). The formed convergence layer for time of *t-to>0.8h* vanishes ($C' \to +0$, $C \to -0$) to about 150km heights. In this case a decrease in *C'* at the upper heights is also accompanied with an increase of ambipolar diffusion displacement rate, which causes the convergence layer with $H_{ic} \approx 5.6km$ to vanish at z>137km ($H_{ic} = \left(2D_a / VC'\right)^{1/2}$). The formation of the Es type layer and its localization to the height regions with *C=0* ($\mathrm{w}_i = 0$) and *C'>0* , or $VC' \to +0$ and $VC(z) \to 0$ ($\mathrm{w}_i \to 0$) are expectable relatively faster at greater horizontal wind velocity (**V**).

Figure 4 presents the behavior of the normalized electron density height profile $N_e(h,t)/N_{om}$ in the mid-latitude lower thermosphere in case of horizontal wind with *V*=150 m/s directed to (n) north - φ=0, (n-w) north-west - φ=45^o , (w) west - φ=90^o , (w-s) west-south - φ=135^o, (s) south - φ=180^o, (s-e) south-east - φ=225^o, (e), east - φ=270^o, (e-n) east-north - φ=315^o. Here for the Es type layers the peak densities and thicknesses at *t-to=1.5h* are: $N_e(z_m \approx 108km,\ \varphi = 0) / N_{om} = 5.7, H_{ic} = 1.4km$; $N_e(z_m \approx 97km,\ \varphi = 45^o) / N_{om} \approx 6.8, H_{ic} \approx 1.18km$; $N_e(z_m \approx 95k,\ \varphi = 90^o) / N_{om} \approx 6.8, H_{ic} \approx 1.18km$; $N_e(z_m \approx 98km,\ \varphi = 135^o) / N_{om} \approx 4.1, H_{ic} \approx 1.4km$;

$N_{em}(z_m = 143km, \varphi = 270^o) / N_{om} \approx 1.3, H_{ic} \approx 5.2km$; $N_e(z = z_m, \varphi = 315^o) / N_{om} = 5.3, H_{ic} \approx 1.26km$.

Figure 4 shows that the formation of Es type layer under the influence of horizontal wind with V=150m/s occurs similarly but faster for its north (Figure 4n), north-west (Figure 4n-w), west (Figure 4w), west-south (Figure 4w-s) and east-north (Figure 4e-n) directions, than for wind velocity *V=100m/s* (Figure 3). The rates of formation and descend to the regions with $VC(z) \to +0, VC' \to +0$ [$z_m(\varphi = 0) \approx 108km$, $z_m(\varphi = 45^o) \approx 97km$, $z_m(\varphi = 90^o) \approx 95km$ and

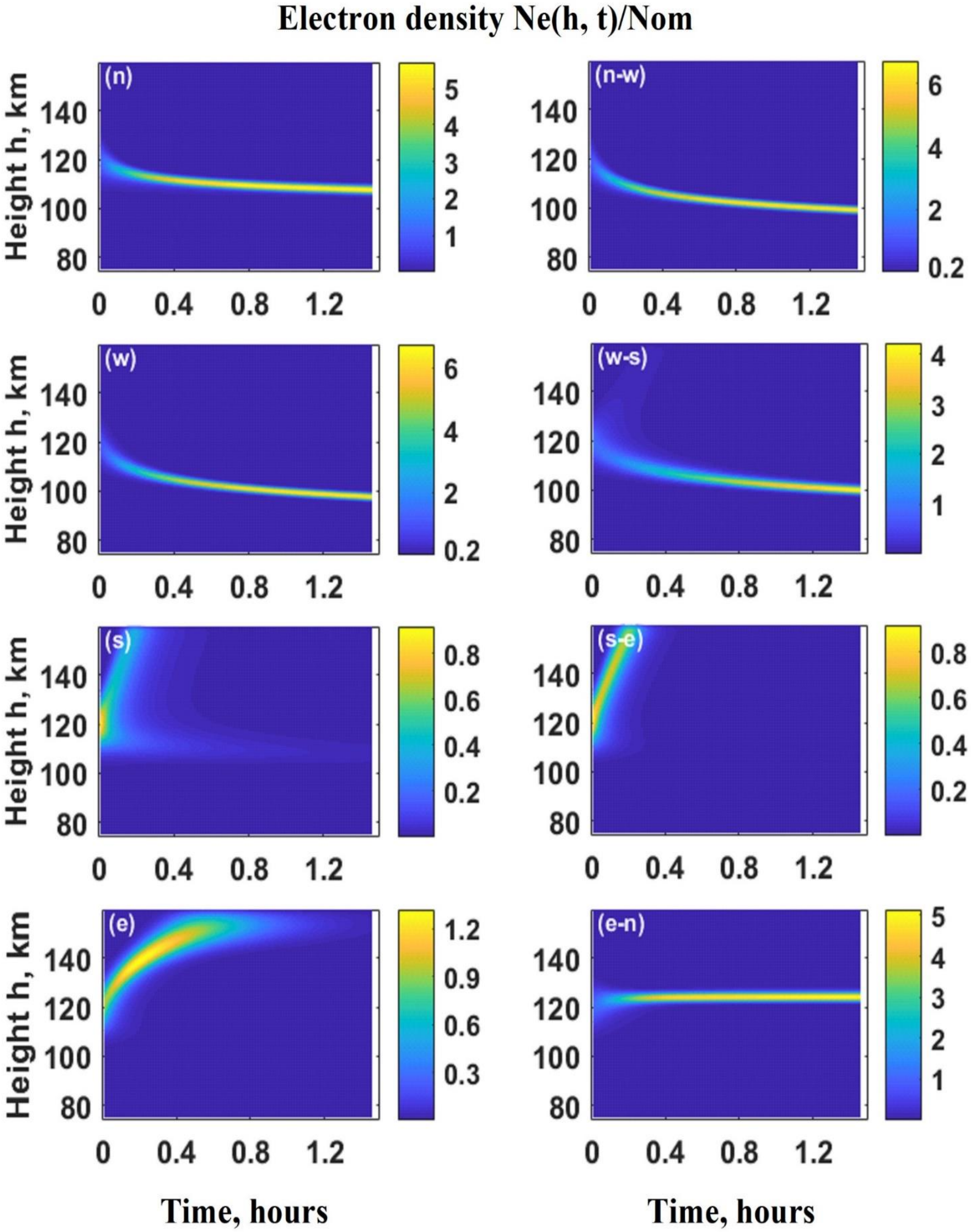

Figure 4. Same as Figure 3 but for the horizontal wind velocity *V=150m/s* are applied.

than those for the same directions of the wind velocity V=100m/s (see Figure 3). In these cases 1.5-time increase rate in electron densities is accompanied by about 1.5-time decrease in time of their descend to their final location to the regions with $VC(z) \to +0,\ VC^{'} \to +0$, where changes in their relatively small increased peak density and descent (than that of the for *V=100m/s*) vanish.

$z_m(\varphi = 135^o) \approx 98km$] of comparatively high density ($N_{me}(z, t - t_o = 1.5h) / N_{om} \approx 1.3 - 6.8$) and thin Es layers ($H_{ic} \approx 0.9 - 5.2km$) are about 1.5 times greater ($\frac{\partial N_e}{\partial t} \propto C'V$, $\frac{\partial z_m}{\partial t} \propto -CV$).

Note that small increase in Es type layer density in these locations at the bottom of the lower thermosphere can also be balanced or reduced by its decrease due to ion/electron recombination $\propto N_e^2$ [16, 26**].** The latter can be included in equation (6) and correspondingly in the suggested theoretical model simulations.

Relatively big increase in the peak electron density occurs during increase in the east-north directed ($\varphi = 315^o$) wind (Figure 4e-n). In this case 1.5-time increase in the wind velocity causes about 1.5 times quicker localization of the convergence layer to the region $z_b \approx 124km, C(z \approx 124km, \varphi = 315^o) = 0$, where its peak density increases (about $\propto \sqrt{V}$) and correspoding thickness (about $H_{ic} \propto 1/\sqrt{V}$) is smaller (Figure 3e-n and Figure 4e-n). For the greater values in opposite west-south directed ($\varphi = 135^o$) wind velocity *V=150m/s*, the electrons downstream flow is more noticeable (*C>0*) from IDDP $z_d(\varphi = 135^o) \approx 126km$, which converges into Es type layer below ICDP $z_c(\varphi = 135^o) \approx 112km$, at height $z_m(\varphi = 135^o) = 98km$ where $VC(z) \to +0$ ($w_i \to -0$), $VC' \to +0$.

Figure 4e shows that increase in the eastward wind velocity up to 150m/s correspondingly increases the charge particles vertical flow and high ambipolar diffusion in the upper heights gives less value in ion/electron convergence layer density $N_{em}(z_m \approx 143km, \varphi = 270^o) / N_{om} \approx 1.3$ ($H_{ic} \approx 5.2km$) with $z_m(\varphi = 270^o) \approx 139km$ formed in relatively short time ($\propto 1/V$), than in the case of smaller V=100m/s (Figure 3e). In this case the time of electron convergence layer existence is also shorter than that for smaller horizontal wind velocity (Figure 3). During greater horizontal wind velocity the electron convergence rate (*C'V>0*) and their vertical drift (*CV*<0) to the upper regions where $C'V < 2D_a / H_{ic}^2$, equation (9), $C' \to 0$ and $C \to -0$ causes relatively quick damping of its convergence layer than during V=100m/s (Figure 3e).

In case of wind direction $270^o < \varphi < 285^o$ the ion/electron convergence layer formation above 140 km with $H_{ic} \approx (2D_a / C'V)^{0.5}$ is similar to the one demonstrated on Figure 4e. The Es type layer formation and localization at height about 115-140km, where *C=0,* occur similarly to those shown in Figure 4 E-N during the other east-west directed wind (e.g., for wind direction with $\varphi = 285^o$, $\varphi = 325^o$ and $\varphi = 345^o$, is demonstrated on Figure S1). In this heigh region, in addition to wind velocity, the Es layer peak density also increases with decrease ($\propto 1/\sqrt{D_a}$) in ion ambipolar diffusion coefficients.

Figures 4s and 4s-e also show that the divergence of ion/electron from $z_d(\varphi = 180^0) \approx 121km$ and $z_c(\varphi = 255^0) \approx 140km$ regions happens faster under the influence of greater winds (V=150m/s) directed to south and south-east, than in case of its relatively smaller value of V=100m/s**.** In the presented simulation, the structural data of the lower thermosphere are used from NRLMSISE-00 model, for midlatitude *45°±2°N, 45°±2° E* and *I=61°±2°* regions in spring of 1998, between Solar maximum and minimum phases. Similarly, the results are extendable for other mid-latitude regions of the northern or southern hemispheres, for various directions and values of the horizontal wind.

So, we have shown theoretically and correspondingly numerically, that in the main observable heights of about 95-150km [4, 5] of the mid-latitude lower thermosphere the formation of sporadic E is possible during homogeneous horizontal wind. Besides Es layer formation in this region, its other observable features are also revealed.

The formation of Es type layer is expected more frequently during dominance of northward or westward components of the wind velocity (*C>0*) at heights below 120 km (Figures 3 and 4), which is the observed phenomenon [5]. The descent of the Es type layer, which is an observable phenomenon [3, 4, 5], occurs in most cases of its formation under the influence of horizontal homogeneous wind, equation (9), (Figures 3n-3w-s and Figures 4n-4w-s). In these cases an increase in the electron density in the regions of 95km-110km also can cause higher loss rate of the molecular ion (e.g., NO+) [26], and the long-lived metallic ions become dominant, which is also observed [27, 28]. In the framework of suggested theory seasonal variations in Es layers occurence are expectable [3, 5, 8, 29] determined by ion/electron density changes, as well as its regional peculiarities caused by geomagnetic declination changes and wind field variations for given midlatitude regions.

Note that for higher wind velocities, which are observable mostly at 100km-120km heights [24], they should have some vertical components [30], which also influences ion vertical drift velocity [16, 17]. In this case, in addition to northward or/and westward wind componentს, its downward component can cause ions additional downward flux and correspondingly Es layer shift to the bottom of the lower thermosphere at 90-100km height regions, which can be developed in the framework of the suggested theory. Since the Es layers could be formed by zonal or northward component of wind velocity, they could be observed more frequently at mid-latitudes, than in equatoial ($I \approx 0$) and polar ($I \approx 90^o$) regions (3-5).

So, according to the presented theoretical mechanism, many observational properties of the mid-latitude Es layer formation and location can be determined by horizontal wind direction and value. This mechanism does not exclude the additional influence of wind with vertical ($\partial V/\partial z \neq 0$) or horizontal shear on ion convergence and formation of sporadic E [17, 31, 32, 33]. In the lower thermpsphere the horizontal wind velocity **V** can be determined by the sum $\mathbf{V} = \mathbf{V_o} + \mathbf{V_w(z,t)}$, where $\mathbf{V_o}$ is homogeneous velocity and $\mathbf{V_w(z,t)}$ is varying perturbation caused by atmospheric waves, tidal motion or shear instability [5, 15, 17]. Here atmospheric waves or tidal wind, in addition to background horizontal wind ($\mathbf{V_o}$), could also lead the ion/electron additional convergence (when $C\,\partial V/\partial z = C\partial V_n/\partial z > 0$) or divergence (when $C\,\partial V/\partial z = C\partial V_n/\partial z > 0$) in the regions of polarization changes of perturbed velocity $\mathbf{V_w(z,t)}$. Wave induced convergence/divergence processes of charge particles could amplify or weaken the ones caused by background horizontal wind ($\mathbf{V_o}$). Such wave induced convergence of charged particles ($\propto C\frac{\partial V_w}{\partial z}$), equation (6), for vertical wavelength about 20-60km and with amplitude of about 50-100m/s, could be of the same order as the convergence caused by homogeneous horizontal wind ($\propto C'V_o$) with velocity 50-150m/s at the ICDP (Figure 1). Depending on the wavelength and amplitude of perturbed wind velocity, the additional convergence of ions at height regions, where it changes the polarization, and formation of multi-layered sporadic E are also possible [17]. In these cases, it is also important to take into account the influence of neutrals wind velocity direction and vertical changes of ions drift velocity, like the one in the presented theoretical model for homogeneous wind, and makes more predictable the behavior of ion/electron density in the lower thermosphere, thus the formation of sporadic E, its dynamics and location region [9, 10].

4. Conclusions

Theoretically and by corresponding numerical simulations it has been shown that the formation and localization of sporadic E (Es) layer in its mainly observable mid-latitude lower thermosphere heights of about 95-150km can be determined by homogeneous horizontal wind velocity direction and value. In this theory, differently from 'windshear' theory, the wind direction and value, in addition to geomagnetic field and vertically changing ion-neutral collision frequency, determine the minimal negative value of the heavy metallic ions (Fe+) drift velocity divergence, which in turn causes ion convergence into Es type horizontal thin layer. In the upper heights of the lower thermosphere, the Es layer peak density and thickness, in addition to the wind direction and values, are also controlled by ambipolar diffusion. Here, the decrease of the ambipolar diffusion coefficient produces increase of the Es layer density caused by horizontal wind.

It has been shown that in the lower thermosphere of the northern hemisphere, the Es layer caused by horizontal homogeneous wind can be located at height regions where (1) the ions vertical drift velocity is zero and its divergence is negative (east-northward wind), (2) the ions drift downward (northward and westward wind), which occurs more frequently, or (3) the ions drift upward (eastward wind), and their negative divergences vanish, and (4) in the case of dominance of southward wind the divergence of ion drift velocity is positive consequently ion density divergence occurs and Es type layer formation is not expectable. These ion/electron convergence/divergence processes faster for greater values in the horizontal homogeneous wind. In this case the speed of Es layer vertical motion to its expectable location is also faster for greater values of the horizontal wind velocity.

The importance and possibility of development of the suggested theory of sporadic E layer formation in case of horizontal wind with vertical shear has been noted.

Acknowledgements: This study is supported by Georgian Shota Rustaveli National Science Foundation Grant no. FR17-357.

References

[1] Whitehead J. D. J. Atmos. Terr. Phys., 1960, v.51, pp. 20-49 .
[2] Axford W. I. J. Geophys. Res., 1963, v.68, pp. 769-779.
[3] Whitehead J. D. J. Atmos. Terr. Phys., 1989, v.51, pp. 401-424.
[4] Mathews J.D. J. Atmos. Sol.-Terr. Phys., 1998, v.60, pp. 413-435.
[5] Haldoupis C. Space Sci. Rev., 2012, v.168, pp. 441–461, DOI 10.1007/s11214-011-9786-8.
[6] Bishop R. L., et al. J. Geophys. Res., 2005, v.110, (A04309), doi:10.1029/2004JA010686.
[7] Yeh W.-H., J.-Y. Liu, C.-Y. Huang and S.-P. Chen. J. Geophys.Res. Atmos., 2014, v.119, pp. 4568–4579, doi:10.1002/2013JD020798
[8] Liu, Y. et al. Adv. Space Res., 2018, v.62, pp. 426–439, doi.org/10.1016/j.asr.2018.04.026.
[9] Didebulidze G.G., Dalakishvili G., Todua M. AGU Fall meeting 2019, SA21B-3100.
[10] Dalakishvili G., Didebulize G.G., Todua M. LPMR2019_Abstractbook, 2019, pp. 10.
[11] Nygrén, T., Jalonen L., Oksman J., Turunen T. J. Atmos. Terr. Phys., 1984, v.46(4), pp. 373-381.
[12] Haldoupis C., Pancheva D. J. Geophys. Res., 2002, v.107, doi:10.1029/2001JA000212.
[13] Didebulidze G.G., Lomidze L. Ann. Geophys. 2008, v.26, pp. 1741-1749..
[14] Didebulidze G. G., Lomidze L.N., Phys. Lett. A, 2010, v.374, pp. 952-959, doi:10.1016/j.physleta.2009.12.026.
[15] Hysell D. L., Munk J., McCarrick M. Geophys.Res. Lett., 2014, v.41, pp. 6987–6993, doi:10.1002/2014GL061691.
[16] Yokoyama T., Yamamoto M., Fukao S. J. Geophys. Res., 2003, v.108(A2), 1054, doi:10.1029/2002JA009513.
[17] Didebulidze G.G., Dalakishvili G., Lomidze L., Matiashvili G. J. Atmos. Sol.-Terr. Phys., 2015, v.136, pp. 163-173, http://dx.doi.org/10.1016/j.jastp.2015.09.012
[18] Banks P.M., Kockarts G. Aeronomy. 1973, Part A, Academic, New York.
[19] Picone J. M., Hedin A.E., Drob D.P., Aikin A.C. J. Geophys. Res., 2002, v.107(A12), 1468, doi.org/10.1029/2002JA009,430.
[20] Du Fort E. C., Frankel S. P. MTAC. 1953, v.7, pp. 135-152.
[21] Lanser D., Verwer G. J. J. Com.Appl. Math., 1999, v.111, pp. 201-216.
[22] Hundsdorfer W., and G. J., pp. 325-417, Springer-Verlag Berlin Heidelberg.
[23] Portnyagin Y. I., Solovjova T. V. Ann. Geophys., 2000, v.18, pp. 300-315, doi:10.1029/2002JA009513.
[24] Larsen M.F. J. Geophys. Res.,2002, v.107 (A8), 1215, doi:10.1029/2001JA000218.
[25] Drob D. P., et al. J. Geophys. Res., 2008, v.113, A12304, doi:10.1029/2008JA013668.
[26] Lin Y.C., Chu Y.H. J. Geophys. Res. Space Phys., 2017, v.122, pp. 2505–2529, doi:10.1002/2016JA022855.
[27] Kopp E. J. Geophys. Res., 1997, v.102 (A5), pp. 9667-9674.
[28] Roddy P. A., et al. J. Geophys. Res., 2007, v.112, A06312, doi:10.1029/2006JA011713.
[29] Pietrella M., Pezzopane M., Bianchi C. Adv. Space Res., 2014, v.54, pp. 150–160.
[30] Hysell D. L., Larsen M. F., Sulzer M. P. J. Geophys.Res. Space Phys., 2014, v. 119, pp. 2345–2358, doi:10.1002/2013JA019621.
[31] Chimonas G. J. Geophys. Res. 1971, v.76, pp. 4578-4586.
[32] Shalimov S., Haldoupis C., Voiculescu M., Schlegel K. J. Geophys. Res., 1999, v.104, 28207.
[33] Shalimov S., Haldoupis C. Ann. Geophys., 2002, v. 20, pp. 1193–1201.

სპორადული E (Es) ფენის ფორმირება ერთგვაროვანი ჰორიზონტალური ქარის მიერ

გ. დალაქიშვილი, გ. დიდებულიძე, მ. თოდუა

რეზიუმე

თეორიული და შესაბამისი რიცხვითი გამოთვლებით ნაჩვენებია, რომ დედამიწის საშუალო განედების ატმოსფეროს ქვედა თერმოსფეროში სპორადული E (Es)ფენის ფორმირება და ლოკალიზაცია შესაძლებელია განისაზღვროს ერთგვაროვანი ქარის სიჩქარის მიმართულებით და სიდიდით. "ქარის წანაცვლების" (windshear theory) თეორიისაგან განსხვავებით, შემოთავაზებულ თეორიაში ქარის სიდიდე და მიმართულება, გეომაგნიტურ ველთან და სიმაღლის მიხედვით ცვლად იონ-ნეიტრალების დაჯახების სიხშირესთან ერთად, განსაზღვრავს მძიმე მეტალური იონების (Fe+) დრეიფის სიჩქარის დივერგენციის მინიმალურ უარყოფითი მნიშვნელობას, რომელიც, თავის მხრივ, იწვევს იონების მაღალი სიმკვრივის Es ტიპის ვიწრო ფენად კონვერგენციას. ქვედა თერმოსფეროს ზედა სიმაღლეებისთვის Es ფენის პიკის სიმაღლე ასევე კონტროლდება იონების ამბიპოლარული დიფუზიით.

ჩრდილოეთის ნახევარსფეროს ქვედა თერმოსფეროში ჰორიზონტალური ერთგვაროვანი ქარით გამოწვეული Es ფენა შესაძლებელია ლოკალიზდეს რეგიონებში სადაც (1) იონების დრეიფის სიჩქარე ნულია და მისი დივერგენცია უარყოფითია (აღმოსავლეთ-ჩრდილოეთის ქარი), (2) იონები დრეიფობენ ქვემოთ (ჩრდილოეთის და დასავლეთის ქარი), რომელიც უფრო ხშირია, ან (3) იონები დრეიფობენ ზემოთ და მათი უარყოფითი დივერგენცია ქრება და (4) სამხრეთის ქარის დომინირებისას იონების დრეიფის სიჩქარის დივერგენცია დადებითია, შესაბამისად, ადგილი აქვს მათი სიმკვრივის დივერგენციას და Es ტიპის ფენის ფორმირება არაა მოსალოდნელი. ქარის სიჩქარის დიდი მნიშვნელობებისთვის უფრო სწრაფია Es ფენის ფორმირება და ლოკაცია რეგიონებში, სადაც დრეიფის სიჩქარე ნულია ან ქრება. შენიშნულია შემოთავაზებული თეორიის გამოყენება ვერტიკალურად არაერთგვაროვანი ქარისთვის.

Формирование спорадического E (Es) слоя под воздействием однородного горизонтального ветра

Г.Т. Далакишвили, Г.Г. Дидебулидзе, М.М. Тодуа

Резюме

Теоретически, а также соответствующим численным моделированием показано, что образование и локализация спорадического E (Es) слоя в среднеширотной нижней термосфере Земли (где они в основном наблюдаемы) возможно определить с помощью величины и направления горизонтального ветра. В предложенной теории, в отличии от теории "ветрового сдвига" (windshear theory), в дополнении к геомагнитному полю и вертикально меняющейся частоте столкновения ионов с нейтральными частицами, направление и величина горизонтального ветра определяют минимальное отрицательное значение дивергенции скорости дрейфа тяжелых металлических ионов (Fe+), что, в свою очередь, вызывает их конвергенцию в горизонтальный узкий и плотный Es слой. В этом случае, в верхних высотах низкой термосферы высота максимальной плотности Es слоя также контролируется амбиполярной диффузией.

В нижней термосфере северного полушария, Es слой, возникший под воздействием однородного горизонтального ветра, локализуется в регионах, где (1) скорость вертикального дрейфа ионов равна нулю (восточно-северный ветер), (2) ионы дрейфуют ниже (северный и западный ветры), что бывает более часто, или (3) ионы дрейфуют вверх (восточный ветер) и их отрицательная дивергенция исчезает и (4) в случае превосходства южного ветра, дивергенция дрейфа скорости положительна и формирование Es слоя не ожидается. Формирование Es слоя и его локализация в ожидаемом регионе происходит быстрее для больших скоростей ветра. Отмечена возможность применения предлагаемой теории для вертикального неоднородного ветра.