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Global structure and seasonal variability of the migrating terdiurnal tide in the mesosphere and lower thermosphere

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ABSTRACT

The morphology of the migrating terdiurnal tide with zonal wavenumber 3 (TW3) in the mesosphere and lower thermosphere (MLT) is revealed using the TIMED satellite datasets from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) and the TIMED Doppler Interferometer (TIDI) instruments from 2002 to 2009, as well as the Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM). The annual mean structures of the TW3 from the TIME-GCM clearly resemble the first real symmetric (3,3) Hough mode. The TW3 temperature and zonal wind components have three peaks at midlatitudes and near the equator, while the TW3 meridional wind components show four peaks at mid and low latitudes. These features are consistent with those resolved in SABER temperature and TIDI zonal wind above ~95 km. TW3 components in the TIME-GCM are stronger during winter and spring months at midlatitudes, which is in agreement with previous ground-based radar measurements. On the other hand, TW3 components of temperature, zonal and meridional winds from SABER and TIDI display different seasonal variations at different altitudes and latitudes. The results presented in this paper will provide an observational basis for further modeling study of terdiurnal tide impacts on the thermosphere and ionosphere.

1. Introduction

Atmospheric thermal tides are prominent global-scale fluctuations in pressure, temperature, wind, density, and airglow emissions with periods being harmonics of a solar day (i.e. 24 h, 12 h, 8 h, etc.). Thermal tides can be excited by the daily absorption of solar radiation by water vapor in the troposphere and by ozone in the stratosphere, as well as latent heat release due to deep convection in the tropics (Chapman and Lindzen, 1970; Zhang et al., 2010). Since the terdiurnal (period of 8 h) tide is more transient and usually weaker than the diurnal and semidiurnal tides in the mesosphere and lower thermosphere (MLT), there have been much fewer observational and modeling efforts undertaken to characterize and understand the terdiurnal tide. In particular, there are very few reported satellite observations of terdiurnal tides.

The observations of terdiurnal tidal winds in the MLT were mostly made using ground-based radars in the Northern Hemisphere (NH) (Glass and Fellous, 1975; Manson and Meek, 1986; Teitelbaum et al., 1989; Thayaparan, 1997; Younger et al., 2002; Belton et al., 2006; Jiang et al., 2009; Rao et al., 2011). Different seasonal variabilities of the terdiurnal tide have been observed using radars located at different latitudes, and occasionally even at similar latitudes. As recently summarized by Rao et al. (2011), the maximum amplitude of the terdiurnal tide measured by radars in horizontal winds occurs in fall at high latitudes, in winter and early spring at midlatitudes, near equinoxes at low latitudes, and in late spring and early summer over the equator. Note that the radar-measured terdiurnal tide is the superposition of both migrating (herein referred to as TW3 with westward zonal wavenumber 3) and nonmigrating terdiurnal components. In addition, a few satellite observations revealed the global structures of the migrating terdiurnal tide in the MLT (Smith, 2000; Forbes and Wu, 2006; Forbes et al., 2006, 2008). Using the wind measurements from the High Resolution Doppler Interferometer (HRDI) on the Upper Atmosphere Research Satellite (UARS), Smith (2000) found that the maximum wind amplitude of the terdiurnal tide at ~95 km occurs during fall and winter months at midlatitudes, and that the annual mean amplitude of TW3 is 15 m/s for the zonal wind and 5 m/s for the meridional wind. Using

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temperature measurements during 2002–2006 from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite, Forbes et al. (2008) found that the TW3 in temperature at 100 km showed a 6–8 K maximum in the low-latitude Southern Hemisphere (SH) during January–March, along with a band of maxima near 10°N during the rest of the year. Nonetheless, the height, latitudinal and seasonal variations of the terdiurnal tide discovered from various observations do not agree with each other due to the transient feature of the terdiurnal tide and its relatively weak amplitude.

Only a few theoretical and modeling studies have been attempted to characterize the terdiurnal tide and examine its excitation mechanisms. Two mechanisms have been proposed to account for the excitation of TW3. One is the 8-h harmonic of direct solar heating (Chapman and Lindzen, 1970; Glass and Fellous, 1975; Akmaev, 2001; Smith and Ortland, 2001). The other is the nonlinear interaction of the migrating diurnal tide (westward zonal wavenumber 1, or DW1) and migrating semidiurnal tide (westward zonal wavenumber 2, or SW2) (Teitelbaum et al., 1989; Huang et al., 2007). In addition, tidal modulation of the gravity wave momentum flux may generate an 8-h local fluctuation with much weaker amplitude (Miyahara and Forbes, 1991).

The impact of the terdiurnal tide on the ionosphere and thermosphere has gained more attention in recent years. Gong and Zhou (2011) reported an observational study of the terdiurnal tide in the ionosphere and thermosphere in January 2010 using the Arecibo incoherent scatter radar. Their study indicated that the terdiurnal tide was as important as the diurnal and semidiurnal tides in both the E-region and F-region during this period. Miyoshi et al. (2009, 2011) suggested that the upward propagating terdiurnal tide might play a key role in the generation of the midnight temperature/density maximum (MTM) and equatorial mass density anomaly (EMA) in the thermosphere, along with the in situ generated diurnal and semidiurnal tides. During Sudden Stratospheric Warming (SSW) events, an increase in the terdiurnal tide in the lower thermosphere is found in the Whole Atmosphere Model (WAM), which can subsequently alter the electrodynamical response in the ionosphere (Fuller-Rowell et al., 2010; Wang et al., 2011). In addition, Gong et al. (2012) found that the terdiurnal tide played a major role in causing the rapid drop in HmF2 during an ionospheric collapse observed in January 2010. A comprehensive understanding of TW3 in the MLT region using both observations and GCM simulations is a prerequisite for precisely determining the influence of the terdiurnal tide on the thermosphere and ionosphere.

In this work, we present TW3 observations in 2002–2009 from two instruments on the TIMED satellite – the TIMED Doppler Interferometer (TIDI) and SABER – that together, to provide global coverage of the wind and temperature in the MLT region. The National Center for Atmospheric Research (NCAR) Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM) output for year 2006 is examined to compare with the observations. By gathering the information from these datasets, an unprecedented global view of TW3 in the MLT will be provided in this paper.

2. Instrumentations, model and data analysis

2.1. SABER temperature measurements

The TIMED satellite was launched on 7 December 2001 into a 625 km 74.1° inclined orbit with a precession rate that provides 24-hour local time coverage every 60 days. SABER, a broadband infrared limb sounder, began temperature observations in January 2002 that have continued virtually uninterrupted to the present day. The temperature retrievals are produced by inversion of CO_2 15 μm and 4.3 μm vertical radiance profile measurements collected every ~53 s (Russell et al., 1999). Single profile temperature uncertainties are ~4–5 K in the upper mesosphere (Remsberg et al., 2008). Temperatures used in this study are SABER Version 1.07 (http://saber.gats-inc.com/) results for the period between 2002 and 2009. Because the spacecraft yaws every 60 days causing alternate polar region coverage (Xu et al., 2007), we only consider the SABER temperature between 50°S and 50°N.

To process the data, the zonal mean temperature and pressure, as well as the tidal components are first separated using least squares fitting of the space-time series (Wu et al., 1995; Xu et al., 2009). The temperature at any latitude ψ and altitude z can be considered to be a superposition of zonal mean, migrating and nonmigrating tides for periods longer than 1/5 day and for a zonal wavenumber smaller than 6

$$T(t,\lambda) = \overline{T}(t) + \sum_{m=-5}^{5} \sum_{s=1}^{4} T_{s,m} \cos\left[s\omega_0 t + m\lambda + \beta_{s,m}\right] \tag{1}$$

where $\omega_0 = 2\pi/24$ (h), λ is longitude (in radians) and t is the universal time, respectively. $\overline{T}(t)$ is the zonal mean field. $T_{s,m}$ and $\beta_{s,m}$ are the amplitudes and phases of tides with $s=1, 2, 3, 4$ corresponding to the diurnal, semidiurnal, terdiurnal and quatradiurnal periods. $m=-5, \ldots, 5$ are the zonal wavenumbers. $s=m$ is for migrating tides and $s \neq m$ is for nonmigrating tides. A 70-day moving window is used here to obtain full 24-h coverage of local time. A detailed discussion of the extractions of the diurnal, semidiurnal, terdiurnal and quatradiurnal tides from the SABER data was given by Xu et al. (2007). We note that because there exists a varying zonal mean and diurnal or semidiurnal component, the finite 70-day window introduces aliasing of zonal mean field and tidal variations into the fitted terdiurnal tides (e.g., Smith, 2000; Oberheide et al., 2003; Xu et al., 2009).

2.2. TIDI wind measurement

Another instrument on the TIMED satellite, TIDI, is a limb-scan Fabry-Perot interferometer. The line of sight (LOS) wind is retrieved from the Doppler shift in the airglow emissions, such as rotational lines in the O_2 (0–0) bands at 763.51 nm (Killeen et al., 2006; Wu et al., 2006, 2008). Because TIDI scans the LOS wind from an altitude of 75 km to 110 km during the daytime, and 80 km to 105 km during the night, we limit the terdiurnal tidal analysis to the altitude range between 80 km and 105 km. The tidal retrieval procedure from TIDI data is identical to that used for the SABER data. The NCAR/HAO TIDI data version 3.07a between 2002 and 2009 are analyzed in this paper (http://timed.hao.ucar.edu/tidi/index.html). Climatologies of the diurnal and semidiurnal tides from the TIDI wind were reported by Wu et al. (2008, 2011).

The level of uncertainty in the TIDI tidal retrievals is discussed in the Appendix. The uncertainty for the SABER tidal components is negligible. The resulting spectral TW3 peaks due to TIDI measurement uncertainties are about 1–2 m/s, indicating the level of contamination that can be expected from noise. We conclude that the upper bound of the noise floor for TIDI TW3 winds is roughly 2 m/s.

2.3. TIME-GCM simulations

The TIME-GCM is a three-dimensional time-dependent first-principles model. It extends from near 30 km to the upper atmosphere (~500 km during solar minimum) and simulates the circulation, temperature, electrodynamics and compositional structure of the middle and upper atmosphere and ionosphere (Roble and Ridley, 1994; Roble, 1995). The spatial resolution of the TIME-GCM is 2.5° × 2.5° × 0.25 scale height. The diurnal and semidiurnal tidal components can be specified at the lower boundary from the Global