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Excitation mechanism of non-migrating tides

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ABSTRACT

Using an atmosphere-ionosphere coupled model, the excitation source and temporal (seasonal and interannual) variations in non-migrating tides are investigated in this study. We first focus our attention on temporal variations in eastward moving diurnal tide with zonal wavenumber 3 (DE3), which is the largest of all the non-migrating tides in the mesosphere and lower thermosphere (MLT). Our simulation results indicate that upward propagation of the DE3 excited in the troposphere is sensitive to the zonal mean zonal wind in the stratosphere and mesosphere. The DE3 amplitude is enhanced in the region where the vertical shear of the zonal mean zonal wind is positive (westerly shear). Quasi-2-year variation in the DE3 amplitude in the MLT region is generated by quasi-2-year variation in the zonal mean zonal wind between 40 and 70 km, which is modulated by the stratospheric QBO. The excitation mechanisms of SW3 (westward moving semidiurnal tide with zonal wavenumber 3) and SW1 (westward moving semidiurnal tide with zonal wavenumber 1) are also investigated. During equinoxes, the SW3 and SW1 are excited by tropospheric heating (latent heat release and solar radiative heating) associated with cumulus convection in the tropics, and propagate upward into the MLT region. On the other hand, during solstices, SW3 and SW1 are generated in the winter stratosphere and mesosphere through the nonlinear interaction between the stationary planetary wave and migrating semidiurnal tide, and propagate upward to the lower thermosphere. The excitation sources of other non-migrating tides are also discussed.

1. Introduction

Atmospheric tides in the mesosphere and lower thermosphere (MLT) plays an important role in the general circulation of the atmosphere. The amplitudes of the temperature and zonal wind components of atmospheric tides in the MLT reached several tens of K and m/s, respectively (e.g., Chapman and Lindzen, 1970). The migrating diurnal and semidiurnal tides, which move westward with the sun, are the largest of the atmospheric tides. These migrating tides are expressed as follows.

$$A_k \cos(\Omega kt + kx - \delta_k) \quad (1)$$

where x, t and Ω are the longitude, universal time (UT), and $2\pi/24$, respectively. A_k and δ_k are the amplitude and phase, respectively. $k=1$ in Eq. (1) denotes the migrating diurnal tide (DW1), whereas $k=2$ denotes the migrating semidiurnal tide (SW2). The features of DW1 and SW2 are described in detail by Pancheva and Mukhtarov (2011) and Forbes et al. (2008).

Atmospheric tides that do not move with the sun, i.e., non-migrating tides, have also been studied (Kato, 1989). For example, the diurnal variation in surface pressure is larger over land than that over ocean. This difference in the diurnal variation is explained by non-migrating diurnal tides that are excited by the land–sea contrast of solar radiative heating near the surface (Kato et al., 1982). Non-migrating tides are expressed as follows.

$$A_{kl} \cos(\Omega lt + kx - \delta_{kl}) \quad (k \neq l) \quad (2)$$

$k>0$ $(k<0)$ in equation (2) indicates westward (eastward) moving non-migrating tides. For example, $l = 1, k=2$ denotes a westward moving diurnal tide with zonal wavenumber 2 (DW2), whereas $l = 1, k = -3$ is an eastward moving diurnal tide with zonal wavenumber 3 (DE3). As for semidiurnal tides, $l = 2, k=1$ a denotes westward moving tide with zonal wavenumber 1 (SW1), whereas $l = 2, k = -2$ is an eastward moving tide with zonal wavenumber 2 (SE2).

Satellite observations enable us to estimate the global structures of migrating and non-migrating tides. In particular, recent satellite

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observations, such as UARS and TIMED, have revealed the latitudinal structure of and temporal variations in non-migrating tides in the MLT (Talaat and Lieberman, 1999; Oberheide and Gusev, 2002; Forbes et al., 2003). Using Nimbus 7 LIMS observations, Lieberman (1991) showed that the non-migrating diurnal tide has considerable amplitude in the stratosphere and lower mesosphere. Moreover, SABER observations revealed the seasonal and interannual variations in non-migrating tides in the MLT (Forbes et al., 2008). DE3 is the largest of the non-migrating diurnal tides in the MLT (~17 K at 110 km height), although the eastward moving diurnal tide with zonal wavenumber 2 (DE2) also has a large amplitude (~7 K at 110 km height). In the 90–100 km height region, DW2 and D0 (zonal symmetric component of the diurnal tide) have considerable amplitudes (~7 K at 100 km height). SW3 is the largest of the non-migrating semidiurnal tides in the MLT (~8 K at 110 km height), although SW1 (~ 6 K at 110 km height) and SE2 (~5 K at 110 km height) are also important (Forbes et al., 2008; Pancheva and Mukhtarov, 2011).

Numerical simulations are useful tools for investigating the global structure of non-migrating tides. Using a general circulation model (GCM), Tokioka and Yagai (1987) showed that DE3 and DW5 (westward moving diurnal tide with zonal wavenumber 5) are excited in the troposphere and have considerable amplitudes in the stratosphere and mesosphere. Miyahara et al. (1993) showed upward propagation of non-migrating tides from the troposphere to the MLT. Numerical studies have shown the excitation sources and upward propagation of non-migrating tides (Hagan and Forbes, 2002, 2003; Miyahara, 1993; Miyoshi, 2006; Akmaev et al., 2008).

It has been recognized that non-migrating tides affect electron density distribution in the ionosphere. Recent observations have found that the electron density in the F-region has a wave-4 structure in the longitudinal direction (Immel et al., 2006). This structure is considered to be generated by the longitudinal modulation of the zonal electric field ($\vec{E}\times\vec{B}$ drift), which is caused by the zonal wind due to DE3 through the E-region dynamo (Hagan et al., 2007; Jin et al., 2008). Moreover, DE2 produces a wave-3 structure of the electron density in the longitudinal direction, whereas SW3 and SW1 generate a wave-1 structure of electron density. Therefore, non-migrating tides in the lower thermosphere play an important role in the distribution of electron density in the ionosphere.

It is well known that migrating tides are excited by the absorption of solar radiation in the atmosphere and at the surface. On the other hand, there seem to be two main excitation sources for non-migrating tides: nonlinear wave interaction between two waves and thermal excitation associated with cumulus convection in the troposphere. However, the excitation sources of non-migrating tides remain unclear. Moreover, seasonal and interannual variations in non-migrating tides in the MLT, and their relations to excitation sources, are not completely understood. Therefore, in this study, we investigate the excitation sources of non-migrating tides and their relations to seasonal and interannual variations in non-migrating tides in the MLT. We focus on the sources and temporal variations in DE3, SW3, and SW1. The rest of the paper is organized as follows. We review excitation sources for non-migrating tides in Section 2. We briefly describe the SABER observation and the numerical simulation in Section 3. Results relating to DE3, SW3, and SW1 are presented in Sections 4 and 5. Finally, our conclusions are given in Section 6.

2. Excitation sources of non-migrating tides

As shown previously, two excitation sources are apparently responsible for non-migrating tides (nonlinear interaction and latent heat release). The nonlinear interaction mechanism responsible for the excitation of non-migrating tides is explained as follows. The nonlinear interaction between the stationary planetary wave ($A\cos kx$) and the migrating tide ($A_l\cos(l\Omega t + lx)$) generates two non-migrating tides (Angelats I Coll and Forbes, 2002):

$$A\cos kx \times A_l\cos(l\Omega t+lx) \Longrightarrow \frac{1}{2}AA_l\cos(l\Omega t+(k+l)x)+\frac{1}{2}AA_l\cos(l\Omega t+(l-k)x) \quad (3)$$

For example, the nonlinear interaction between the stationary planetary wave with zonal wavenumber 1 ($A\cos x$) and the migrating diurnal tide ($A_1\cos(\Omega t + x)$) produces DW2 ($\cos(\Omega t + 2x)$) and D0 ($\cos(\Omega t)$). It is plausible that the nonlinear interaction between the planetary wave and the migrating tide is active in the winter stratosphere and mesosphere, because the stationary planetary wave has a large amplitude. For example, using the SABER temperature observations, Pancheva et al. (2009) showed that the enhancement of D0 and DW2 amplitudes occurs during a sudden stratospheric warming event in the northern hemisphere (NH).

The nonlinear interaction between the stationary planetary wave with zonal wavenumber 1 ($A\cos kx$) and the migrating semidiurnal tide ($\cos(2\Omega t + 2x)$) generates SW3 and SW1. Using the MLS temperature measurements on board the UARS satellite, Forbes and Wu (2006) investigated the temporal and spatial distributions of SW3 and SW1 amplitudes. They showed that SW3 and SW1 amplitudes poleward of 60°N are enhanced during the winter and attenuated during the summer. This result is explained by the fact that SW3 and SW1 are generated during the winter when the planetary wave has a large amplitude. Using GCM simulation, Yamashita et al. (2002) showed that SW1 is generated in the winter stratosphere, propagating upward and equatorward. This equatorward propagation of SW1 from the winter to summer hemisphere produces a large SW1 amplitude near the south pole in the lower thermosphere (Forbes et al., 1995). Moreover, the nonlinear interaction between the planetary wave with zonal wavenumber 2 and the migrating diurnal (semidiurnal) tide generates DW3 and DE1 (SW4 and S0).

The other excitation source of non-migrating tides is the latent heat release associated with cumulus convection in the troposphere. The absorption of solar radiation in the atmosphere and at the surface has diurnal variation, producing diurnal variation in the cumulus convective activity. In cases where the convective activity has a zonally non-uniform structure, non-migrating tides are excited by the latent heat release (Hagan and Forbes, 2003). For example, the 24 h variation in the cumulus convective activity with zonal wavenumber 4 excites DW5 and DE3.

$$A\cos 4x \times A_1\cos(\Omega t+x) \Longrightarrow \frac{1}{2}AA_1\cos(\Omega t+5x)+\frac{1}{2}AA_1\cos(\Omega t-3x) \quad (4)$$

Because the zonal wavenumber 4 component is the largest in the land–sea distribution at low latitudes, the cumulus convective activity has a large zonal wavenumber 4 component (Tokioka and Yagai, 1987). This means that DE3 and DW5 are excited by the latent heat release in the tropical troposphere. Moreover, the 12 h variation in cumulus convection ($A_2\cos(2\Omega t + 2x)$) with zonal wavenumber 4 excites SW6 and SE2.

Using a global scale wave model (GSWM), Hagan and Forbes (2002) investigated the impact of latent heat release on non-migrating tides in the MLT region. They showed that the temperature component of the simulated DE3 amplitude at an altitude of 115 km reaches 30 K, which is larger than the observed DE3 amplitude (~17 K). This indicates that latent heat release is important for DE3 excitation. As mentioned previously, the nonlinear interaction between the planetary wave with zonal wavenumber 4 and the migrating diurnal tide also generates DE3 and DW5. However, the amplitude of the planetary wave with zonal wavenumber 4 is small in the middle atmosphere, and hence, DE3 generated by the nonlinear interaction is also considered to be small. Therefore, latent heat release is the most plausible excitation source of DE3 and DW5.

The 24 h variation in cumulus convection with zonal wave number 1 excites DW2 and D0. Hagan and Forbes (2002) showed that DW2 excited by latent heat release reaches 5 K at an altitude of 115 km,