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Exponential and local Lamb waves in the nonisothermal atmosphere as an obstacle to the acoustic-gravity disturbance propagation up to the ionosphere

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ABSTRACT

In this study generalized Lamb waves in a nonisothermal atmosphere have been examined theoretically. Our results suggest that the pressure component of the Lamb wave decreases exponentially upwards near the layer with an extremum of sound speed. We find that local wave disturbances of the wave pressure component are formed in the resonance layer at which the horizontal phase velocity is equal to the sound speed. These resonance layers are the reason for a filtration of atmospheric disturbances. Such filtration is an obstacle to the acoustic-gravity wave propagation up to the ionosphere.

1. Introduction

Lamb waves are fundamental free oscillations of a dissipationless, compressible, and isothermal atmosphere. These wave solutions describe by the exponential decrease in amplitude of the pressure wave. There is no wave disturbance of the vertical velocity. Lamb waves occur over a solid Earth. The dispersion equation of these waves has the form $\omega = k_\perp c_s$, where ω is the frequency, $k_\perp$ is the horizontal component of the wave vector, and c_s is the sound speed. The atmospheric Lamb waves have from time to time received considerable attention in theoretical and experimental works (Grigor'ev et al., 1987; Le Pichon et al., 2009; Watada and Kanamori, 2010). Historically, Lamb analyzed this type of wave in the isothermal atmosphere (Lamb, 1932). Then this theory was developed for a slowly nonisothermal atmosphere (Bretherton, 1969; Lindzen and Blake, 1972).

Actually, the Earth's atmosphere is well nonisothermal. Therefore, the approximation of an isothermal atmosphere is a rough model of the actual situation. In this work, we study both the main possibilities, including the formation of Lamb waves, in which the amplitude of the wave pressure decreases exponentially upward, and the local wave disturbances, into which the waves can be converted in the nonisothermal atmosphere.

Explaining the role of acoustic-gravity waves (AGW) in the transfer of the oscillating processes from the Earth's surface to the upper atmosphere is an actual problem (Rapoport et al., 2004; Bespalov and Savina, 2012). The reason for the surface generation of this waves can be earthquakes, explosions, sea waves, and other artificial and natural processes (Blank, 1985). In the study of the AGW propagation possibility it is important to know what waves and for what reasons are filtered on the wave propagation route.

It will be shown below that in the Earth's atmosphere the temperature profile is such that there is a range of wave phase velocities (or a frequency range with fixed horizontal dimensions of the source), in which the waves generated on the Earth's surface do not pass upwards because of the proposed filtration mechanism. In order to emphasize the basic reason for the effect examined, we do not take the wind into consideration. At the same time, since a singularity appears in a narrow local region, the calculation of wind will lead to the Doppler frequency shift, which will require additional refining calculations, but will not affect the main point of the phenomenon.

The paper is organized in the following way. In Section 2, we present some analytical properties of exponential and local Lamb waves in the nonisothermal atmosphere. Section 3 describes our results of full-wave calculations for AGW in the nonisothermal atmosphere in a framework of the original computer code. We

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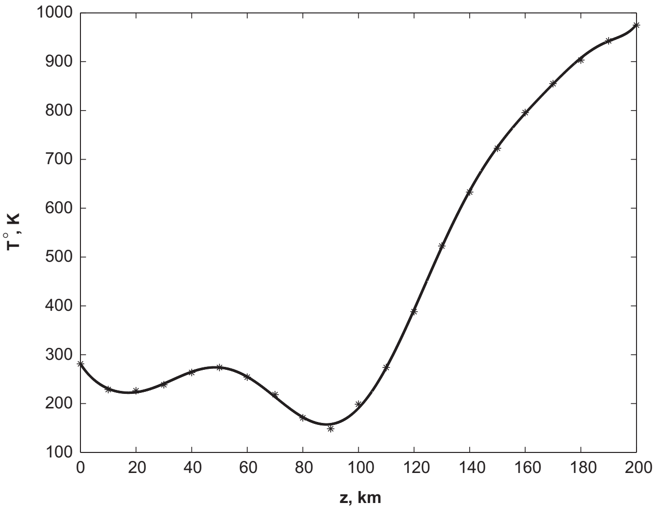

Fig. 1. Typical atmosphere temperature profile $T(z)$ as obtained from the MSIS-E-90 model marked by asterisks and theoretical curve $T(z)$.

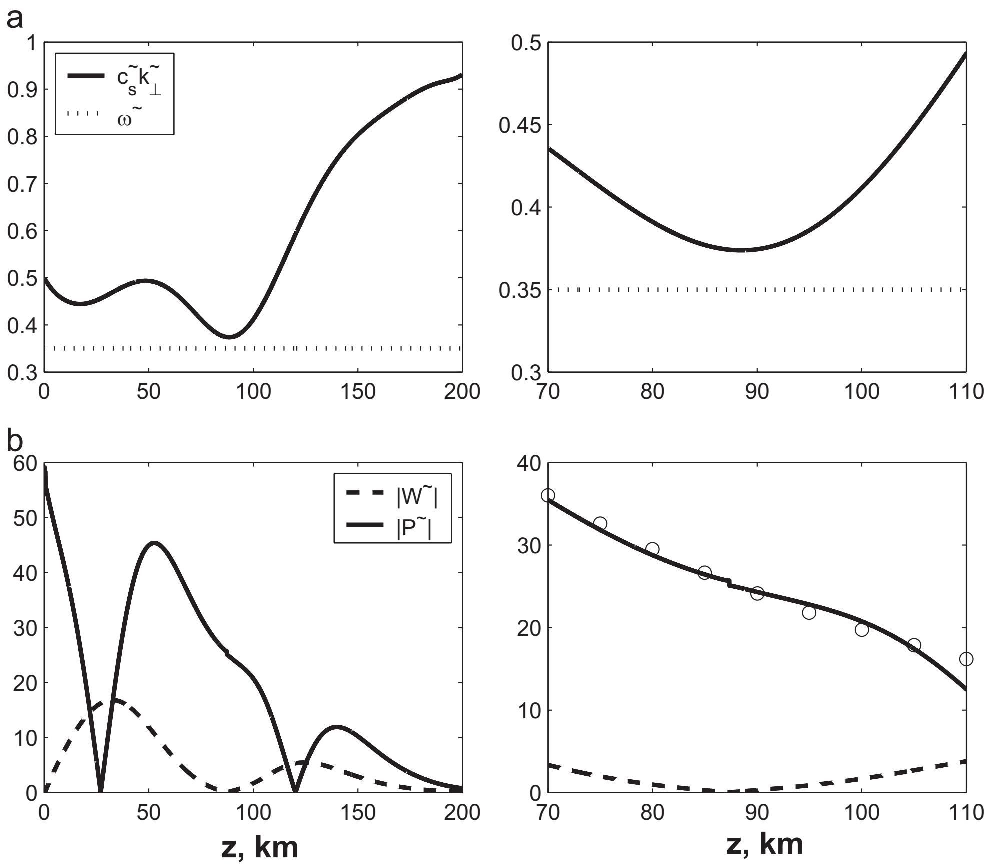

Fig. 2. Results of numerical calculations of AGW in the atmosphere (left column) and near the local disturbance (right column). Top figures are $\tilde{\omega}(z)$ (dotted line) and $\tilde{c}_s(z)\tilde{k}_\perp$ (solid curve). Bottom figures are $|\tilde{W}(z)|$ (dashed curve) and $|\tilde{P}(z)|$ (solid curve) as functions of z in the different altitude regions. Circles on the right bottom panel correspond to $\exp(-\Gamma z)$. On the right bottom panel the dependencies $|\tilde{W}(z)|$ and $|\tilde{P}(z)|$ are given in more detail for same simulation.

present the conclusions of this study in Section 4. Analytical solution on specific features of the fields of acoustic gravity waves at the resonance is given in Appendix A.

2. Some analytical properties of exponential and local Lamb waves in the nonisothermal atmosphere

Consider a two-dimensional acoustic-gravity wave in the plane-parallel nonisothermal atmosphere. We select axis z in the vertical direction and axis x in the horizontal direction. In this work, we consider the atmospheric perturbations without regard to a regular wind and viscosity. The linearized system of equations of gas dynamics for the pressure disturbances $p_\sim$, the horizontal velocity $v_\sim$ and the vertical velocity $w_\sim$ is well known. To simplify these equations, it is convenient to introduce new field variables (Gossard and Hooke, 1975), namely, $V=(\rho/\rho_E)^{1/2}v_\sim$, $W=(\rho/\rho_E)^{1/2}w_\sim$, and $P=(\rho/\rho_E)^{1/2}p_\sim$, where ρ and ρ_E are the basic state densities in the current layer and at the ground level, respectively. Field variables are proportional to $\exp(-i\omega t+ik_\perp x)$ for a monochromatic signal in plane atmospheric layers. Then the system of equations for the wave perturbation can be reduced to (Gossard and Hooke, 1975)

$$[-\omega^2+\omega_g^2(z)]W-i\frac{\omega}{\rho_E}\left[\frac{\partial}{\partial z}+\Gamma(z)\right]P=0, \tag{1a}$$

$$[-\omega^2+c_s^2(z)k_\perp^2]P-i\omega\rho_E c_s^2(z)\left[\frac{\partial}{\partial z}-\Gamma(z)\right]W=0. \tag{1b}$$

Here, i is the imaginary unit,

$$\omega_g^2=\frac{(\gamma-1)g^2}{c_s^2}+\frac{g}{T}\frac{\partial T}{\partial z},$$
$$\Gamma=\frac{(2-\gamma)g}{2c_s^2}-\frac{1}{2T}\frac{\partial T}{\partial z}, \tag{2}$$

where γ is the ratio of specific heats at constant pressure and volume, respectively, g is acceleration due to gravity, and $T(z)$ is the