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The 8-h tide in the mesosphere and lower thermosphere over Collm (51.3° N; 13.0° E), 2004–2011

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Abstract. The horizontal winds in the mesosphere and lower thermosphere (MLT) at heights of about 80–100 km have been measured continuously since summer 2004 using an all-sky 36.2 MHz VHF meteor radar at Collm, Germany (51.3° N, 13° E). A climatology of the 8-h solar tide has been constructed from these data. The amplitude shows a seasonal behaviour with maximum values during the equinoxes, and it is generally increasing with altitude. The largest amplitudes are measured in autumn, partly reaching values up to 15 m s^{-1}. The phase, defined as the time of maximum eastward or northward wind, respectively, has earlier values in winter and later ones in summer. Except for summer, the phase difference between the zonal and meridional components is close to +2 h, indicating circular polarization of the tidal components. The vertical wavelengths are short in summer (∼20 km) but significantly longer during the rest of the year. The terdiurnal tide is generally assumed to originate from either a terdiurnal component of solar heating or nonlinear interaction between the diurnal and semidiurnal tide. Analysing monthly means reveals positive correlation during the spring maximum, but negative correlation in autumn.

1 Introduction

The dynamics of the mesosphere and lower thermosphere (MLT) are strongly influenced by atmospheric waves, including the solar tides with periods of a solar day and its harmonics. Their wind amplitudes usually maximise around 100–120 km (e.g. Hagan et al., 1995). 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) and the semidiurnal tide (SDT) have attracted more attention. But recently, also the terdiurnal tide (TDT) has been considered to play an important role as well, because occasionally their amplitudes are as large as the ones of DT and SDT.

DT and SDT are essentially forced by absorption of solar radiation through tropospheric water vapour and stratospheric ozone, respectively. But the forcing mechanism of the TDT is still under debate, and both direct solar heating in the lower and middle atmosphere and nonlinear interaction between the DT and SDT (Teitelbaum et al., 1989) or gravity waves are also thought to excite the TDT. Observations in the Arctic mesosphere showed a relationship between the vertical wavelengths of the TDT, SDT and DT when the TDT had large amplitudes. This indicates, at least to a certain degree, the existence on nonlinear coupling (Younger et al., 2002). Model analyses gave partly inconclusive results. Akmaev (2001) concluded from circulation model calculations that nonlinear interaction makes a contribution to the excitation of the TDT. Smith and Ortland (2001) performed calculations that indicate that the direct solar forcing of the TDT is the dominant mechanism at middle and high latitudes, while nonlinear interactions contribute to the TDT at low latitudes. Huang et al. (2007) used a nonlinear tidal model and concluded that the migrating TDT can be significantly excited by the nonlinear interaction between the diurnal and semidiurnal tides in the MLT region. These models have used prescribed lower boundary TDT fields. Du and Ward (2010) analysed CMAM Global Circulation Model results with respect to correlations between TDT and DT/SDT on the short-term or seasonal time scale. Since the correlation was significant essentially on the seasonal and not on the short-term scale, they concluded that possible correlation is due to corresponding source or propagation condition variability rather than nonlinear interaction. To summarize, model results still show somewhat inconclusive results, and the dominant forcing mechanism of the TDT is still not clear.

Observations of the TDT are relatively rare. A global characteristics at 95 km, derived from Upper Atmosphere Research Satellite/High Resolution Doppler Imager (UARS/HRDI) measurements, have been presented by Smith (2000). There, a winter amplitude maximum was visible. The characteristics of the TDT observed by radar have been described on few occasions (e.g. Beldon et al., 2006; Jacobi, 2011). Often, the zonal amplitude has been found to be larger than the meridional one. A clear seasonal cycle is apparent, with smaller amplitudes in summer and two maxima in spring and autumn, while the latter one is dominating. The amplitudes range from 1–10 m s^{-1} at altitudes at ∼90 km depending on season and latitude. Observations at high latitudes have shown no spring maximum below 95 km (Younger et al., 2002), while it was clearly visible at mid-latitudes (Beldon et al., 2006; Jacobi, 2011). The phase varies with latitude and season. Often the phase difference between the zonal and meridional components is close to +2 h, indicating a circular polarized wave. Noticeable differences only occur during summer (Beldon et al., 2006). The reported values of the vertical wavelength strongly vary, and are sometimes contradicting. Observations made at Arctic latitudes show wavelengths of about 25–90 km (Younger et al., 2002). Considering the results at mid-latitudes (ranging from ∼22–>1000 km in the course of a year) by Namboothiri et al. (2004) or Thayaparan (1997) and the observations at lower latitudes (∼12–32 km) reported by Tokumoto et al. (2007), some differences are seen.

In this paper some features of the TDT measured at Collm, Germany (51.3° N; 13.0° E) are presented, using the dataset from August 2004 to June 2011. This data represents an update of the one presented by Fytterer and Jacobi (2011) and Jacobi (2011).

2 Collm meteor radar wind measurements and tidal analysis

The data used in this study have been measured by VHF meteor radar at Collm Observatory, Germany (51.3° N, 13° E). It is operating since July 2004, and the 7-yr dataset from August 2004–July 2011 is used here to investigate the peculiarities of the TDT. The meteor radar operates at 36.2 MHz with a pulse repetition frequency of 2144 Hz by using a transmitter of 6 kW peak power with a pulse width of 13 µs. Meteor reflections are detected by a five element antenna array forming an asymmetric cross, acting as an interferometer. This allows the calculation of azimuth and zenith angle. In combination with range measurements, the meteor trail position is determined. Radial wind velocity along the line of sight is obtained from the Doppler phase progressions with time at each receiver, which are averaged to form the mean Doppler frequency. The number of meteors varies between approximately 3500 and 7000 per day, depending on season (e.g. Arras et al., 2009). Meteors are mainly detected between 80 and

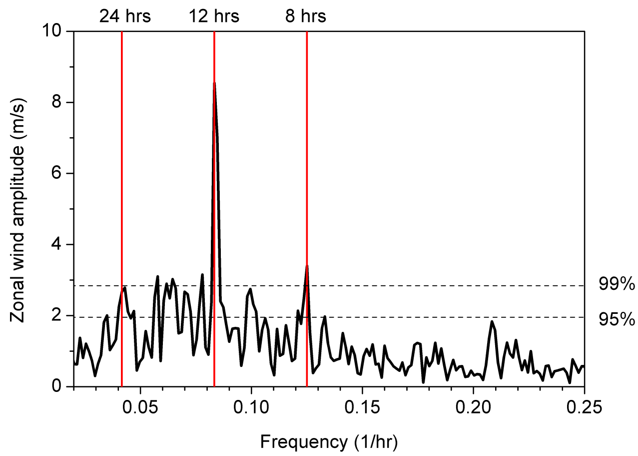

Fig. 1. Example of a zonal mean wind spectrum over Collm. The data used are March 2005 hourly means over the 85–95 km altitude region. The dashed lines indicate the 95 % and 99 % significance levels according to a χ^2-test.

100 km altitude, with a maximum around 90 km. Individual radial winds calculated from the meteors are summarized to form hourly or half-hourly mean values through projection of the horizontal wind on the individual radial winds, using least-squares fitting and assuming that vertical winds are negligible (Hocking et al., 2001; Jacobi, 2011). In Fig. 1, a sample FFT spectrum derived from hourly mean winds that have been calculated using meteors between 85 and 95 km is presented. While, as expected, the major signal is owing to the SDT, a peak at 8 h is visible as well, which is, at least in this case, even larger than the well-known DT peak at 24 h.

For characterizing the horizontal wind field in the MLT, in the following the observed height interval is divided in six not overlapping height gates centred at 82, 85, 88, 91, 94 and 98 km. Owing to the meteor detection rates strongly decreasing with altitude above 95 km, the real mean altitude of the uppermost height gate is only 97 km (Jacobi, 2011). The amplitudes and phases of the TDT within each height interval in a given 15-day time interval are calculated by a multiple regression analysis of 15 days of half-hourly zonal or meridional wind components, which includes the mean wind, as well as the 8-, 12-, and 24 h oscillations. Thus, the horizontal winds are modelled as:

$$v_m(t) = v_0 + \sum_{i=1}^{3} a_i \sin\left(\frac{2\pi}{P_i}\right)t + b_i \cos\left(\frac{2\pi}{P_i}\right)t, \tag{1}$$

with v_m as the measured half-hourly (either zonal or meridional) wind, v_0 as the prevailing (mean) wind and using the periods $P_1 = 24$ h, $P_2 = 12$ h, $P_3 = 8$ h. The amplitudes A_3 and phases T_3 of the TDT are calculated from the regression coefficients a_3 and b_3 through:

$$A_3 = \sqrt{a_3^2 + b_3^2}, T_3 = \frac{P_3}{2\pi} \operatorname{atan}\left\{\frac{a_3}{b_3}\right\}. \tag{2}$$

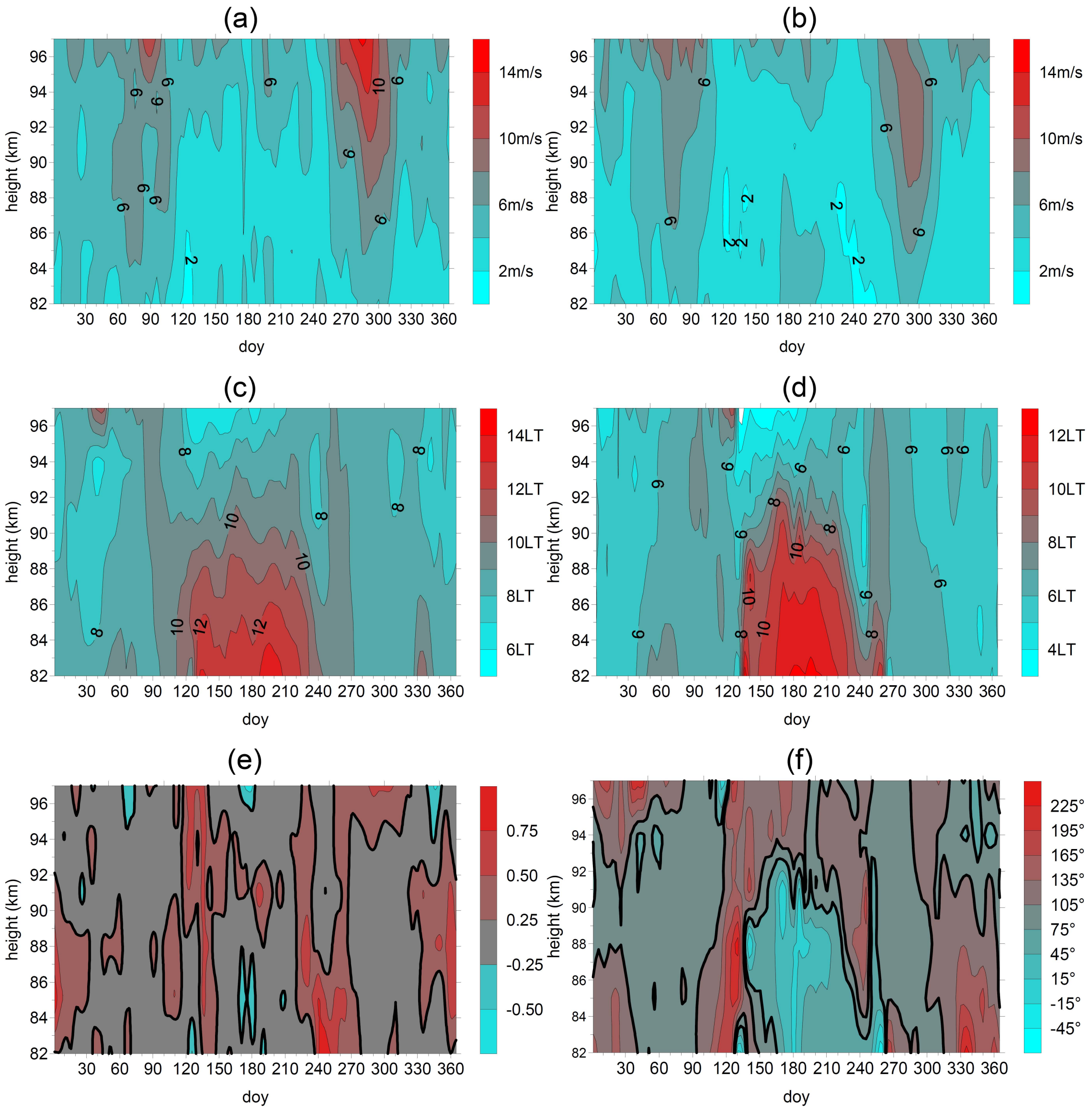

Fig. 2. Zonal amplitudes **(a)** and phases **(b)**, meridional amplitudes **(c)** and phases **(d)** of the terdiurnal tide over Collm. Relative amplitude differences after Eq. (3) are shown in panel **(e)**; the regions of amplitude differences smaller than 25 % are indicated by heavy isolines. Phase differences $\Delta\varphi$ in degrees are given in panel **(f)**. Positive values of the phase difference indicate later westerly than northerly wind maxima. The regions of $\Delta\varphi = 90 \pm 15°$ are indicated by heavy isolines. Data are 7-yr means constructed from regression analyses including 15 days of data each, updated from Jacobi (2011).

3 7-yr mean tidal amplitudes and phases

Figure 2 presents TDT zonal (a) and meridional amplitudes (b), and zonal (c) and meridional phases (d). Note that the scaling of the meridional phase is shifted by 2 h with respect to the zonal one to more clearly indicate seasons and regions where the TDT components are in quadrature. The average standard error has been taken from daily analyses, i.e. applying Eqs. (1) and (2) but including only one day of data each. For the amplitudes below 91 km, the error ranges between 0.50–0.53 m s^{-1}, and increases to 0.62/0.66 m s^{-1} for the zonal/meridional component at 97 km. The average phase standard error is 0.19 h for both components, largely independent of height. Standard errors of individual 15-day mean amplitudes approximately range between 1 and 2 m s^{-1}. Zonal and meridional amplitudes both maximise in autumn, while a second maximum is found in spring. Generally, amplitudes tend to increase with altitude during the entire year. An exception is the region below ~90 km in midsummer, where a slight tendency for constant or decreasing amplitudes with height is visible. On an average, zonal and meridional amplitudes are of similar order of magnitude.

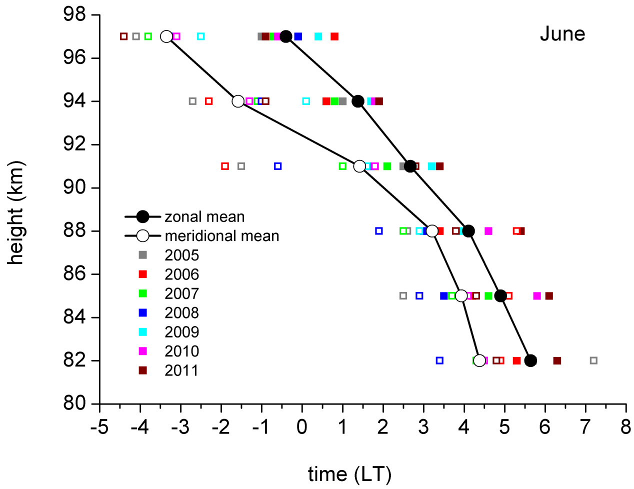

Fig. 3. June TDT phases for individual years (small squares) and for 7-yr means (large circles).

Figure 2e presents relative amplitude differences ΔA_3:

$$\Delta A_3 = 2\frac{A_{3,z} - A_{3,m}}{A_{3,z} + A_{3,m}}, \tag{3}$$

with $A_{3,z}$ and $A_{3,m}$ as the zonal and meridional TDT amplitudes. Zonal amplitudes are slightly smaller than meridional ones during the March maximum at the upper height gates, while the contrary is the case during the autumn maximum. During early and late summer, there is a tendency for slightly larger zonal than meridional amplitudes. The summer meridional amplitudes below 90 km appear to be smaller than the zonal ones, but generally the amplitudes in summer are very small, and differences are insignificant.

TDT phases (Fig. 2c and d) clearly change between winter and summer. Phase change with height is very small during winter, and therefore the vertical wavelength is very long then, generally exceeding 200 km. Since the wavelengths are calculated from the phase change with altitude, such large values cannot be determined with accuracy. However, the results are in agreement with the ones by Namboothiri et al. (2004). On the contrary, there is a strong phase change with altitude in summer. This results in a short wavelength of about 20 km, which is even shorter than those reported by Namboothiri et al. (2004) and Thayaparan (1997). The zonal and meridional phases are close to being in quadrature when the amplitude is strong, i.e. in autumn and late winter/early spring. In summer, zonal and meridional phase difference changes with altitude, with a rather sharp change around 90 km (Fig. 3), and connected with a change in amplitude gradient (see Fig. 2a, b). This indicates that at least two TDT modes are present in the summer mid-latitude MLT.

4 Interannual variability

Interannual variability of the TDT amplitudes and phases at 91 km is shown in Fig. 4. Here the 7-yr mean, calculated from individual data each based on 15 days of measurements, is represented as the solid line, while the dots show the respective amplitudes (upper panels) and phases (lower panels) of single years. In most months, the amplitude variability is very strong, and during some years amplitudes of less than $1\,\mathrm{m\,s^{-1}}$ are occasionally found. An exception is represented by the autumn maximum (a multi-year average of $\sim 9\,\mathrm{m\,s^{-1}}$), which has considerably large amplitudes in every year. On the contrary, the spring maximum ($\sim 7\,\mathrm{m\,s^{-1}}$ on an average) is less stable. Beldon et al. (2006) showed that for the case of the UK radar the spring amplitudes are not larger than the winter ones. The phases generally range within about 3 h from year to year, but the interannual variability is smaller in March and October, when the amplitudes are larger. During summer, the meridional phase is extremely variable, which is partly due to the choice of the height gate presented here. At 91 km, the transition between the two summer modes is seen (Fig. 3), and while the zonal component shows the same vertical phases gradient at all heights considered, the meridional one changes with altitude, and the 91 km value obviously belongs to different modes in different years.

Since the phase variability is weakest during spring and autumn, the March and October amplitudes are well suited to investigate interannual variability. Du and Ward (2010) have used correlation analysis between the TDT and the DT or SDT, respectively, from CMAM model results in order to explain possible coupling processed between tides. They found significant correlation between TDT and SDT amplitudes, which, however, change with height and latitude and show a rather complicated picture in the MLT near 50° N. In Fig. 5 time series of monthly mean amplitudes at 88 km are shown for these months. For comparison, and to indicate possible corresponding variability with the SDT, the SDT amplitudes are also shown. During March there is a positive correlation between TDT and SDT amplitudes (correlation coefficient $r = 0.56$, however, r increases for lower height gates, reaching $r = 0.72$ at 82 km), while in October the correlation is negative ($r = -0.59$, and its magnitude also increasing at lower heights). However, the time series used is still too short to draw substantial conclusions, and the correlations are not significant at the 95 % level. Correlation between TDT and mean wind (not shown here) is weak and inconclusive.

5 Conclusions

The Collm meteor radar has been operated nearly continuously since summer 2004, measuring daily mean winds and tidal amplitudes and phases. Here we focus on the TDT, and a 7-yr climatology is presented. Generally, from a point measurement as is used here, one cannot prove that the analysed

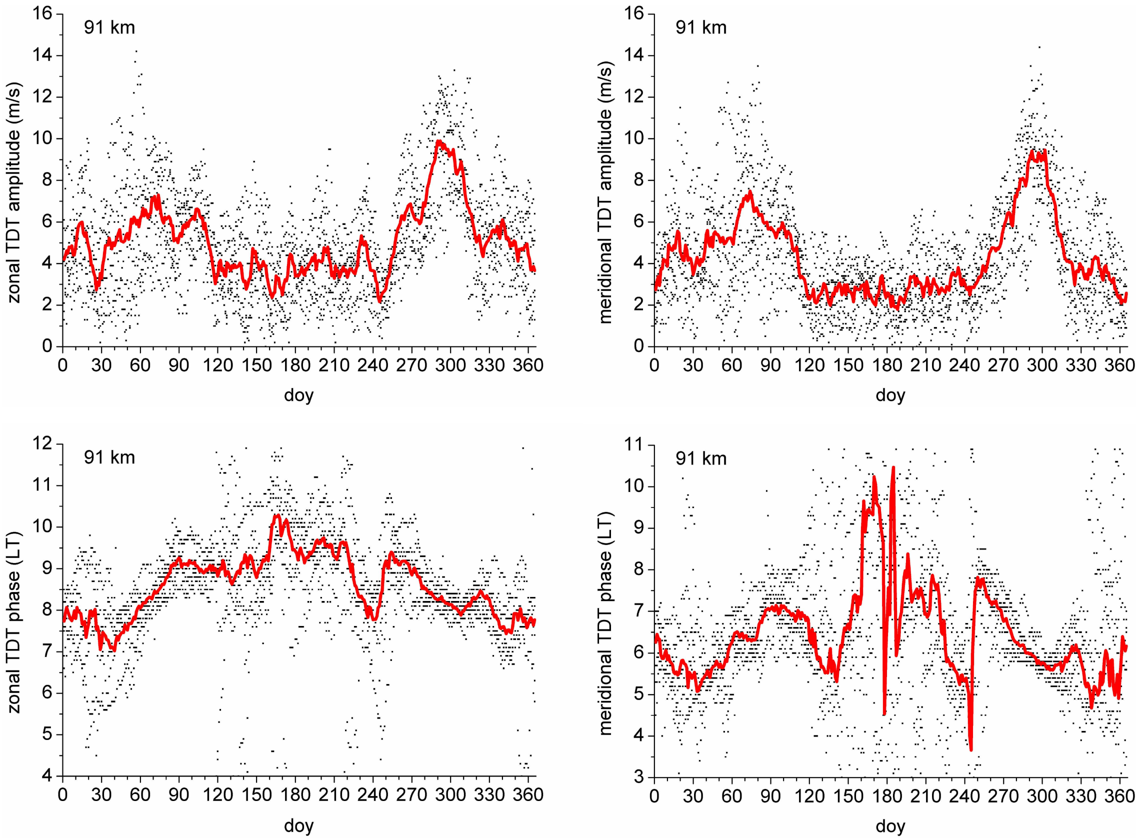

Fig. 4. Zonal (left panels) and meridional (right panels) amplitudes (upper panels) and phases (lower panels) of the TDT over Collm at 91 km. The solid line denotes the 7-yr mean while the dots represent data from individual years. Data are calculated from regression analyses based on 15-days of half-hourly means each.

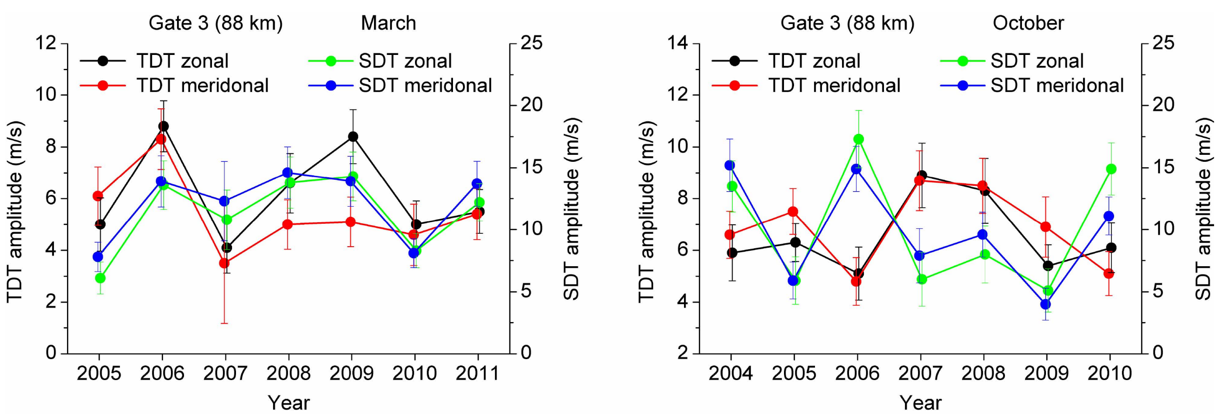

Fig. 5. Time series of monthly mean TDT and SDT amplitudes at 88 km in March (left panel) and October (right panel).

oscillations really belong to waves rather than other kind of fluctuations. However, we have seen from comparison with literature that some essential features of the 8-h oscillation at Collm – e.g. the seasonal cycle of the vertical wavelength – are likewise found at other stations, which indicates that the 8-h feature is a large-scale one and not a local pattern only. Furthermore, circular polarization of the horizontal components at those times when the amplitude is large is consistent with an upward propagating inertio-gravity wave. Therefore we may consider the 8-h oscillation at Collm as the signature of the TDT, although a final proof is not given.

Maximum amplitudes of the TDT are found in spring and autumn. The autumn maximum is quite stable, while the spring maximum is broader and less stable; sometimes small amplitudes are found. Vertical wavelengths are short (∼20 km) in summer, but very long in winter.

Interannual variability of amplitudes has been analysed for March and October, when the phases are only weakly varying from year to year. TDT amplitudes are positively correlated with SDT ones in spring, but negatively in autumn. This indicates a possible interaction between TDT and SDT, but the underlying process is not clear and probably different in different seasons.

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