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Gravity waves in the thermosphere: Solar activity dependence

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Abstract

A statistical study of the thermospheric gravity waves has been carried out using multiwavelength daytime oxygen airglow emission intensity and equatorial electrojet (EEJ) strength data, which originate from four different altitude regions of the thermosphere. The thermospheric daytime oxygen airglow emission intensities at wavelengths 557.7, 630.0, and 777.4 nm, obtained during the January to March period in the three years 2011–2013, have been used. The percentage number of days in which waves with spectral periods in the gravity wave range have occurred are found to be greater for the relatively higher solar activity duration (in 2013) compared to that of low solar activity (in 2011). This observation is explained to be due to the altering background atmospheric density and temperature (that vary with solar activity), which, in turn, influences the propagation and dissipation of waves. Moreover, the higher frequency gravity waves (of periods Brunt–Väisälä to 30 min) have been found to be present in greater numbers in the thermosphere compared to that of low-and-moderate frequency gravity waves (of periods 30–60 min). This behavior in the frequency selection by ambient conditions at thermospheric altitude is in accordance with earlier theoretical and simulation works. The ratios of high- to low-frequency occurrences have also been found to be greater in higher solar activity period of 2013 compared to that of the relatively low solar activity period of 2011. These results thus provide experimental evidence to the earlier simulation works suggesting similar behavior, as found here, for thermospheric gravity waves.

Keywords: Dayglow; Gravity waves; Atmospheric coupling; Sun–Earth interaction

1. Introduction

The upper atmosphere of the Earth is affected by both incoming solar radiation and waves from the lower atmosphere. Most of the waves and instabilities present in the atmosphere are generated in the troposphere. The negative temperature gradient in the troposphere supports convective activities that generate waves. Many of these waves can propagate upward and dominate the motions in the upper atmospheric altitudes (e.g. Vadas and Fritts (2005), Laštovička (2009), Yiğit and Medvedev (2014)). From modeling studies (Yiğit et al., 2008) it was shown that small-scale gravity waves influence the general circulation in the thermosphere and the modeled gravity wave effects

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are comparable to ion-drag effects up to ionospheric F-region altitudes (Yiğit et al., 2009). Wave propagation into upper atmosphere is affected by various types of dissipations, such as, radiative damping, nonlinear wave-induced diffusion, eddy diffusion, molecular diffusion and thermal conduction, and ion-drag (Pitteway and Hines, 1963; Vadas and Fritts, 2005; Yiğit et al., 2008, 2009). Among them, the first three are dominant below the turbopause (∼100 km altitude) and the last two are active above the turbopause. The waves of lower amplitudes are stable and do not interact with each other or with themselves, but, with decreasing atmospheric density the wave amplitudes increase and at some height these waves become unstable due to non-linear effects and break down. From numerical simulations, it was shown that the non-linear wave-wave interaction maximizes at the mesosphere lower thermosphere (MLT) altitudes (Weinstock, 1982; Medvedev and Klaassen, 2000; Yiğit et al., 2008). Thus, many of these waves dissipate at MLT altitudes and accelerate the mean flow, which, in turn, excite secondary waves with much larger horizontal scale-sizes. The dominant dissipation parameters in the lower thermosphere are the molecular diffusion and thermal conduction (Vadas and Fritts, 2005; Yiğit et al., 2008), both are related with the molecular transport mechanism. The molecular kinematic viscosity at thermospheric altitudes (v_{mol}) is given by (Yiğit and Medvedev, 2010):

$$v_{mol} = 3.563 \times 10^{-7} T^{0.69} / \rho \ [\mathrm{m^2\ s^{-1}}] \quad (1)$$

and the thermal diffusivity (α) is given by

$$\alpha = \kappa / \rho c_p \ [\mathrm{m^2\ s^{-1}}] \quad (2)$$

where, κ is the thermal conductivity, ρ is the number density [kg m^{-3}], T is the ambient neutral temperature, and c_p is the specific heat at constant pressure. Both the dissipation parameters are inversely proportional to density and weakly proportional to temperature and are related to each other as they are governed by molecular transport processes (Vadas and Fritts, 2005; Yiğit et al., 2008, and references therein; Yiğit and Medvedev, 2010).

Solar or lower atmospheric forcings at MLT heights have been studied widely by many researchers using radar winds (e.g. Gurubaran et al. (2001), Hoffmann et al. (2011)), Lidar (e.g. Rauthe et al. (2008)), sounding rocket (Hirota, 1984), VLF radio sounding (e.g. Boskova and Laštovička (2001)), and airglow measurements (e.g. Takahashi et al. (1992), Taylor et al. (1997), Chakrabarty et al. (2004), Lakshmi Narayanan et al. (2010), Laskar and Pallamraju (in press)). Though, the experimental observations of the effects of individual gravity wave forcing into the thermospheric regions have been studied to some extent, the detailed dynamical influences are not well understood, particularly during daytime, due to a lack of continuous neutral measurements spanning different levels of solar activity and at multiple heights. In comparison, there are several studies that used night-time or magnetic data sets (e.g. Taylor et al. (1997), Shiokawa et al. (2009), Shume et al. (2014)) to study the gravity waves. Satellite-based continuous measurements of dayglow are available (e.g. Shepherd et al. (1993)), but are inherently limited by poor temporal resolution that prevents a detailed study of gravity waves. Direct effects of lower atmospheric gravity waves are sparse owing to several observational constraints. However, due to the availability of the high performance computation systems in the recent times, a few modeling works using general circulation models have provided insights into the thermal (Yiğit and Medvedev, 2009) and dynamical (Yiğit et al., 2009) influences of gravity waves in the thermosphere. Numerical simulations were also conducted to study the thermal and dynamical effects of the dissipating gravity waves in the thermosphere during varying levels of solar activity (e.g. Fritts and Vadas (2008), Yiğit et al. (2009), Yiğit and Medvedev (2010)).

The importance of the gravity waves in the thermospheric dynamics has been discussed in the literature (e.g. Hocke and Schlegel (1996), Oliver et al. (1997), Chakrabarty et al. (2004), Pallamraju et al. (2010, 2014), and references therein). For the study of gravity waves at different altitudes of the thermosphere multiwavelength airglow measurement is an effective method. Night-time airglow measurements are widely used for the investigations of the thermosphere (e.g. Shiokawa et al. (2009), Smith et al. (2000), Taylor et al. (1997), Lakshmi Narayanan et al. (2010), Sekar et al. (2012)), but due to the presence of moonlit brightness these measurements are not available in-and-around full-moon periods which prevents continuity in data. Due to the technical difficulty of measuring the daytime airglow in the presence of the strong scattered sunlight, there were few daytime measurements. In the recent past there has been an increase in the studies of daytime upper atmosphere by ground-based measurements, as innovative techniques have become available (e.g. Pallamraju et al. (2013, 2014), Marshall et al. (2011), Laskar et al. (2013), Laskar and Pallamraju (in press)). Further, the daytime airglow measurements are not constrained by full-moon conditions as opposed to nighttime airglow measurements. Therefore, continuous daytime optical datasets enable information on the large-scale waves in the thermosphere (e.g. Pallamraju et al. (2010), Laskar et al. (2013)).

With an increase in solar activity the incoming extreme ultraviolet and X-ray radiation increases which results in the change of background conditions, such as, density and temperature in the thermosphere. Due to these varying background conditions, the dissipation characteristics of the waves change. In an earlier study (Laskar et al., 2013) using stratospheric wind, equatorial electrojet (EEJ) strength, multi-wavelength oxygen dayglow emission intensities, and total electron content measurements it was shown that the vertical coupling of atmospheres via the planetary wave type variations is stronger during low solar activity and weaker during high solar activity. In the current study, an attempt is made to understand the behavior of the thermospheric gravity waves by statistically

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