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Parameterization of Mesoscale Stationary Orographic Wave Forcing for Use in Numerical Models of Atmospheric Dynamics

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Abstract—Polarization relations for mesoscale stationary orographic waves (MSOWs) and formulas for calculating vertical profiles of the total vertical flux of wave energy and amplitudes of horizontal speed are obtained by taking account the rotation of the atmosphere. Expressions are derived for the total wave heat flux, accelerations of the mean flow, and heat influxes generated by MSOWs. Calculations of the characteristics of MSOWs propagating in the atmosphere from the surface to the lower thermosphere are made. It was shown that MSOWs may significantly affect the circulation and thermal regime of the middle and upper atmosphere.

Keywords: atmospheric dynamics, mesoscale waves, orography, wave acceleration, heat influx, parametrization

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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. Interest in studying accelerations of the mean flow and heat influxes generated by IGWs has increased in recent years due to numerical modeling of the general circulation of the atmosphere. Interpreting IGW observations and including IGW effects in numerical atmospheric models necessitate the development of simple numerical schemes that would satisfactorily describe the wave oscillations and demand minimal computer time.

The topography of the earth's surface is one important source for IGWs. The incoming airflow interacts with irregularities of the relief so that mesoscale stationary orographic waves (MSOWs) can arise. Quasi-stationary orographic waves have been observed in the troposphere [1, 2] and the stratosphere [3–5] via various techniques. Stationary wave structures with horizontal lengths of about 36 km aligned parallel to the Andes mountain system and having the properties of orographically generated gravity waves propagating up into the upper atmosphere were visible in the images of nighttime airglow emissions at 80- to 100-km altitudes over Argentina [6].

Orographic waves and their potential impact on the thermal regime and dynamics of the mesosphere and lower thermosphere have been studied extensively by Russian scientists over the Ural Mountains [7–9] and the Caucasus range [10, 11]. These experimental data demonstrate the existence of quasi-stationary temperature disturbances with amplitudes of ~10 K over mountain systems at 80–90 km. Estimates of the spatial distribution of energy fluxes of orographic waves into the mesopause region in the lee of a mountain range were made in [12]. The wave-energy fluxes were estimated in [12] to be ~3 mW/m^2 on average. The possibility that orographic waves could influence the circulation and thermal regime of the middle atmosphere was discussed in [13–16]. The mesoscale variability of temperatures in the troposphere and stratosphere was analyzed and its enhancement over mountain systems was demonstrated in [17] using low-orbit GPS satellite data.

Several parameterizations have been developed for MSOWs, for example, [18, 19], but these parameterizations do not take into account all the details of the propagation and impact of the waves in the atmosphere. In [18] most attention has been given to the parametrization of the earth's surface relief and to the estimation of parameters of MSOWs near their sources, but parameters of the waves at high altitudes have not been considered. In [19], the dissipation of MSOWs in the atmosphere is disregarded. This simplification is permissible in calculations of the vertical profiles of tropospheric MSOWs, but the dissipation of wave energy becomes significant as the altitude increases. Furthermore, several parameterizations do not calculate vertical profiles of heat fluxes and wave accelerations induced by MSOWs, correct formulas for which can be obtained only by taking into account the rotation of the atmosphere.

In this study we have developed a parametrization for MSOWs propagating in the atmosphere from the earth's surface, improved polarization relations for MSOWs, and derived formulas to calculate the total vertical flux of wave energy and the amplitude of horizontal speed that take into account the rotation of the atmosphere.

2. DYNAMIC AND THERMAL EFFECT OF OROGRAPHIC WAVES

According to the theory of mesoscale stationary disturbances arising when an incoming airstream flows over a mountain, these disturbances can be referred to as IGWs with frequencies $\sigma = 0$. When the IGWs propagate in an inhomogeneous rotating atmosphere with dissipation, the mean flow and the waves exchange energy and the atmosphere is warmed by the dissipation of IGW energy. From [20], the wave-energy balance equation for stationary and horizontally homogeneous wave-period-averaged quantities can be written as

$$\frac{\partial F_E}{\partial z} = -\bar{\rho} D - \overline{\rho v_\alpha} a_{w\alpha},$$
$$a_{w\alpha} = -\frac{1}{\bar{\rho}} \frac{\partial(\bar{\rho}\, \overline{v'_\alpha w'})}{\partial z}, \qquad (1)$$
$$F_E = \overline{p'w'} + \overline{\rho v_\alpha}\, \overline{v'_\alpha w'} - \overline{(\sigma'_{z\beta} + \tau'_{z\beta}) v'_\beta},$$

where p and ρ are the atmospheric pressure and density, respectively; v_α and w are the velocity components along the horizontal axes x_α and the vertical axis z, respectively; repeated Greek subscripts assume summation; F_E is the total wave-energy flux, which includes the flux of wave energy and its transport by the mean flow and by turbulent and molecular diffusion; D is the dissipation rate of wave energy; $a_{\alpha w}$ is the components of the wave acceleration of the mean flow that enter the equation for the horizontal component of the mean velocity; $\sigma_{\alpha\beta}$ and $\tau_{\alpha\beta}$ are the molecular and turbulent viscous stress tensors, respectively; the overbar denotes averaging over a wave period; and primes denote wave components of the corresponding quantities.

On the right-hand side of the first equation in (1), there are terms that describe the dissipation rate of wave energy and the work of nonlinear wave—mean flow interaction forces, which depends on the velocity of the mean flow and wave acceleration. For a correct description of the energetics of the dynamic processes considered here, it is important to know the relation between the indicated sources and sinks of wave energy. It is shown in [20] that analytical expressions relating the rate of wave-energy dissipation and wave accelerations can be obtained if there is a vertical gradient of the mean wind. These expressions serve as a basis for our research.

When we consider the propagation of plane monochromatic wave components, it is convenient to direct one horizontal axis ξ along the horizontal wave vector **k** and the other axis η normally to **k**. For the component of the wave acceleration generated by a plane IGW along the ξ axis, the following formula may be obtained in a stationary horizontally uniform model for the height-varying mean wind $(\partial \overline{v_\xi}/\partial z \neq 0)$ in [20]:

$$a_{w\xi} = \frac{k}{\sigma - k\bar{v}_\xi}\left\{D - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left[\overline{(\sigma_{z\beta} + \tau_{z\beta}) v'_\beta} - \left(\frac{\partial \bar{v}_\xi}{\partial z}\right)^{-1} \times \left(\frac{p'}{\bar{\rho}} + v'_\xi\left(\bar{v}_\xi - \frac{\sigma}{k}\right)\right)\frac{\partial(\sigma_{\alpha\xi} + \tau_{\alpha\xi})}{\partial x_\alpha}\right]\right\}, \qquad (2)$$

and the total heating rate due to IGW energy dissipation and transport is described by

$$\varepsilon_w = D + \bar{v}_\xi a_{w\xi} - \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left[\frac{(\gamma - 1)\bar{\rho}\bar{T}}{gB}\overline{(\varepsilon'_t + \varepsilon'_m + \varepsilon'_r)s'}\right], \qquad (3)$$

where $B = (\gamma - 1) + g^{-1}\partial c^2/\partial z$ is the parameter of statistical stability of the atmosphere; $\gamma = c_p/c_v$ is the ratio of heat capacities; T is the temperature; g is the acceleration due to gravity; ε'_t, ε'_m, ε'_r are the wave components of heat influxes due to turbulent and molecular viscosity and radiative heat exchange, respectively; s' is the wave component of entropy; and c is the speed of sound. Using a standard theory of atmospheric waves in a plane rotating atmosphere (e.g., [21]), it is possible to derive polarization relations for stationary gravity waves with frequencies $\sigma = 0$ and rather high vertical and horizontal wave numbers $|m| \gg 1/(2H)$ and $k^2 \gg f^2/c_s^2$ (where H is the height of a uniform atmosphere, c_s is the speed of sound, and f is the Coriolis parameter). These polarization relations can be written as

$$U = -k^2\bar{v}_\xi c_s^2 mX; \quad V = ifkc_s^2 mX; \quad W = \bar{v}_\xi k^3 c_s^2 X;$$
$$R = [(k^2\bar{v}_\xi^2 - f^2)m + ik^2c_s^2N^2/g]X; \qquad (4)$$
$$P = \gamma c_s(k^2\bar{v}_\xi^2 - f^2)mX;$$
$$\Theta = [(\gamma - 1)(k^2\bar{v}_\xi^2 - f^2)m - ik^2c_s^2N^2/g]X,$$

where U, V, and W are the amplitudes of fluctuations of the velocity components along the axes ξ, η, and z; R, P, and Θ are the amplitudes of relative density, pressure, and temperature variations, respectively; and X is an arbitrary constant. A comparison of the first two formulas of (4) show that, for the wave components with $|k| \gg f/|\bar{v}_\xi|$, the amplitude of fluctuations of the velocity U along the ξ axis parallel to the wave vector **k** far exceeds the amplitude of the velocity V in the perpendicular direction and this "transverse"