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Research Paper

Propagation of non-stationary acoustic-gravity waves at thermospheric temperatures corresponding to different solar activity

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ABSTRACT

Numerical simulation of non-stationary nonlinear acoustic-gravity waves (AGWs) propagating from the surface wave source to the thermosphere reveals that their propagation conditions and parameters depend on changes in background temperature, density, composition, molecular viscosity and heat conduction caused by changes in solar activity (SA). At small wave source amplitudes, AGW amplitudes, momentum fluxes and wave accelerations of the mean flow are slightly larger at altitudes about 150 km at low SA because of smaller mean density and $\rho_0^{-1/2}$dependence of wave amplitudes at low dissipation. Larger kinematic coefficients of molecular viscosity and heat conduction lead to stronger decrease of wave amplitudes and momentum fluxes at altitudes above 150 km at low SA. At large amplitudes of surface wave excitation, AGW breaking and smaller-scale inhomogeneities appear at altitudes 100–150 km, which are stronger at low SA. Increased dissipation of breaking AGWs may produce wave-induced jet streams with velocities close to the wave horizontal phase speed and near-critical layers at altitudes 110–150 km, which dramatically decrease amplitudes and momentum fluxes of the primary AGW mode propagating from the surface wave source. The wave-induced horizontal wind becomes smaller above altitude of 150 km and allows growing amplitudes of the primary wave mode partially penetrating through the near-critical layer and of secondary AGW modes, possibly generating in the wave induced jet stream. The wave amplitude grows at altitudes higher than 150 km is larger at high SA due to smaller velocities of wave-induced mean wind and smaller molecular viscosity and heat conduction. Accelerations of the mean flow by dissipating AGWs are generally larger at low SA. This determines faster grows of wave-induced jet streams in time at low SA. In almost all simulated cases, velocities of the wave-induced mean flows are higher at low SA compared to high SA. Resulting SA impact at a given thermospheric altitude depends on competition between AGW amplitude increase due to smaller molecular dissipation and smaller energy transfer to the wind-induced mean flow and amplitude decrease caused by larger density and stronger reflection at higher SA.

1. Introduction

Numerous studies show that acoustic-gravity waves (AGWs) continuously exist in the middle atmosphere (e.g., Fritts and Alexander, 2003). Observations frequently detect AGW presence in the thermosphere (e.g., Djuth et al., 2004; Park et al., 2014; Yue et al., 2010). Modeling atmospheric general circulation demonstrated that AGWs can propagate from the lower atmosphere to the thermosphere in the Earth's atmosphere (e.g., Yiğit et al., 2014; Yiğit and Medvedev, 2009, 2012, 2015) and at other planets (Yiğit et al., 2015a; Yiğit and Medvedev, 2016, 2017).

AGWs are frequently studied with non-hydrostatic numerical models. Baker and Schubert (2000) simulated nonlinear AGWs in the atmosphere of Venus. Some studies (Andreassen et al., 1998; Fritts and Garten, 1996; Fritts et al., 2009, 2011) used two-dimension modeling of wave breaking, turbulence generating and Kelvin-Helmholtz instabilities in the atmosphere. They exploit three-dimensional simulations of AGWs and turbulence in atmospheric regions with fixed vertical and horizontal sizes. These numerical algorithms made use of Galerkin-type series to alter partial differential equations to the ordinary equations for the coefficients of the spectral series. Liu et al. (2009) modeled propagation of AGWs and generation of Kelvin-Helmholtz vortexes in the mesopause region. Yu and Hickey (2007) and Liu et al. (2008) have applied two-dimensional numerical models to describe atmospheric AGW propagation.

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AGWs coming from the troposphere to the thermosphere were simulated in general circulation models (e.g., Yiğit et al., 2012a, 2014) with a state of the art whole atmosphere gravity wave parameterization of thermal and dynamical impacts of dissipating and saturated atmospheric waves (Yiğit et al., 2008). This nonlinear scheme alleviates the majority of the weaknesses of ad hoc linear GW schemes and it especially removes the necessity of any tuning parameters. Applications of this scheme to a Martian general circulation model (GCM) has demonstrated that tropospheric GWs can propagate into the thermosphere (Medvedev et al., 2013; Yiğit et al., 2015a). More recently, the whole atmosphere scheme has successfully been used to interpret Martian thermospheric GWs observed by the MAVEN spacecraft (Yiğit et al., 2015b).

AGWs can propagate from below, break and generate turbulence in the middle and upper atmosphere. Tropospheric mesoscale turbulence and convection may generate AGWs (e.g., Fritts and Alexander, 2003; Fritts et al., 2006). Turbulent wave sources can be more extensive in tropospheric jet streams, which have maxima in the upper troposphere (e.g., Medvedev and Gavrilov, 1995; Gavrilov and Fukao, 1999; Gavrilov, 2007). Non-hydrostatic models of the general circulation of thermosphere-ionosphere revealed that AGWs constantly exist in the thermosphere (e.g. Yiğit et al., 2012b).

Gavrilov and Kshevetskii (2013a) simulated nonlinear AGWs using a two-dimensional numerical model involving basic conservation laws. This numerical model allowed non-smooth solutions of equations of nonlinear AGWs and provided the needed numerical stability (Kshevetskii and Gavrilov, 2005). A three-dimensional version of this algorithm was build up by Gavrilov and Kshevetskii (2013b, 2014a) for simulating atmospheric nonlinear AGWs. The authors modeled AGWs excited by monochromatic horizontally homogeneous wave source at the ground. Karpov and Kshevetskii (2014) used the same numerical scheme for simulating infrasound propagation from non-stationary localized surface wave sources and found substantial infrasound thermal effects in the thermosphere. Dissipating AGWs can be also responsible for wave accelerating the mean flow in the upper atmosphere (e.g., Fritts and Alexander, 2003). However, peculiarities of the mean flows and thermal effects produced by non-stationary nonlinear atmospheric AGWs require further elucidations.

There are many evidences of the influence of solar activity (SA) on AGW characteristics in the thermosphere (e.g., Gavrilov, 1995; Klausner et al., 2009; Yiğit and Medvedev, 2010). SA changes the absorption of solar radiation producing changes in the thermospheric temperature and related changes in the density, static stability and dissipation, which can alter AGW propagation conditions. Differences of AGW characteristics in relatively cold and hot thermosphere were analyzed previously (e.g., Hickey, 1987; Yiğit and Medvedev, 2010). Numerical simulations of AGW propagation to the thermosphere from tropospheric convective sources at temperature profiles for different solar activity (Vadas and Fritts, 2006; Vadas, 2007; Fritts and Vadas, 2008) demonstrated better AGW propagation at high SA due to reduced dissipation. However, increased AGW reflection caused by larger temperature gradients can compete with enhanced propagation. These conclusions are in agreement with earlier studies (Francis, 1973; Richmond, 1978; Gavrilov et al., 1994).

In the present study, with the computational model developed in the works by Gavrilov and Kshevetskii (2013b, 2014a), we simulate nonlinear AGWs propagating from non-stationary wave source, located on Earth's surface, into the thermosphere using vertical profiles of background temperature, density, molecular weight, kinematic molecular viscosity and heat conduction characteristic for different SA levels. We applied simple AGW sources corresponding to plane wave spectral components of surface vertical velocity and compared wave characteristics and wave thermal and dynamical effects at different thermospheric altitudes at low and high SA levels. Nonlinear model involves wave-wave and wave-mean flow interactions, which lead to the energy transfer from primary AGW to secondary waves and to the mean flow. Differences in these processes at different SA levels can change AGW characteristics in the middle and upper atmosphere in addition to changes in wave dissipation and reflection processes.

2. Numerical model

In the present paper, we used the three-dimensional high-resolution AtmoSym model simulating atmospheric AGWs, which was developed by Gavrilov and Kshevetskii (2013a,b, 2014a,b,c). Recently this model becomes available for free online simulations for all users (AtmoSym, 2016). The AtmoSym is a three-dimensional high-resolution model and uses the plain geometry. The model calculates atmospheric velocity components and deviations of temperature, pressure, and density from their background values. Used in AtmoSym nonlinear three-dimensional primitive equations (Gavrilov and Kshevetskii, 2013a,b; 2014a) of continuity, motion and heat balance take into account nonlinear and dissipative processes accompanying wave propagation. They can describe, in particular, such complex phenomena as wave breaking and turbulence generation (e.g., Kshevetskii and Gavrilov, 2005).

The AtmoSym numerical model provides a self-consistent description of wave processes and takes into account the changes in atmospheric parameters due to energy transfer from decaying waves to the atmosphere. Vertical profile of the background temperature $T_0(z)$ is taken from the semi-empirical atmospheric models NRLMSISE-00 (Picone et al., 2002). Background molecular dynamic viscosity, η_0, and heat conductivity, κ_0, are approximated with the Sutherlands formula

$$\eta_0 = \frac{1.46\times10^{-6}\sqrt{T_0}}{1+110/T_0}\quad\left(\frac{kg}{m\cdot s}\right)$$
$$\kappa_0 = \frac{\eta_0}{\mathrm{Pr}_m};\quad \mathrm{Pr}_m = \frac{4\gamma}{9\gamma-5}, \tag{1}$$

where T is temperature, Pr_m is the molecular Prandtl number, γ is the ratio of air heat capacities at constant pressure and volume (Kikoin, 1976). The AtmoSym also takes into account vertical profiles of the background turbulent viscosity and thermal conductivity with maxima about 10 m^2s^{-1} near the ground and at altitude of 100 km, and a minimum of 0.1 m^2s^{-1} in the stratosphere (Gavrilov and Kshevetskii, 2013a,b; 2014a).

At the upper boundary $z \approx 600$ km, we assume zero vertical velocity and zero vertical gradients of the other wave parameters (Gavrilov and Kshevetskii, 2014a; b; c). These conditions can produce reflections of waves propagating from below. Our estimations show that such reflected waves become negligible below 400–450 km due to high dissipation and density increase. In the present research, we made calculations in a three-dimension region of the atmosphere and assume horizontal periodicity of wave source and solutions at horizontal boundaries (see Gavrilov and Kshevetskii, 2014a). At the lower boundary (the Earth's surface), we assume zero horizontal velocity and zero vertical gradients of temperature, density and pressure. For the wave excitation at the lower boundary, we assume horizontally periodical distributions of vertical velocity at the Earth's surface in the form of

$$w_{z=0} = W_0\cos\left(\sigma t - \vec{k}\cdot\vec{s}\right), \tag{2}$$

where σ is frequency, $\vec{s} = (x_1, x_2)$is radius-vector in horizontal plane, $\vec{k} = (k_1, k_2)$ is horizontal wave number and k_1 and k_2 are wavenumbers along the horizontal axes x_1 and x_2, respectively; W_0 is the surface amplitude of the considered wave mode. The plane wave excitation (2) can approximate spectral components of turbulent and convective AGW sources (Townsend, 1965, 1966). Studies of AGW generation by meteorological and turbulent processes in the atmosphere (e.g. Medvedev and Gavrilov, 1995) showed a broad variety of periods, wavelengths, amplitudes and other wave parameters.

Solar activity produces substantial changes in the background fields, which influence AGW propagation in the middle and upper atmosphere.