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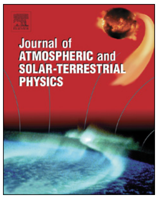

Interpretation of the vertical structure and seasonal variation of the diurnal migrating tide from the troposphere to the lower mesosphere

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ABSTRACT

The latitudinal–vertical structure and the seasonal variation of the diurnal migrating tide (DW1) from the troposphere to the lower mesosphere are investigated, using reanalysis data from the Modern Era Retrospective analysis for Research and Applications (MERRA) and a linear tidal model. For the latitudinal-vertical structure, the observed feature is well represented by the four lowest-order classical Hough modes each of which shows its own unique vertical propagation characteristics. The tropospheric profile of DW1 temperature in the tropics is found to be mainly controlled by the first symmetric propagating Hough mode. The constant phase in the troposphere is due to the small static stability in the troposphere. For the seasonal variation, the amplitude from the stratosphere to the lower mesosphere maximizes at solstices. This is caused by a major contribution from the anti-symmetric propagating Hough mode. It is found that this seasonal variation is not explained by that of diabatic heating. Using a linear model, we found that background zonal wind is important for the seasonality. Also, using a modified mode-coupling approach, we interpret that in addition to primary tides generated by diabatic heating, secondary tides generated by meridional advection of background zonal momentum have a large contribution to the DW1, creating the above-mentioned seasonal variation from the stratosphere to the lower mesosphere in the tropics. It is suggested that both excitation and propagation characteristics can be physically interpreted in terms of the superposition of independent classical Hough modes. That is, each Hough mode is not only primarily excited by diabatic heating but also secondarily by mechanical forcing, and then propagates by following its own vertical propagation characteristics.

1. Introduction

Tidal variability in the lower atmosphere greatly influences the upper atmosphere, particularly the mesosphere and lower thermosphere region (MLT region), since tides are mainly excited in the troposphere and the stratosphere and propagate upward. Sakazaki et al. (2012) (hereafter referred as S12) revealed the global picture of diurnal migrating (westward-moving zonal wavenumber 1) tide (DW1) in temperature from the troposphere to the lower mesosphere with a focus on the latitudinal–vertical structure and the seasonal variation, using data from Thermosphere–Ionosphere–Mesosphere-Energetics and Dynamics/Sounding of the Atmosphere using Broadband Emission Radiometry (TIMED/SABER) and from six global reanalyses during 2002–2006. S12 showed that the latest reanalyses including the Modern Era Retrospective analysis for Research and Applications (MERRA) reproduce the latitudinal–vertical structure and seasonal variation qualitatively well, although the amplitude from the upper stratosphere to the lower stratosphere is 30–50% smaller in reanalyses than in SABER. This finding warrants the use of MERRA data for investigating the DW1 throughout this study with a caution that we limit the discussion to the qualitative features.

For the latitudinal–vertical structure (Figures 6, 7 and 10 of S12), S12 showed that the amplitude of temperature DW1 basically maximizes in the tropics while it is also large in the midlatitude upper stratosphere. The phase in the tropics is constant within the troposphere at ~1800 LT and shows a downward progression in regions from the stratosphere to the lower mesosphere. In contrast, the phase at extratropical latitudes is constant at ~1800 LT at all altitudes. For the seasonal variations in the stratosphere (Figures 6 and 11 of S12), S12 showed that the amplitude maximum in the midlatitude upper stratosphere is larger in the summer hemisphere than in the winter hemisphere. In contrast, the amplitude in the stratosphere and the lower mesosphere in the tropics maximizes at the solstices and the location of maximum is largely anti-symmetric with respect to the

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equator. In this paper, we will seek to understand the reason for these characteristics.

The simplest and most fundamental approach for tidal studies is the classical tidal theory, which is based upon the assumption that the basic atmosphere is at rest and the background temperature depends only on altitude (Chapman and Lindzen, 1970). For a tidal component with certain frequency and wavenumber (e.g., DW1), the governing equations are separable and an exact analytical solution is given by a superposition of the so-called Hough modes. Each Hough mode has its own unique characteristic latitudinal shape as derived by Laplace's tidal equation, and associated vertical structure as derived by the vertical structure equation (see Appendix A for details). Thus, many previous studies used the classical tidal theory for the interpretation of latitudinal and vertical structure of tides (e.g., Chapman and Lindzen, 1970; McLandress, 2002b; Mukhtarov et al., 2009). An important point in this theory is that each mode is independent so that the amplitude in a particular mode of excited tides basically follows that of diabatic heating, although the efficiency of excitation needs to be considered (i.e., a certain mode is most efficiently excited by the heating whose depth is half of the vertical wavelength of the mode (Salby and Garcia, 1987)).

In the classical theory, the effects of background zonal-mean zonal wind and latitudinal gradient of background temperature (hereafter, 'non-classical terms') are not considered. The linear equations including the non-classical terms become non-separable and cannot be solved analytically (Lindzen and Hong, 1974; Forbes and Garrett, 1979; Walterscheid and Venkateswaran, 1979a,b). The only way to solve the equations accurately is to use numerical calculations (Forbes and Hagan, 1988; Miyahara, 1975, Wood and Andrews, 1997a,b, Zhu et al., 1999; McLandress, 2002b; Achatz et al., 2008). The numerical simulations are useful to quantify the contribution from non-classical terms; however, it is difficult to make a physical and qualitative interpretation of their roles. Thus, two different approaches have been usually adopted for the interpretation: (1) the generalized Hough mode approach and (2) the mode-coupling approach. In the case of (1), one interprets the changes of the classical Hough modes as due to the non-classical terms; these transformed modes are called generalized Hough modes (Ortland, 2005a,b). In the case of (2), the non-classical terms are considered as forcing terms so that the classical Hough modes are still applicable and are used for the discussion (Lindzen and Hong, 1974) (see also Walterscheid and Venkateswaran, 1979a,b). Note that Lindzen and Hong (1974) started with the linearized primitive equation reduced to pressure; thus, the forcing terms were so complex that the physical interpretation of the forcing was still generally quite complicated.

In previous studies, the latitudinal–vertical structure in the stratosphere and the mesosphere was interpreted in terms of the superposition of different classical Hough modes mainly using temperature data (Lieberman, 1991; Mukhtarov et al., 2009). But the actual Hough mode decomposition was done using satellite data only at low latitude regions (<30–50°). In addition, the extratropical data ($>30^\circ$) from satellites may be subject to sampling issues as pointed out by S12; thus, the results from the satellites may have been partly affected by spurious signals. Within the troposphere, the underlying mechanism of the vertical profile, particularly the constant phase in vertical, has not been examined except that Zeng et al. (2008) suggested that the constant phase might result from the dominance of trapped Hough modes. Note that the actual Hough mode decomposition has not been performed by Zeng et al. (2008) so that this suggestion has not been confirmed.

For the seasonal variations in the stratosphere, the amplitude in the midlatitude upper stratosphere follows that of diabatic heating there (i.e., ozone radiative heating) which is larger in the summer hemisphere (Mukhtarov et al., 2009; Xu et al., 2010). In contrast, the mechanism of the seasonal variations from the stratosphere to the lower mesosphere in the tropics has yet to be understood, although they were basically simulated in linear tidal models (Wood and Andrews, 1997b; Zhu et al., 1999). For the mesosphere, McLandress (2002b) and Zhu et al. (2005) found that the background zonal wind is important for the seasonal variation of DW1 by performing linear model simulations. McLandress (2002b) also found that the anti-symmetric propagating Hough mode, the (1, 2) mode, is strongly generated at the solstices due to the mode-coupling. It was suggested that the meridional gradient of the background zonal wind changes the vertical propagation condition of the mode, affecting its amplitude. However, again note that there has been no previous studies about the seasonal variation in the stratosphere.

The purpose of this study is to interpret (1) the latitudinal–vertical structure from the troposphere to the lower mesosphere and (2) the seasonal variation from the stratosphere to the lower mesosphere in the tropics. We mainly analyze MERRA data which have been validated by S12 for the above two points. For (1), we perform the Hough mode decomposition using MERRA data which cover the whole latitude region from 90°S to 90°N from the troposphere to the lower mesosphere without being affected by sampling issues. Then, the latitudinal–vertical structure is interpreted as the superposition of Hough modes each of which has its own vertical propagation characteristics. For (2), we examine the relationship between diabatic heating and tidal responses (i.e., temperature) for each Hough mode in MERRA, and also examine the contribution from non-classical terms by using linear model experiments. In addition, we use the mode-coupling approach in a different formulation from the one by Lindzen and Hong (1974), to give a clear physical meaning to the non-classical terms, and to interpret the excitation mechanism of each classical Hough mode. By examining the underlying dynamical processes, we finally aim at understanding the excitation and propagation processes of the DW1 in terms of the superposition of independent classical Hough modes; that is, we clarify how each Hough mode is excited and propagates.

The remaining sections are organized as follows. Section 2 describes the data and analysis methods and a linear model, while introducing the classical Hough modes and a modified mode-coupling approach used in this study. Section 3 examines the latitudinal–vertical structure of the DW1, using the Hough mode decomposition. Section 4 examines the seasonal variations from the stratosphere to the lower mesosphere in the tropics, using the linear model and the mode-coupling approach. Finally, Section 5 summarizes the main findings.

2. Data and methods

2.1. Descriptions of data and analysis methods

We analyze 3-hourly (0000 UTC, 0300 UTC 0600 UTC, 0900 UTC, 1200 UTC, 1500 UTC and 2100 UTC) data from the MERRA (Rienecker et al., 2011) for the period from 2002 to 2006. Four variables are considered: temperature (T), zonal wind (u), meridional wind (v), and geopotential height ($Z=\Phi/g_0$), where Φ is geopotential and $g_0=9.80665\ \mathrm{m\ s^{-2}}$ is the global average of gravitational force at the mean sea level. Data are provided on pressure levels at 1000–0.1 hPa. Hereafter, the 'altitude' means the vertical coordinate in log-pressure coordinate, defined as $z^* = -H \log (p/p_0)$, where $H=7$ km is the scale height, p is the pressure level and $p_0 = 1000$ hPa is the reference pressure.

In addition, total diabatic heating rate data (variable name: 'DTDTTOT') from MERRA during 2002–2006 are analyzed in order