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Formation of ionospheric sporadic E layers by atmospheric gravity waves

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Abstract

In this work the formation of mid-latitude sporadic E (Es) layer under the influence of atmospheric gravity waves (AGWs) evolving in the horizontal shear flow is studied. AGWs can be excited in the background horizontal wind with a linear horizontal shear (horizontal shear flow). These *in-situ* excited atmospheric waves, which act on metallic ions through ion-neutral collisions and Lorentz forcing, influence the ion vertical motion and can lead to their convergence into thin horizontal layers. The formation of sporadic E is investigated using a numerical model in two-dimensional case and temporal evolution of multi-layered sporadic E is demonstrated. The ion/electron density of Es layers depends on the amplitude of AGWs and spatial location of the layers is determined by the vertical wavelength of atmospheric gravity waves.

1. Introduction

The formation and behaviour of sporadic E (Es) in the lower thermosphere is one of the manifestation of atmosphere-ionosphere coupling [1-3]. Behavior of the ions and electrons in the lower thermosphere is influenced by the background neutral wind at this region, by the atmospheric waves [4-9], and by the tidal motions as well [10-12].

It is well established that at mid-latitudes the formation of sporadic E is mainly determined by the vertical shear in the horizontal neutral wind [13], while the existence of inhomogeneous neutral winds (with vertical shear) are associated with atmospheric tides ([12] and references therein).

Recently it was suggested that the vortical-type perturbations (shear waves) excited in the shear flows could also lead to vertical convergence of metallic ions, and thus the formation of sporadic E

[8, 9]. For such cases, the altitude of ion convergence is determined by the vertical wavelength of the excited perturbation, and therefore sporadic E could have multilayer structure, which itself is an observed phenomenon (see e.g. [16]).

In [8] and [9] it was found that behaviour of Es, formed by shear waves, could be influenced by AGW. On the other hand it is known that vortical perturbations (shear waves) excited in a horizontal shear flow can be transformed into AGW [17]. In this paper we show that AGWs, which evolve in the shear flow of neutral wind, could lead to the formation of multilayer sporadic E.

2. Methodology and Model description

2.1 Sporadic E Model

In order to investigate the variations of electron/ion density height profile in the nighttime mid-latitude lower thermosphere by influence atmospheric gravity waves, the continuity equation for the charged particles should be solved:

$$\frac{\partial N}{\partial t} + \nabla(N\mathbf{V}_i) = 0. \tag{1}$$

Here N is the concentration of ions (because of quasi-neutrality of ionospheric plasma, ion and electron densities are about same) and $\mathbf{V}_i$ is their velocity. In Eq. (1), which is used for heavy metallic ions, the production and loss rates are neglected. This is a valid assumption because (1) we consider nighttime conditions (no ion production) and (2) metallic ions have longer lifetime compared to the time scales that characterize AGWs.

The ion velocity $\mathbf{V}_i$ is influenced by their interaction with neutrals due to the collisions, by the Earth magnetic field and by a plasma thermal pressure. After neglecting inertial terms and electric field, the equation of motion of ions has the following form [16]:

$$-\frac{1}{NM}\nabla p + \frac{q}{M}\mathbf{V}_i \times \mathbf{B} + \nu_{in}(\mathbf{V}_n - \mathbf{V}_i) = 0. \tag{2}$$

In Eq. (2) $\mathbf{B}$ is the Earth magnetic field, M is the ion mass, ν_{in} is the ion-neutral collision frequency, p is the thermal pressure, $\mathbf{V}_i$ and $\mathbf{V}_n$ are ion and neutral velocities, respectively.

From Eq. (2) the expressions for horizontal U_i-northward, V_i-westward and vertical W_i components of ion velocity can be derived:

$$U_i = \frac{\mathrm{U_n}\cdot(k^2+\cos^2 I)}{1+k} - \frac{V_n\cdot k\cdot\sin I}{1+k^2} - \frac{W_n\cdot\sin I\cdot\cos I}{1+k^2} - \frac{2\cdot K_B\cdot T\cdot(k^2+\cos^2 I)}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial x}$$
$$+\frac{2\cdot K_B\cdot T\cdot k\cdot\sin I}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial y} + \frac{2\cdot K_B\cdot T\cdot\cos I\cdot\sin I}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial z} \tag{3a}$$

$$V_i = \frac{\mathrm{U_n}\cdot k\cdot\sin I}{1+k} - \frac{V_n\cdot k^2}{1+k^2} - \frac{W_n\cdot k\cdot\cos I}{1+k^2} - \frac{2\cdot K_B\cdot T\cdot k\cdot\sin I}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial x}$$
$$-\frac{2\cdot K_B\cdot T\cdot k^2}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial y} - \frac{2\cdot K_B\cdot T\cdot k\cdot\cos I}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial z} \tag{3b}$$

$$W_i = \frac{\mathrm{U_n}\cdot\sin I\cdot\cos I}{1+k} - \frac{V_n\cdot k\cdot\cos I}{1+k^2} - \frac{W_n\cdot(k^2+\sin^2 I)}{1+k^2} - \frac{2\cdot K_B\cdot T\cdot\cos I\cdot\sin I}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial x}$$
$$+\frac{2\cdot K_B\cdot T\cdot k\cdot\cos I}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial y} - \frac{2\cdot K_B\cdot T\cdot(k^2+\cos^2 I)}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial z} \tag{3c}$$

Here the x axis is directed from South to the North, y axis is directed form East to the West and z points upward. Here K_B is the Boltzmann constant, T is ion and electron mean temperature, I is inclination angle of the geomagnetic field, $\sin I = -\frac{B_z}{B}$, $\cos I = \frac{B_x}{B}$, $k = \frac{\omega_i}{\nu_{in}}$ and $\omega_i = \frac{e\cdot B}{M}$ is ion gyro-frequency.

After the substitution of Eqs. (3a-3c) into Eq.(1) we see that the term proportional to $\frac{\partial N}{\partial x}$ in Eq.(3a), term proportional to $\frac{\partial N}{\partial y}$ in Eq.(3b) and the term proportional to $\frac{\partial N}{\partial z}$ in Eq. (3c) behave as diffusive terms $\propto \frac{2\cdot K_B T(k^2+\cos^2 I)}{NM\nu_{in}(1+k^2)}$, $\propto \frac{2\cdot K_B\cdot T\cdot k^2}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}$ and $\propto \frac{2\cdot K_B\cdot T\cdot(k^2+\cos^2 I)}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}$, respectively , and one could solve reduced equation (1) in 3D case. In the present study, however, we consider two dimensional case, neglect terms with $\frac{\partial}{\partial x}$ and in the continuity equation substitute the following expressions for V_i and W_i:

$$V_i = \frac{\mathrm{U_n}\cdot k\cdot\sin I}{1+k} - \frac{V_n\cdot k^2}{1+k^2} - \frac{W_n\cdot k\cdot\cos I}{1+k^2} - \frac{2\cdot K_B\cdot T\cdot k^2}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial y} - \frac{2\cdot K_B\cdot T\cdot k\cdot\cos I}{N\cdot M\cdot\nu_{in}\cdot(1+k^2)}\frac{\partial N}{\partial z} \tag{3d}$$

$$W_i = \frac{\mathrm{U_n} \cdot \sin I \cdot \cos I}{1+k} - \frac{V_n \cdot k \cdot \cos I}{1+k^2} - \frac{W_n \cdot (k^2 + \sin^2 I)}{1+k^2} + \frac{2 \cdot K_B \cdot T \cdot k \cdot \cos I}{N \cdot M \cdot \nu_{in} \cdot (1+k^2)} \frac{\partial N}{\partial y} - \frac{2 \cdot K_B \cdot T \cdot (k^2 + \cos^2 I)}{N \cdot M \cdot \nu_{in} \cdot (1+k^2)} \frac{\partial N}{\partial z} \qquad (3e)$$

2.2 Atmospheric Gravity Wave Model

In order to determine the ion velocity components, we need have values of neutral velocity components. For this purpose we solve the set of the hydrodynamic continuity, momentum and energy equations for neutrals gas in the inviscid isothermal case [18]:

$$\frac{\partial \rho_n}{\partial \mathrm{t}} + \nabla(\rho_n \mathbf{V}_n) = 0$$

(4a)

$$\rho_n \left[\frac{\partial \mathbf{V_n}}{\partial t} + (\mathbf{V_n} \cdot \nabla)\mathbf{V_n} \right] = -\nabla p + \rho_n \mathbf{g}, \qquad (4b)$$

$$\frac{d(p \rho_n^{-\gamma})}{d\mathrm{t}} = 0 \qquad (4c)$$

Here ρ_{n} is neutral mass density, and γ is the ratio of the specific heats $(\gamma = 1.4)$.

To determine the evolution of atmospheric perturbations, the linearized set of Eqs. (4a-4c) (see [8]) are solved numerically.

Atmospheric waves spectrum in the horizontal shear flow with velocity $\mathbf{U_{0n}} = (\mathrm{a} \cdot \mathrm{y}, 0, 0)$, has the following form [17]:

$$\omega_g(t) = \left\{ \frac{1}{2} c_s^2 \left(|\boldsymbol{k}(t)|^2 + \frac{1}{4H^2} \right) - \sqrt{\frac{1}{4} c_s^4 \left(|\boldsymbol{k}(t)|^2 + \frac{1}{4H^2} \right)^2 - \omega_b^2 c_s^2 \left[k_x^2 + k_t^2(t) \right]} \right\}^{\frac{1}{2}}. \qquad (5)$$

Here $\omega_b = [(\gamma - 1) g / (\gamma H)]^{1/2}$ is the isothermal Brunt-Väisälä (B-V) frequency and $\omega_b^2 / a^2 >> 10$ is assumed. $\mathbf{g}$ is the acceleration due to gravity, $c_s = (\gamma g H)^{1/2}$ is the speed of sound.

The components of velocity perturbation $\mathbf{v}(u, v, w)$ for AGWs are described in the following form:

$$u(x, y, z, t) = e^{z/2H} \cdot \mathrm{Re}\{u_k(t)\exp[i\phi(x, y, z, t)]\}, \tag{6a}$$

$$v(x, y, z, t) = e^{z/2H} \cdot \mathrm{Re}\{v_k(t)\exp[i\phi(x, y, z, t)]\}, \tag{6b}$$

$$w(x, y, z, t) = e^{z/2H} \cdot \mathrm{Re}\{w_k(t)\exp[i\phi(x, y, z, t)]\}, \tag{6c}$$

where $u_k(t)$, $v_k(t)$ and $w_k(t)$ are spatial Fourier harmonic (SFH) amplitudes of shear wave's horizontal u, v and vertical w velocities (see [8], [9]), respectively. $\phi(x, y, z; t) = k_x x + k_t y + k_z z$, $k_t(t) = k_y - ak_x t$ and $\mathbf{k}(t) = \mathbf{k}(k_x, k_t(t), k_z)$ is the time variant wavenumber, $z = h - h_0$ is the difference between an actual height h and some initial height h_0, H is the atmospheric scale height.

The linearized form of the set of Eqs. (4a-4c) are solved numerically and the obtained values for neutrals velocities are substituted into equations (3e-3d). Next, the equations (3d-3e) are substituted into the continuity equation (1) and the obtained parabolic type equation is again solved numerically.

3. Formation of multilayered sporadic E

Fig.1 shows the evolutions of Fourier amplitudes of perturbed velocity components of AGW.

We consider the case when initially AGWs are absent and only background neutral winds (U_{0n}), characterized by horizontal shear, influences electron density. Figure 1 also shows that horizontal and vertical velocity amplitudes evolve in a different manner. In addition, Fig.1 illustrates the tendency of formation of short-period oscillations at later times with a dominant horizontal perturbation. The AGWs described in Fig. 1 is expected to influence the behavior electron/ions density, and corresponding process is the subject of our investigation.

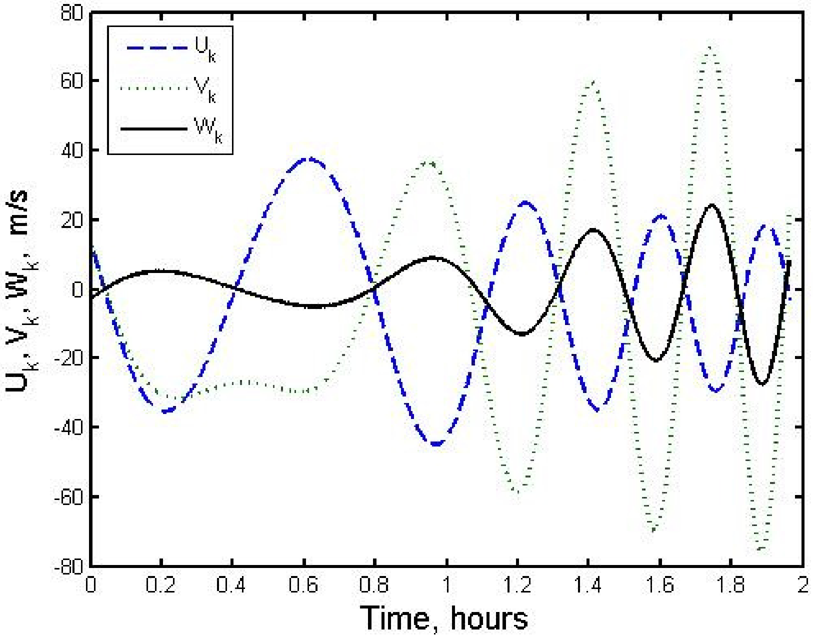

Figure 1. Time evolution of spatial Fourier harmonics (SFH), of the velocity perturbation amplitudes for AGWs in the horizontal shear flow. $U_k - x$ component, (dashed line), $V_k - y$ component (dotted line) and $W_k - z$ component (solid line). for shear $a = 5 \cdot 10^{-4} s^{-1}$, vertical wavelength $\lambda_z = 12\ km$ and horizontal wavelengths $\lambda_x = \lambda_y = 120 km$.

As it was mentioned, we solve numerically the equation (1) for distribution of plasma density in two-dimensional case, when horizontal (V_{iy}) and vertical drift velocities (V_{iz}) of ions are determined by Eqs. (3b) and (3c), and take into account all three components (U_n, V_n, W_n) of AGWs' velocity given in Fig. 1.

In our simulation for the ion-neutral collision frequency we use the expression $\nu_{in} = (2.62\ [N_2] + 2.61\ [O_2] + 1.43\ [O]) \cdot 10^{-10}\ s^{-1}$ [19] where neutral densities $[N_2]$, $[O_2]$, $[O]$ are taken from MSISE-90 [20] atmospheric model. Simulations are performed for the mid-latitude lower thermosphere and for $I = 60^o$, $\omega_B = 80\ s^{-1}$ and shear parameter $a = 5 \cdot 10^{-4} s^{-1}$.

In Figure 2a the initial (Gaussian type) distribution of ions in the mid-latitude lower thermosphere is shown. Figure 2b shows how density changes in time in the presence of ambipolar diffusion only. Here the half-width of the ions/electrons initial distribution is taken 30 km, the height of the maximum does not change with horizontal coordinate and is located at 100 km altitude. We see that in this case when only diffusion acts on the plasma, the maximum density of plasma distribution decreases about by 20% in comparison with its initial value in 1 hour .

In Fig. 2c the temporal evolution of electrons/ions density under the influence of AGWs is demonstrated. The results show that around the initial maximum of the electron/ions height distribution, AGWs lead to the vertical convergence of ions at about 95 and 110 km altitudes. The areas with enhanced electron density evolve during 30 minutes and the layers become thinner where density increases. Let us note that presence of AGW increases density of the ion/electron density by about 15% in comparison to the case when only diffusion influences ion/electron density at same altitude. It is important to note that, the vertical distance between these layers is close to the vertical wavelength of waves (12 km). Also note that the formation of other layers above and below the initially formed layers also occurs, but the electron densities in the secondary layers are relatively small.

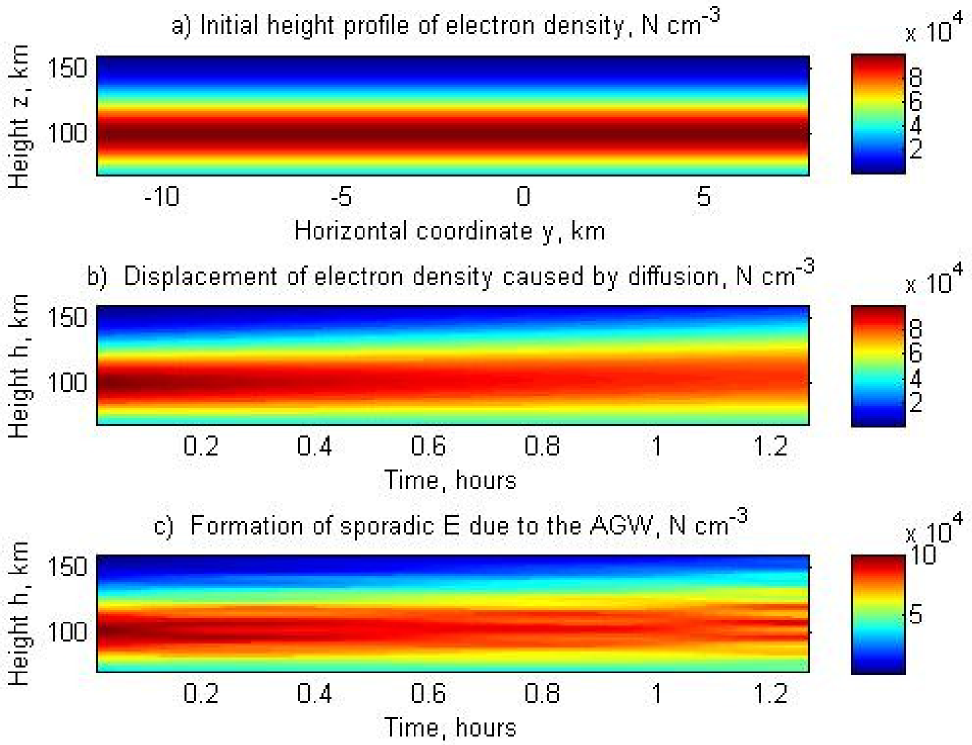

Figure 2. (a) The initial (Gaussian type) distribution of ions/electron in the mid-latitude lower thermosphere, (b) its (redistribution) by the ambipolar diffusion only and (c) formation and evolution of multi-layered sporadic E under influence of AGWs. The horizontal shear and wave parameters are the same as for Fig. 1.

On Fig.2c we see that initially the structures with enhanced electron density are formed (with characteristic timescale of $t_a = \frac{k_y}{ak_x}$)). Later, the electron density starts to oscillate, the oscillation period of electron density is related to the behavior of AGWs (Fig.1). In Fig. 2c we also see that Es has multilayer structure and distance between the layers is about the vertical wavelength λ_z of excited AGWs. In the demonstrated case after times greater than t_a, the converging power of

AGWs around Es layers (at 95 km and 110 km) decreases and the diffusion of charge particles starts to dominate.

The Results clearly demonstrate that AGWs play an important role in formation and evolution of Es. In addition, they could lead to the convergence ions at multiple nodes, and therefore the formation of Es with a multilayer structure varying in time.

4. Conclusion

We have shown that AGWs, evolving in the horizontal shear flow, can form mid-latitude nighttime sporadic E. The AGWs cause the vertical convergence of heavy metallic ions at the convergence nodes. Such spatial scales of the convergence areas depend on the vertical wavelength of the AGWs. After certain time, the dominant oscillation in AGW velocity occurs in the vertical direction with periods close to its shorter Brunt-Väisälä (B-V) period. In such case the convergence of metallic ions is comparatively faster than their diffusion, which could lead the formation of the sporadic E .

The evolution of AGWs in the horizontal shear flow also depends on the shear parameter, which could also affect the horizontal convergence of ions. This topic is, however, subject of the future studies.

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სპორადული იონოსფერული E ფენების ფორმირება ატმოსფერული გრავიტაციული ტალღებით

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რეზიუმე

ჩვენ განვიხილეთ სპორადული E (Es) ფენის ფორმირება და ევოლუცია საშუალო განედების ქვედა თერმოსფეროს ჰორიზონტალურ წანაცვლებით დინებებში ევოლუციონირებადი ატმოსფერული გრავიტაციული ტალღების (აგტ) გავლენით. ჰორიზონტალურ ფონურ ქარში, რომელსაც აქვს ჰორიზონტალური წრფივი წანაცვლება (ჰორიზონტალური წანაცვლებითი დინება) შესაძლებელია აღიგზნას აგტ. ამგვარი ადგილზე აღძრული ატმოსფერული ტალღები, იონების ნეიტრალურ ნაწილაკებთან დაჯახებისა და ლორენცის ძალის კომბინირებული მოქმედებით, გავლენას ახდენენ მძიმე იონების ვერტიკალურ მოძრაობაზე და იწვევენ მათ თავმოყრას ჰორიზონტალურ თხელ ფენაში (ფენებში) და შესაბამისად Es ფენის (ფენების) ფორმირებას. დემონსტრირებულია ორგანზომილებიანი შემთხვევა მრავალფენიანი სპორადული E ფორმირებისა. სპორადული E ფენების სიმკვრივე დამოკიდებულია აგტ ამპლიტუდაზე და მათი განლაგება მის ვერტიკალურ λ_z ტალღის სიგრძეზე.

Формация спорадических E слоев под воздействием атмосферных гравитационних волн

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Реззюме

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В этой работе рассматривается формирование спорадическогоE(Es)в нижних слоях термосферы под воздействуем в горизонталном в сдвиговых течениях возбуждаемых атмосферных гравитационных волн (АГВ). В фоновом горизонтальном ветре имеющий линейный горизонтальный сдвиг (горизонтальное сдвиговое течение) может возбуждатся АГВ.Эти атмосферные волны через столкновеный ионов с нейтральными частицами в комбинаций сылой Лоренца вызивает горизонтальное движение тяжелых металических ионов и их собрание в узкых горизонтальных слоях. Численный результат развития этих процессов и создание многослойных спорадического E демонстрируется в двумерном случае. Плотность спорадических слоев зависит от амплитуды АГВ и их расположение на вертикальном длине волны λ_z .