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Dynamical and thermal effects of nonsteady nonlinear acoustic-gravity waves propagating from tropospheric sources to the upper atmosphere

Nikolai M. Gavrilov [a], Sergey P. Kshevetskii [b]

[a] Atmospheric Physics Department, Saint-Peterburg State University, Saint-Peterburg, Russia
[b] Theoretical Physics Department, Immanuel Kant Baltic Federal University, Kaliningrad, Russia

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Abstract

We performed numerical simulations of nonlinear AGW propagation to the middle and upper atmosphere from a plane wave forcing at the Earth's surface with period $\tau = 2 \times 10^3$ s. After activating the surface wave forcing, initial pulse of acoustic and very long gravity modes in a few minutes can reach altitudes above 100 km. Dissipation of this initial pulse produces substantial mean heating and wave-induced mean winds at altitudes above 200 km. This may influence AGW propagation and produce enhanced vertical gradients of temperature, horizontal velocity and increased wave dissipation in the lower part of the wave-induced mean flows helping their downward expansions. Later, AGWs may produce layers of convective instability and peaks of the wave-induced jets at altitudes 100–120 km. Shorter AGWs with smaller horizontal wave speeds produce smaller mean heating and wave-induced mean velocities in the upper atmosphere at fixed amplitudes and periods of the surface wave excitation. Numerical simulation of nonlinear AGW propagation helps better understanding the details of dynamical and thermal influence of waves coming from the troposphere on the mean temperature and wind in the middle and upper atmosphere.

Keywords: Atmosphere; Acoustic-gravity waves; Nonlinear interactions; Numerical modeling; Wave drag

1. Introduction

Observations show the continuous presence of GWs in the middle atmosphere (Fritts and Alexander, 2003, and the references therein). Increasing amount of observations suggest that GW can be frequently detected in the thermosphere (Djuth et al., 2004; Park et al., 2014). Recent general circulation modeling studies have demonstrated that lower atmospheric GWs can propagate into the thermosphere and produce appreciable dynamical (Yiğit et al., 2009) and thermal effects (Yiğit and Medvedev, 2009). Propagation and the resulting effects of small-scale GWs in the thermosphere exhibit significant variations during sudden stratospheric warmings (Yiğit and Medvedev, 2012a; Yiğit et al., 2014). A comprehensive review of internal gravity wave propagation into the thermosphere and their effects was made by Yiğit and Medvedev (2015).

Non-hydrostatic numerical models are useful for AGW and turbulence studies. For example, Baker and Schubert (2000) performed modeling nonlinear AGWs in the Venus' atmosphere. They simulated waves in an atmospheric region with vertical and horizontal dimensions of 48 and 120 km, respectively. Other authors (Fritts and Garten, 1996; Andreassen et al., 1998; Fritts et al., 2009, 2011; Liu et al., 2009) made two-dimension modeling Kelvin–Helmholtz

E-mail addresses: n.gavrilov@spbu.ru (N.M. Gavrilov), renger@mail.ru (S.P. Kshevetskii)

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instabilities and turbulence generated due to breaking of atmospheric waves. These studies used three-dimensional models treating waves and turbulence in atmospheric boxes with limited horizontal and vertical sizes. The models used modifications of the spectral method and Galerkin-type series to convert partial (versus time) differential equations into the ordinary ones describing the spectral series coefficients. Liu et al. (2009) simulated gravity wave propagating from the lower atmosphere and generating Kelvin–Helmholtz billows in the mesopause region. Yu and Hickey (2007) and Liu et al. (2008) have developed two-dimensional numerical models of atmospheric AGWs.

In addition to direct numerical modeling, mesoscale AGWs generating in the troposphere and propagating to the thermosphere were studied in general circulation models (e.g., Yiğit et al., 2009, 2012a) using parameterizations of wave dynamical and thermal effects to describe their saturation and dissipation in the middle and upper atmosphere (e.g., Yiğit et al., 2008). These AGWs propagate upwards, break and produce turbulence and perturbations in the middle and upper atmosphere. For example, convection and mesoscale turbulence in the troposphere may produce AGWs (e.g., Fritts and Alexander, 2003; Fritts et al., 2006). Turbulent sources may have maxima at altitudes 9–12 km in the regions of tropospheric jet streams (Medvedev and Gavrilov, 1995; Gavrilov and Fukao, 1999; Gavrilov, 2007). Using a nonhydrostatic general circulation model of the thermosphere-ionosphere system, Yiğit et al. (2012b) have demonstrated that gravity waves and acoustic waves are continuously present in the thermosphere even during quiet geomagnetic periods.

Gavrilov and Kshevetskii (2013a) modeled two-dimensional nonlinear AGWs using a numerical scheme accounting for the fundamental conservation laws. This scheme described in more detail by Kshevetskii and Gavrilov (2005) provides the necessary numerical stability and has allowed us to take into account non-smooth solutions of AGW nonlinear equations.

Gavrilov and Kshevetskii (2013b, 2014a) made a three-dimension modification of this algorithm for modeling nonlinear atmospheric AGWs. They simulated AGWs generated by sinusoidal horizontally homogeneous wave forcing at the Earth's surface.

Karpov and Kshevetskii (2014) applied similar three-dimensional numerical model to simulate acoustic wave propagation from localized non-stationary surface wave excitation and found that infrasound could produce substantial mean heating in the thermosphere. Nonlinear dissipating AGWs are also responsible for creating accelerations of the mean flows (e.g., Fritts and Alexander, 2003). At the same time, details of the mean flows and heating produced by nonlinear non-stationary AGWs in the atmosphere need further clarifications.

In this paper, using the numerical model by Gavrilov and Kshevetskii (2013b, 2014a), we continue studying propagation of nonlinear AGWs generated at the Earth's surface into the thermosphere. We considered simple AGW forcing by plane wave oscillations of vertical velocity at the surface and considered details of wave dynamical and thermal effects at different altitudes at different times after activating the wave source. Compared to Karpov and Kshevetskii (2014) we considered lower frequencies of wave sources belonging to gravity wave subrange of AGW spectrum.

2. Numerical model

The numerical AGW model simulates velocity components u, v, and w along horizontal (x, y) and vertical, z, axes, respectively. The model also calculates deviations of density ρ', temperature T', and pressure p' from stationary background fields ρ_0, T_0 and p_0, respectively. One can find the used set of nonlinear hydrodynamic equations in the papers by Gavrilov and Kshevetskii (2013b, 2014a). The set includes equations of continuity, motion and heat balance. The conditions at upper boundary $z = 500$ km include zero vertical gradients of perturbations of pressure, temperature, density and horizontal velocity as well as zero vertical velocity. The lower boundary conditions at the Earth's surface include zero deviations of pressure, density, temperature and horizontal velocity (see Gavrilov and Kshevetskii, 2013a,b, 2014a).

In the present research, we suppose horizontal periodicity of wave solutions:

$$f(x, y, z, t) = f(x + L_x, y + L_y, z, t), \tag{1}$$

where f could be any of the calculated variables, and $L_x = m\lambda_x$, $L_y = n\lambda_y$ are the horizontal lengths of the considered region of the atmosphere, m and n are integer constants, λ_x and λ_y are wavelengths along horizontal axes x and y, respectively. Oscillations of vertical velocity $w_0 = w(x, y)$ at the Earth's surface $z = 0$ force AGWs in the model.

Used numerical scheme is the generalization of two-dimensional algorithm developed by Kshevetskii and Gavrilov (2005) to the three-dimensional situation. Hydrodynamic equations of the model (see Gavrilov and Kshevetskii, 2013b, 2014a) may be written in the form of conservation laws

$$\frac{\partial r}{\partial t} + \frac{\partial X(r)}{\partial x} + \frac{\partial Y(r)}{\partial y} + \frac{\partial Z(r)}{\partial z} = 0, \tag{2}$$

where r denotes any of density, momentum or energy per unit volume, X, Y, Z are components of fluxes of respective quantities along axes x, y, z. We take into account terms containing gravity in the equation for vertical momentum component. In addition to the numerical scheme by Kshevetskii and Gavrilov (2005) the present thermal balance equation includes terms representing heating due to viscosity. Our numerical method uses the Lax and Wendroff (1960) scheme having the second order of accuracy, in which the finite-difference approximation of Eq. (2) has the following form: