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Parametrization of Low Frequency Internal-Gravity Waves in the Shear Flow Driven Ionosphere

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Abstract
The linear mechanism of generation, intensification and further nonlinear dynamics of internal gravity waves (IGW) in stably stratified dissipative ionosphere with non-uniform zonal wind (shear flow) is studied. In the ionosphere with the shear flow, a wide range of wave disturbances are produced by the linear effects, when the nonlinear and turbulent ones are absent.

1. Introduction
Internal gravity waves (IGWs) play an important role in the formation of the general circulation, thermal regime, and composition of the middle and upper atmosphere. According to present knowledge, the main portion of IGW energy reaches the middle and upper atmosphere from tropospheric sources. In the middle and upper atmosphere the amplitudes of waves increase, they break and produce substantial amounts of heat and momentum (Holton, 1983).

Several parametrizations have been developed for the turbulent viscosity, mean low drag and heating rates produced by dissipating IGWs (Lindzen, 1981; Matsuno, 1982; Holton, 1983; Gavrilov, 1990; Fritts and Lu, 1992; Medvedev and Klaassen, 1995; Hines, 1997).

One of the important properties of IGW is their significant influence on the distribution of the electromagnetic waves in atmospheric-ionosphere layers. Consequently, ionosphere electric currents and electromagnetic fields may re-influence the wave properties of IGW at ionosphere altitudes.

The results of long-term observations (Kazimirovskii, 1983) also show that at the atmospheric-ionospheric layers the spatially non-uniform zonal winds - the shear flows are permanently present, produced by nonuniform heating of the atmospheric layers by the solar radiation. In this context the problem of the generation and evolution of ordinary and magnetized waves at different layers of the atmosphere during their interaction with non-uniform zonal wind (shear flow) becomes urgent.

In this paper we study the linear evolution of IGW in shear zonal flows (winds) in different regions of the ionosphere. At the initial linear stage in the dynamic equations the perturbed hydrodynamic quantities are given by SFH, which corresponds to non-modal analysis in a moving coordinate system along the background wind. Non-modal mathematical analysis allows replacement of the spatial non-uniform nature of the perturbed quantities, associated with the basic zonal flow, by temporal one in the basic equations and trace the evolution of SFH disturbances according to time.

2. Nonmodal Analysis of IGW
Analysis of the features of magnetized IGW waves at the linear stage in the ionosphere should be conducted in accordance with a non-modal approach. For this purpose, the moving coordinate system $X_1O_1Y_1$ is more convenient with origin $\boldsymbol{O}_1$ and the axis $\boldsymbol{Y}_1$, which coincides with the same characteristics of the equilibrium local system $\boldsymbol{XOY}$, the axis $\boldsymbol{X}_1$ flowing along the unperturbed (background) wind**.** In this reference frame, For each perturbed quantities, we obtain equations for Spatial Fourier Haronics (SFP):

$$\frac{\partial V_x}{\partial \tau} = -SV_z + k_x P - [b_0 + \nu k^2(\tau)]V_x \,, \qquad (1)$$

$$\frac{\partial V_z}{\partial \tau} = k_z(\tau)P - \rho - [b_y + \nu k^2(\tau)]V_z \,, \qquad (2)$$

$$\frac{\partial \rho}{\partial \tau} = V_z \,, k_x V_x + k_z(\tau) V_z = 0 \,. \qquad (3)$$

Here, $\mathbf{V} = \mathbf{V}_0(z) + \mathbf{V}(x,z,t)$, $\rho = \rho_0(z) + \rho(x,z,t)$, $P = P_0(z) + P(x,z,t)$, $K^2 = k_x^2 + k_z^2 + 1/(4H^2)$, $K_1^2 = K_2^2 - ik_z / H$, $K_2^2 = k_x^2 + k_z^2 - 1/(4H^2)$, S is a shear parameter - $\mathbf{V}_0(z) = v_0(z)\, \boldsymbol{e_x} = S \cdot z \cdot \boldsymbol{e_x}$.

Normalized energy density of the Fourier harmonics have the following form:

$$\overline{\boldsymbol{E}}(\boldsymbol{\tau}) = \frac{\boldsymbol{E}(\boldsymbol{\tau})}{\boldsymbol{E}(0)} = \frac{\left(1 + \boldsymbol{k}_0^2\right)^2}{\left[1 + (\boldsymbol{k}_0 - \boldsymbol{S\tau})^2\right]^{1/2}} \,. \qquad (4)$$

In the initial stage of evolution when $\boldsymbol{k}_0 = \boldsymbol{k_z}(0)/\boldsymbol{k_x} > 0$ (when $\boldsymbol{k_z}(\boldsymbol{\tau}) > 0$) over time $\boldsymbol{\tau}$, $0 < \tau < \tau^* = k_z(0)/(Sk_x)$, in (4) the denominator decreases and, accordingly, the energy density of IGW increases monotonically and reaches its maximum value (exceeding its initial value by an order) at the time $\boldsymbol{\tau} = \boldsymbol{\tau}^*$. Further, at $\boldsymbol{\tau}^* < \boldsymbol{\tau} < \infty$ the energy density begins to decrease (when $\boldsymbol{k_z}(\boldsymbol{\tau}) < 0$), and monotonically returns to its initial approximately constant value. In other words, in the early stages of evolution, temporarily, when $\boldsymbol{k_z}(\boldsymbol{\tau}) > 0$ and IGW perturbations are in the intensification region in wave-number space, the disturbances draw energy from the shear flow and increase own amplitude and energy by an order during the period of time $0 < \tau < \tau^* = k_z(0)/(Sk_x) = 100$. Then (if the nonlinear processes and the self-organization of the wave structures are not turned on), when $\boldsymbol{k_z}(\boldsymbol{\tau}) < 0$, IGW perturbation enters the damping region in wave number space and the perturbation returns energy back to the shear flow over time $\boldsymbol{\tau}^* < \boldsymbol{\tau} < \infty$ and so on. Such transient redistribution of energy in the medium with the shear flow is due to the fact that the wave vector of the perturbation becomes a function of time $\boldsymbol{k} = \boldsymbol{k}(\boldsymbol{\tau})$, i.e. disturbances' scale splitting takes place. The structures of comparable scales effectively interact and redistribute free energy between them. Taking into account the induction and viscous damping the perturbation's energy reduction in the time interval $\boldsymbol{\tau}^* < \boldsymbol{\tau} < \infty$ is more intensive than that shown on fig. 1, the decay curve in the region $\boldsymbol{\tau}^* < \boldsymbol{\tau} < \infty$ becomes more asymmetric (right-hand side curve becomes steeper), and part of the energy of the shear flow passes to the medium in the form of heat.

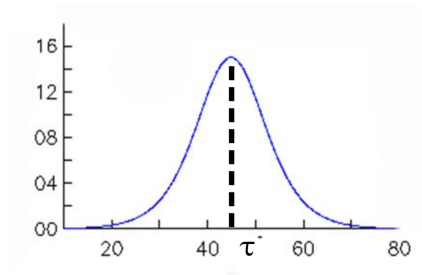

Fig.1

3. Summary and Conclusion

In this article the linear stage of generation and further nonlinear evolution of IGW structures in the dissipative stably stratified ionosphere in the presence of shear flow (non-uniform zonal wind) is studied. A model system of dynamic nonlinear equations describing the interaction of internal gravity structures with viscous ionosphere, non-uniform local zonal wind, and the geomagnetic field is obtained. On the basis of analytical solutions and theoretical analysis of the corresponding system of dynamic equations a new mechanisms of linear transient pumping of shear flow energy into that of the wave perturbation, wave amplification (multiple times) is revealed.

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