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Radar observations of the quarterdiurnal tide at midlatitudes: Seasonal and long-term variations

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ABSTRACT

The seasonal and interannual variability of the quarterdiurnal tide is analysed using meteor radar wind observations at the two midlatitude sites Collm and Obninsk. Generally tidal amplitudes increase with height. Maximum tidal amplitudes are found in winter. Meridional amplitudes are smaller than zonal ones on an average. Phases mainly differ between summer and winter. Zonal and meridional phases differ by slightly less than 90°. The vertical wavelengths are very long in winter, but shorter and on the order of 20 km in summer. Collm and Obninsk amplitudes and phases agree well, indicating that the migrating quarterdiurnal tide may be responsible for a major part of the observed waves. Observations since 1980 show that the tidal amplitudes have increased on a whole, although the increase is not linear but mainly happening during the late 1990s and the early 2000s.

1. Introduction

The dynamics of the mesosphere and lower thermosphere (MLT) are strongly influenced by the solar tides with periods of a solar day and its harmonics. Their wind amplitudes usually maximize at around 100–120 km. In these regions, their amplitudes are of the order of magnitude of the mean wind. As a result, the solar tides drive the global circulation and more accurate knowledge leads to a better understanding of the wind fields in the MLT. Shorter period waves often have smaller amplitudes, so that in the past the diurnal tide (DT), the semidiurnal tide (SDT), and also the terdiurnal tide (TDT) has been particularly considered. The quarterdiurnal tide (QDT), however, although it also forms an integral part of the middle and upper atmosphere dynamics, has attained much less attention, mainly due to its small amplitude in the MLT.

While near the surface the 6 hr-oscillation at times can be a major component e.g. in barographic records (e.g., Warburton and Goodkind, 1977), the QDT amplitude in the MLT is generally substantially smaller than the one of the DT, SDT and also the TDT. Consequently, only few attempts to determine the QDT characteristics from radar or satellite has been made so far, and very few studies included the modelling of the QDT global structure and its sources. Considerable amplitudes have been reported by Walterscheid and Sivjee (1996, 2001) in the high-latitude winter, but they concluded that these were zonally symmetric tides and not migrating ones. Kovalam and Vincent (2003) analysed medium frequency (MF) radar winds over Adelaide, Australia and Davis, Antarctica. They found signatures of 6- and 8-hr tides, but these were belonging to a wavenumber 1 so that they concluded that these oscillations are not thermally forced but may be owing to non-linear interactions. Smith et al. (2004) analysed the QDT over Esrange, Sweden, and found that the QDT wind amplitudes on a monthly average may exceed 5 m/s at 97 km altitude and maximize in winter. They also performed numerical simulations that revealed that much of the wintertime QDT is forced by the 6-hour harmonic of solar heating, but without direct forcing the tide still appears and also maximizes in winter. Liu et al. (2006) noted a 6-hr signature in MF radar data over Wuhan, China, but mainly in their upper height gates above 90 km. 6-hr waves have also been reported in Lidar temperatures (She et al., 2002), but their amplitudes are also small.

The 6-hr harmonics of ozone heating rates have been calculated from Aura/MLS observations by Xu et al. (2012), who noted that the main 6-hr forcing during solstice is in the winter hemisphere. Xu et al. (2014) analysed nonmigrating tides from TIMED/SABER observations. They confirmed earlier results that the QDT is largest in winter, and found indications that the nonmigrating QDT, which is strong in winter but small in summer, is likely to be forced by nonlinear interaction between the DT and TDT, while the interaction between stationary planetary waves and the QDT is weak, likely because of the small amplitudes of the migrating QDT. In a further study, Liu et al. (2015), again using TIMED/SABER data, analysed the migrating QDT between 50°S and 50°N in the middle atmosphere. From their analyses, they considered both direct

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heating and tidal interaction as possible sources of the QDT. The seasonal/latitudinal structure of the QDT is complex; generally, the seasonal cycle exhibits a maximum in winter and also in spring. Concerning the latitudinal distribution, there are three maxima between 50°S and 50°N. Such a complex structure (and another maximum near 60° of the winter hemisphere, which cannot be seen by SABER) has also been modelled by Smith et al. (2004).

To summarise, to date there are rather few analyses of the QDT both locally and on a global scale, and available datasets should be used to contribute to our knowledge of the climatology of the QDT in the MLT. Furthermore, to our knowledge analysis of long-term changes of QDT amplitudes have not been made. Therefore, in this paper we investigate the QDT signature in midlatitude MLT winds using two radars at Collm (51°N, 13°E) and Obninsk (55°N, 37°E). At Obninsk, some measurements are available dating back to 1980, so that a first approach can be made to analyse long-term tendencies of the QDT based on these data.

The remainder of the paper is organized as follows: in section 2 the radar systems are briefly described. In section 3 the climatology of the QDT between 82 and 97 km based on the Collm measurements is presented in section 3. Section 4 provides a comparison of Collm and Obninsk long-term mean monthly means. The interannual and decadal variability of QDT amplitudes is analysed in section 5. Section 6 summarizes the main results and concludes the paper.

2. Measurements and data analysis

The horizontal wind data were estimated from measurements obtained by two meteor radars located at Collm (51°N, 13°E) and Obninsk (55°N, 37°E). At Collm, a SKiYMET meteor radar is operated on 36.2 MHz since summer 2004. Details of the radar and the radial wind determination principle can be found in Jacobi (2012) and Stober et al. (2012). During 2015 the radar had been upgraded, but the transmit frequency is still the same (Stober et al., 2017). The individual meteor trail reflection heights vary between about 75 and 110 km, with a maximum meteor count rate around 90 km (e.g., Stober et al., 2008). The data are binned in 6 different not overlapping height gates centred at 82, 85, 88, 91, 94, and 98 km. Individual winds calculated from the meteors are collected to form half-hourly mean values using a least squares fit of the horizontal wind components to the raw data under the assumption that vertical winds are small (Hocking et al., 2001). An outlier rejection is added. Note that the nominal heights not necessarily correspond to the mean heights, because the meteors show a vertical distribution with increasing/decreasing count rates with height below/above 90 km. Therefore, below/above 90 km mean heights tend to be higher/lower than nominal heights and in particular the real mean height of the uppermost height gate is 97 rather than 98 km. For the other height gates, the difference between real and nominal height is small and may be neglected (Jacobi, 2012).

An example of amplitude spectra of the zonal winds over Collm is shown in the upper panel of Fig. 1. November 2007 half-hourly winds at 91 km have been analysed here. As expected, the major spectral component is due to the SDT. The DT is smaller than the SDT, and in this month it is even smaller than the TDT. The QDT component is also smaller than the TDT, but still both horizontal components are significant at the 5% level. On the lower panel of Fig. 1 monthly mean high-pass filtered (cut-off period 7.5 h) half-hourly zonal winds for November 2007 are shown. There is a quarterdiurnal signal visible in the filtered winds. The phase is not strongly varying with height, indicating a long vertical wavelength.

Height-time cross-sections of MLT wind parameters have been calculated applying a least-squares regression analysis of one month of either zonal or meridional half-hourly horizontal winds *v(t)* on a model wind field v_{mod} including mean wind v_0, diurnal, semidiurnal, terdiurnal and quarterdiurnal oscillation:

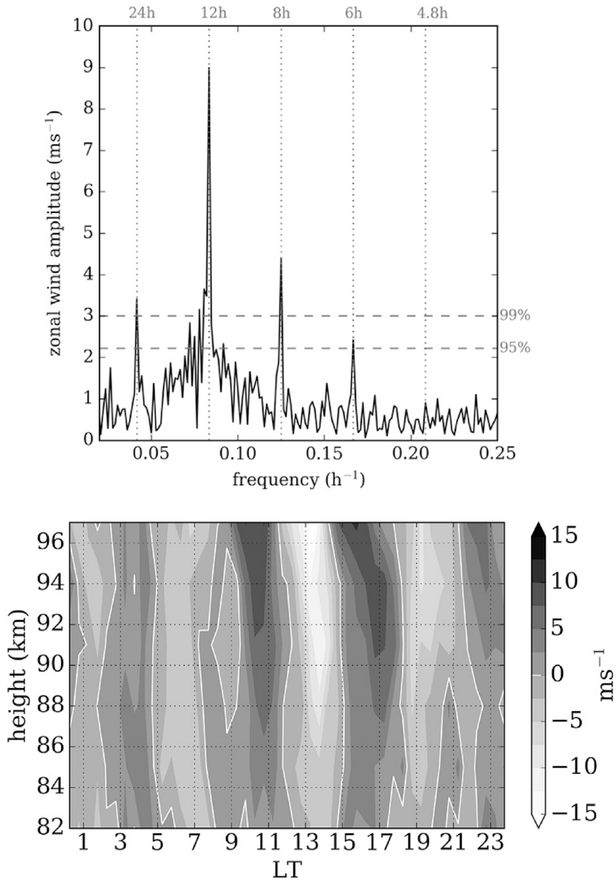

Fig. 1. Amplitude spectrum of zonal winds at 91 km, based on half-hourly means (upper panel), and monthly mean high-pass filtered half-hourly means for different altitudes (lower panel). Data are based on zonal winds measured during November 2007.

$$v_{mod}(t) = v_0 + \sum_{i=1}^{4} a_i sin\left(\frac{2\pi}{P_i}\right)t + b_i cos\left(\frac{2\pi}{P_i}\right)t, \tag{1}$$

and minimising $\sum(v(t) - v_{mod}(t))^2$. Choosing the periods P_i as $P_1 = 6$ h, $P_2 = 8$ h, $P_3 = 12$ h, and $P_4 = 24$ h one obtains the monthly mean tidal amplitudes A_i and phases T_i (e.g., Jacobi et al., 1999):

$$A_i = \sqrt{a_i^2 + b_i^2}, T_i = \frac{2\pi}{P_i} atan\left\{\frac{a_i}{b_i}\right\}. \tag{2}$$

The zonal and meridional phases are defined as the local time of maximum eastward and northward wind, respectively. The prevailing winds are defined positive for northward meridional winds $v_{0,m}$ and eastward zonal winds $v_{o,z}$.

Long-term mean seasonal cross-sections will be shown based on the monthly means from August 2004 through July 2016. Prevailing winds have been arithmetically averaged. Fig. 2 shows the 12-year mean zonal and meridional wind. The tidal amplitudes have been arithmetically averaged as well, while the 12-year mean phases have been obtained from vector averaging of the monthly values from each year. Arithmetic averaging of amplitudes has been preferred against vector averaging, because in the presence of phase shifts vector averaging will result in underestimation of the "most probable" amplitudes (e.g., Manson et al., 1983; States and Gardner, 2000; Jacobi, 2012). Relative tidal amplitude differences ΔA have been calculated from the monthly mean amplitudes:

$$\Delta A = 2\frac{A_{zonal} - A_{meridional}}{A_{zonal} + A_{meridional}}, \tag{3}$$