Climatology of the 8-hour tide over Collm (51.3°N, 13°E)

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Summary

The horizontal winds in the mesosphere and lower thermosphere (MLT) at heights of about 80-100 km have been measured by the SKiYMET meteor radar at Collm, Germany (51.3°N, 13°E). The radar has been operating continuously since July 2004, and the data from December 2004 – December 2009 were used for constructing a climatology of the 8-h tide. The 8-h tide appears to be a regular feature in the MLT. In particular, the amplitude shows a clear seasonal behaviour, with maximum values around the equinoxes, and generally an increase with height. The largest amplitudes occur in autumn, sometimes reaching values above 15 m/s, but they are significantly smaller during summer (~1 m/s). The phase is early in winter and advances to later times in summer. In general, the phase difference between the zonal and meridional components is close to +2 h. The vertical wavelengths are short in summer (~30 km) but significant longer during the rest of the year. The results were compared with observations from locations of different latitudes.

Zusammenfassung

Der Horizontalwind in der oberen Mesosphäre und unteren Thermosphäre (MLT) in Höhen von 80-100 km wurde mit dem SKiYMET-Meteorradar in Collm, Deutschland (51,3°N, 13°E) gemessen. Das Radar liefert seit Juli 2004 kontinuierlich Daten, wobei nur die Datenreihen von Dezember 2004 bis Dezember 2009 für die Klimatologie der 8-stündigen Gezeit verwendet wurden. Letztere ist eine dauerhafte Erscheinung der MLT. Besonders bei der Amplitude sind ein klarer Jahresgang, sowie eine Höhenzunahme erkennbar. Die Maxima treten während der Äquinoktien auf, mit vereinzelten Werten über 15 m/s, wohingegen sie beim Durchlaufen des Sommers deutlich schwächer (~1 m/s) sind. Die Phase nimmt eine Sommer- und Winterposition ein, wobei erstere später auftritt. Generell liegt die Phasendifferenz zwischen zonaler und meridionaler Phase bei +2 Stunden. Die vertikalen Wellenlängen sind im Sommer mit ca. 30 km sehr kurz und im übrigen Jahr deutlich länger. Letztlich wurden die Ergebnisse mit Beobachtungen von Orten verschiedener Breitengrade verglichen.

1. Introduction

The dynamics of the mesosphere and lower thermosphere (MLT) are strongly influenced by atmospheric waves (Andrews et al., 1987), including the solar tides, which are waves with periods of a solar day and its subharmonics. The latter are excited at lower atmospheric regions (troposphere, stratosphere), propagate vertically and transport momentum and energy upward. The wind amplitudes are comparatively small (~cm/s) near the region of forcing, but increase to significantly larger values above 80 km, maximising 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, increasing the amplitudes of the planetary or gravity waves. As a result, the solar tides drive the global circulation and a more accurate knowledge would lead to a better understanding of the wind fields in the MLT. In general, shorter period waves have smaller amplitudes, so that the diurnal tide (DT) and the semidiurnal tide (SDT) have attracted more attention. But recently, also the terdiurnal tide (TDT, periodicities of 8 hours) has been considered to play an important role, because occasionally their amplitudes are as large as the ones of DT and SDT.

The DT and SDT are mainly excited by the absorption of solar radiation through tropospheric water vapour and stratospheric ozone. In contrast, the cause of the excitation mechanism of the TDT is still uncertain. One theory proposes that the tide could be caused by direct solar heating in the lower and middle atmosphere. Other ones mention a non-linear coupling between the DT and SDT (Teitelbaum et al., 1989) or interactions between the DT and gravity waves. Also possible is a combination of these mechanisms. At least, some proofs for non-linear coupling between SDT and DT were found. Observations in the Arctic mesosphere showed a relationship between the vertical wavelengths of the TDT, SDT and DT, but this was only evident when the TDT had large amplitudes (Younger et al., 2002).

The characteristics of the TDT have been described on some limited occasions. They are a persistent feature (e.g. Beldon et al., 2006), and generally the zonal amplitude is larger than the meridional. Furthermore, a clear seasonal cycle is apparent, including 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 at altitudes of ~90 km and depend on season, height and latitude. Observations in high latitudes have shown a missing spring maximum below 95 km (Younger et al., 2002). The phase variability is also differing with latitude and season. At a given altitude, the phase takes a nearly constant summer position from early spring to autumn and is about 1-2 h later than in winter. The phase difference between zonal and meridional components is close to +2 h. Noticeable differences only occur during summer (Beldon et al., 2006). The values of the vertical wavelength strongly vary. Observations made in Arctic regions show wavelengths of about 25-90 km (Younger et al., 2002). Considering the results at mid-latitudes (ranging from ~60-1000 km in the course of a year) made by Namboothiri et al. (2004) and the observations at lower latitudes (~12-32 km) reported by Tokumotos et al. (2007), a significant disagreement is seen.

2. Data collection and analysis

The data used in this study have been measured by a SKiYMET meteor radar located at Collm Observatory, Germany (51.3°N, 13°E). It is operating since July 2004, and the 5-year dataset from December 2004 – December 2009 was used here to investigate

Table 1: *Summarized selection parameters and its limits.*

parameter	limits
radial velocity	$|v_{rad}| < 200$ m/s
range	$r < 400$ km
zenith angle	$20° < \theta < 70°$
minimum number of meteors	$n = 5$
zonal and meridional velocity	$|u,v| < 150$ m/s
outlier rejection	$\Delta v < 40$ m/s

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 length of 2 km. The VHF radio wave emitted by the radar is either completely (overdense) or only partly (underdense) scattered by ionised meteor trails. The back-scattered energy is detected by the antenna array, which has five elements forming an asymmetric cross, acting as an interferometer, allowing the calculation of azimuth and zenith angle. In combination with range measurements, the exact meteor trail position is determined. Radial wind velocity along the line of sight is obtained from Doppler phase progression with time at each receiver. The number of meteors is varying strongly between altitudes of 80 and 100 km, with a maximum around 89-91 km (Viehweg, 2006). For characterization of the horizontal wind field in the MLT, the observed height interval is divided in six not overlapping height gates centred at 82, 85, 88, 91, 94 and 98 km. The data collection procedure is based on a method, described by Hocking et al. (2001). Individual winds calculated from the meteors are summarized to form half-hourly mean values through projection of the horizontal wind on the individual radial winds, using least-squares fitting. The latter algorithm is done by assuming that vertical winds are small. Furthermore, a data selection is added, including an outlier rejection (Table 1). The amplitude and phase of the TDT are calculated by a multiple regression analysis of one month of half-hourly zonal and meridional wind components, which includes the mean wind, as well as 8-, 12-, and 24 h oscillations. This algorithm is repeated for each height interval.

3. Results

3.1 Basic Results

To give an overview of the MLT dynamics, the results of the mean wind, amplitude and phase of the TDT are given in Figure 1. The mean wind shows a clear seasonal behaviour, marked by a maximum in summer (>30 m/s) and two minima (~0 m/s) during the equinoxes. The meridional component is only about half as strong as the zonal one and consequently a significantly smaller seasonal variability is seen. At the beginning of the year, the zonal/meridional wind is eastward/southward directed and reverses in early spring. This reversal begins at high altitudes and progresses downward. In summer, again westerlies are found at greater altitudes, while in the upper mesosphere easterlies are prevailing. In autumn the wind turns back to westerly/northerly.

Considering the TDT amplitudes, a similar seasonal cycle in both components is evident. The amplitudes are smaller during summer (~2-3 m/s) and show larger values in March (~8 m/s) and October (~12 m/s). The maxima occurring during the equinoxes correlate with the minima of the mean wind. The contrary is the case in summer, when the mean wind is strong and the amplitudes have smallest values. Considering the linear wave theory of the solar tides (Chapman et al., 1970), dependence can be suggested. In general, the amplitudes are small at lower altitudes and increase with height. An exception is seen in October, when the meridional component decreases at altitudes above 91 km. This phenomenon has not been reported in other studies and will be investigated in more detail in section 4.2.

The phase is negative, which implies an upward propagating wave. Only in January the opposite case is observed, indicating a downward directed energy

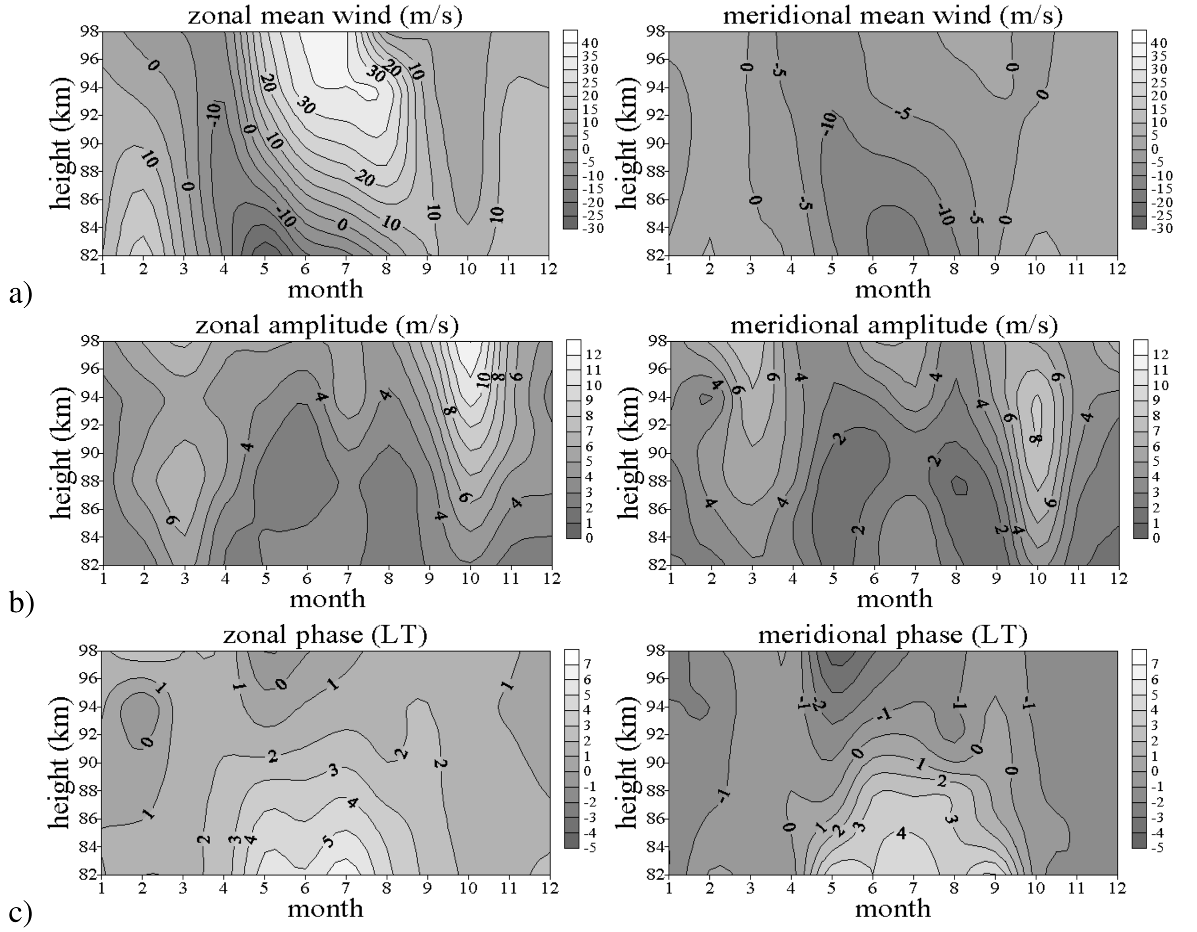

Figure 1: *The seasonal cycle of the zonal (left column) and meridional (right column) components of the a) mean wind, b) amplitude and c) phase of the 8-h tide over Collm, using the data from 2005 – 2009.*

transport. Thus the TDT cannot propagate. A seasonal behaviour is also seen, which shows a similar pattern for both components. The phase difference between the zonal and meridional components is close to +2 h. In winter the phases are the earliest and advance to later times in summer.

3.2 The characteristics of the 8-h tide

The zonal and meridional amplitudes of the TDT at 91 km are presented in Figure 2. This height was chosen, because the statistical errors are smallest there. In general, the observed seasonal cycle includes every significant characteristic, but sometimes differs slightly in detail. The largest amplitudes occur in October (~8 m/s) and March (~6 m/s) and both components reach the smallest values during summer (~2-3 m/s). In July the zonal amplitude shows a weak summer maximum with slightly higher values (~4 m/s). The large error bars indicate a strong inter-annual variability.

Throughout the year, on an average the zonal component is slightly stronger than the meridional (Figure 3). The difference mostly ranges from -1 m/s to +2 m/s, with a few exceptions. There is neither seasonal behaviour nor a clear dependence on height of the amplitude difference. Particularly noticeable is the value at 98 km in October, where the difference is larger than +6 m/s. This is caused by the missing maximum of the meridional amplitude.

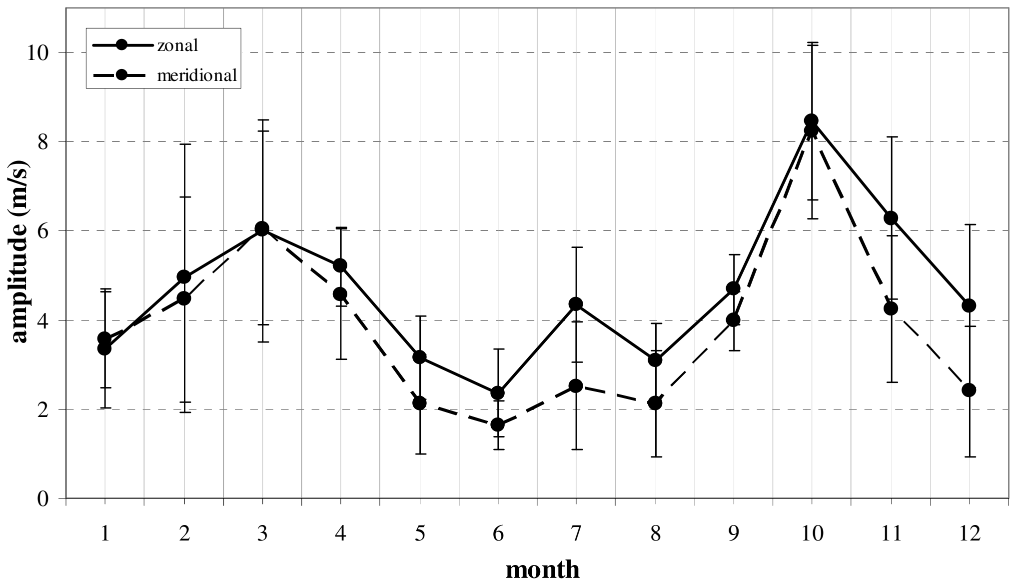

Figure 2: *Seasonal cycle of the zonal (solid line) and meridional (dashed line) amplitude of the 8-h tide at 91 km over Collm, using the data from 2005–2009. The error bars indicate the standard deviation of the individual monthly mean values.*

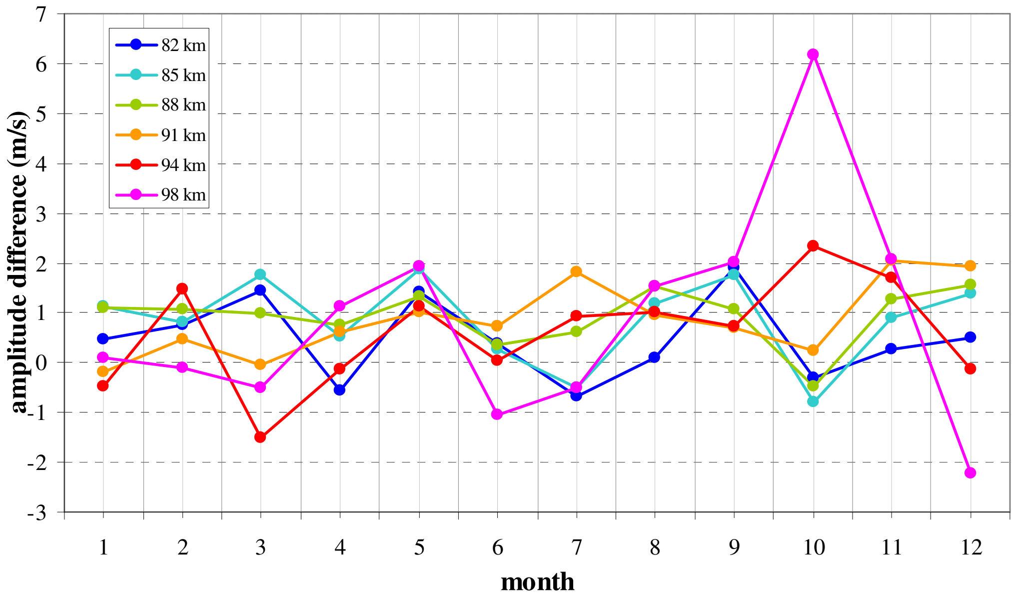

Figure 3: *Seasonal cycle of the amplitude difference between the zonal and meridional component of the 8- tide over Collm, using the data from 2005-2009.*

Figure 4 presents the phase of the TDT at a height of 91 km. Both components show a similar seasonal behaviour and a nearly constant phase difference close to 2 h. The phases are between 0 and 1 LT in winter and change to later times in summer. The phase shifts of 1-2 h occur during the equinoxes, but differ at the individual gates. In general, they are stronger and a bit later at the lower gates (~+4 h). At the highest gate, this relation is reversed, resulting in earlier phases in summer (~3-4 h). Except during the equinoxes, no significant year-to-year variability in phase is evident, also indicated by the comparatively short error bars.

Based on the linear theory of the solar tides, the zonal and meridional phase components differ by +90°. Then for the TDT, a difference close to +2 h is expected.

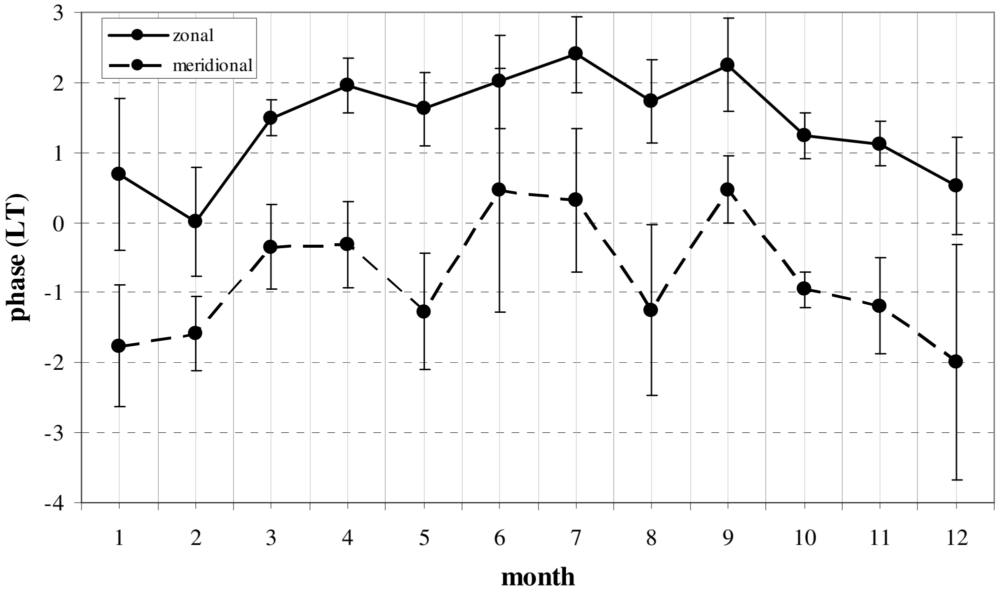

Figure 4: *Seasonal cycle of the zonal (solid line) and meridional (dashed line) phases of the 8-h tide at 91 km over Collm, using the data from 2005–2009. The error bars indicate the standard deviation of the individual monthly mean values.*

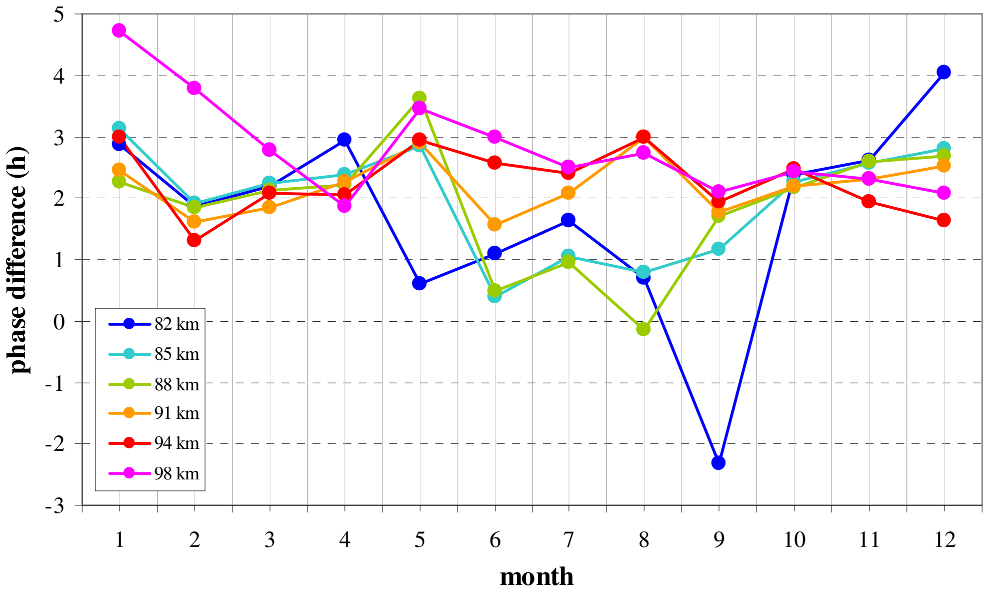

Figure 5: *Time-Height plot of the difference between the zonal and meridional phases of the 8-h tide over Collm, using the data from 2005-2009.*

As seen in Figure 5, this is true on an average, but a few disagreements are observed. In general, the phase difference ranges from 0 h to +3 h. One major exception occurs in summer. In the lower gates being 0-1 h, the phase difference increases to values above +2 h, but remains constant at the upper heights. Variations in gates 1 and 6 are most likely caused by data gaps or small amplitudes (see discussion below). Including the results of the phase variability with height, the observations indicate two different wave modes of the TDT. The first one dominates at heights below 91 km and the second one above 91 km.

To give an overview of the vertical behaviour, a height-profile was constructed for four months (Figure 6). Using a linear regression of the phase with height and also considering the two different wave modes, the vertical wavelengths were calculated

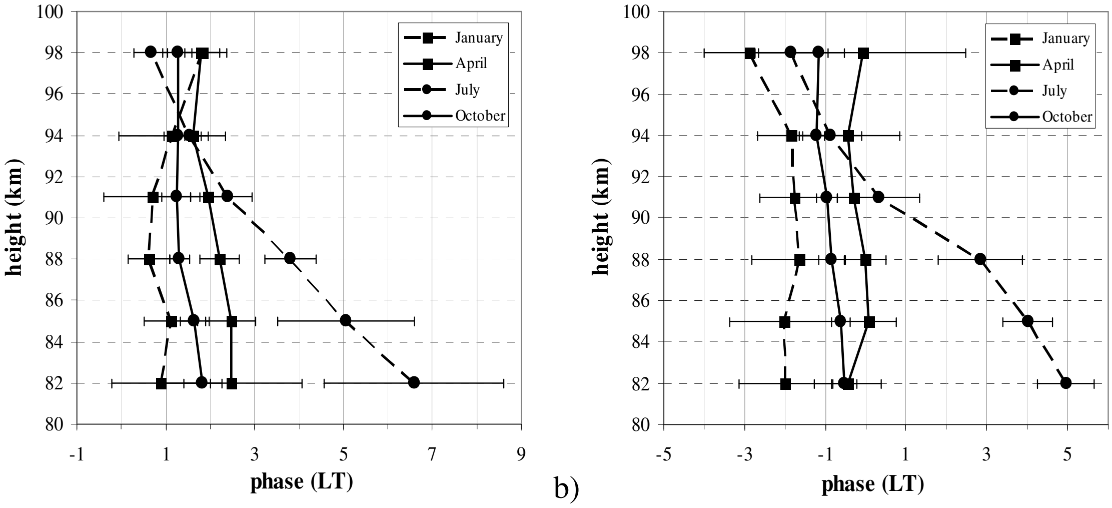

Figure 6: *Height-profile of the a) zonal and b) meridional phases of the 8-h tide over Collm for January, April, July and October, using the data from 2005-2009. The error bars indicate the standard deviation of the individual monthly mean values.*

for each month. Due to large uncertainties, the values of the meridional component at 98 km in February and at 82 km in September were excluded. Finally, the results were summarized for every season and rounded to whole five kilometres (Table 2). It is revealed that the vertical wavelengths are very short in summer (~30 km) and only a bit longer in spring (~50 km). The TDT shows significant longer values in late autumn (~140–175 km) and winter (~75-100 km), sometimes resulting in quasi infinite wavelengths. The chance between winter and summer is smoother than the one from summer to winter. The difference between the zonal and meridional components is most likely caused by the calculating process and the natural variability of the TDT.

4. Discussion

4.1 Comparisons with results from literature

Due to more frequent data gaps in gates 1 and 6, all observations made for these gates have to be analysed with special care. In addition, phases are less reliable when the amplitudes are small. The comparatively short observation period results in larger error bars, also considering the strong inter-annual and short-term variability of the TDT (Younger et al., 2002; Beldon et al., 2006). These aspects have to be taken into account when a comparison with observations made at various latitudes is accomplished.

The results of the mean wind in the measured heights are qualitatively similar to the climatology reported by Fleming et al. (1990); only the observed velocity over Collm shows lower values. An investigation to analyse the dependence between TDT and mean wind was performed, using gate 3 and 4. However, considering the resulting time series (not shown here), no hints were found to support any dependence between mean wind and TDT variability.

Beldon et al. 2006 reported observations made at Castle Eaton, UK (52.6°N, 2.2°W) at 90-95 km (comply with gate 4 and 5) from 1988-2004, using a VHF meteor radar without height finding. The results concerning phase and amplitude are qualitatively the same than the ones reported here. The zonal amplitude is larger than the meridional, but the general smaller amplitudes are causing closer differences between them. In particular, the zonal peak in October (~5 m/s) is smaller and from May to August the meridional amplitude is more dominant. Furthermore, both components of the amplitude are less synchronic. The seasonal cycles of the phases are identical and also the phase shifts in February/March and September/October are similar. Only the difference between zonal and meridional components in June and July is not that close to +2 h over UK than it is here.

Namboothiri et al. (2004) reported observations made at heights of 76–98 km from 1997-2001, using the MF radar at Wakkanai, Japan (45.4°N, 141.7°E). The amplitudes at 82–98 km there show only one peak in winter (~6-10 m/s) and a minimum in summer (~4-7 m/s). In contrast to Collm, the maxima during the equinoxes are both missing. The phase behaviour is qualitatively similar at Wakkainai and Collm, but vertical wavelengths over Wakkanai are longer.

Thayaparan 1997 presented measurements at London, Canada (43°N, 81°W) from 1992-1996 at heights of 85–94 km, again using a MF radar. The results match with the ones reported by Namboothiri et al. (2004). In general, at each station (Collm, Wakkanai, London) a similar seasonal behaviour of the vertical wavelength is evident, but the observed values show differences. At Wakkanai and London the vertical wavelength reaches the longest values (>1000 km) in winter and autumn. This was also observed over Collm, but the wavelength is significantly smaller (~75–175 km). In spring the wavelength decreases to shorter values, in particular at Wakkanai and London. However, the differences are still large, except during summer when there is no difference between Collm (~30 km) and London (~20–35 km). Particularly noticeable is the strong difference between the zonal and meridional components of the vertical wavelength in London and Wakkanai, indicating an interaction of at least two different modes of the TDT.

Observations of the TDT from October 1999 – April 2001 made by the meteor radar at Esrange, Sweden (68°N, 21°E) at about 81-97 km were reported by Younger et al. (2002). In general, their amplitudes were significant smaller (~3 m/s), except for a strong peak in September and October (~9 m/s). The seasonal behaviour of the amplitude at Esrange shows a missing maximum in spring and a lower variability. The phase also takes defined positions in summer and winter, with shifts during the equinoxes. In contrast to Collm, the phase in winter is later and advances to earlier values in summer. Furthermore, the phase shows a different behaviour with height, resulting in shorter vertical wavelengths during winter and spring (~25–40 km) and longer values in summer (~40–60 km) and autumn (~60–90 km).

Table 2: *Vertical wavelengths of the 8-h tide of every season*

Season	vertical wavelengths [km]	
	meridional	zonal
Winter	100	75
Spring	50	50
Summer	30	30
Autumn	140	175

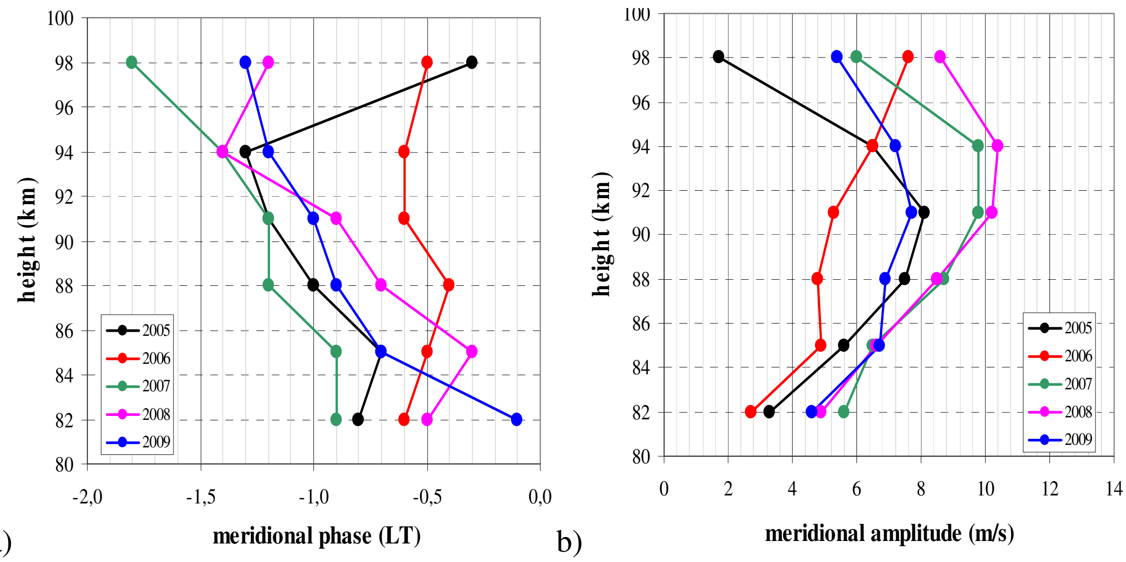

Figure 7: *Height-profile of the meridional a) amplitude and b) phase of the 8-h tide over Collm for October, using the data from 2005 – 2009.*

4.2 Weak meridional amplitudes in October

At the upper height gates, October meridional amplitudes are smaller than zonal ones (see Figure 1b). To investigate this phenomenon in more detail, the meridional amplitude and phase in October for each year is presented in Figure 7. Except for 2006, the amplitudes decrease above 91 km. Due to this similar behaviour, single measurement errors and an effect of a single extreme year can be excluded. The phase is nearly constant with height, which is particularly the case in 2006. The latter one shows an evanescent behaviour (Figure 7b). The amplitudes and phases of the remaining years match each other and no general phase shifts are evident, eliminating the possibility of a superposition between wave modes of the TDT. The phase shift in 2005 in the uppermost gate is most likely due to the small amplitude in gate 6. Therefore, further investigations including interactions with other atmospheric waves are needed to solve this problem of the zonal/meridional amplitude difference in October. But based on the regular occurrence, a physical reason is suggested.

5. Conclusions

The SKiYMET meteor radar located at Collm, Germany (51.3°N, 13°E) has measured the horizontal wind fields at heights about 80–100 km. Here we report results for the 8-hour tide. These are qualitatively similar to those from other observations made at mid-latitudes. Comparisons between mean wind and the 8-hour tide did not show a clear dependence. The amplitudes reach largest values in October (~12 m/s), show a secondary peak in March (~6-7 m/s) and are small during summer (~2-4 m/s). In July, a weak maximum (~5-6 m/s) is observed, and the meridional component shows values comparable to the other two maxima.

The phase shows earlier values in winter and advance to later times in summer. The phase difference between zonal and meridional components is close to +2 h. The amplitudes increase with height, conserving the seasonal cycle. In contrast, the phase profile splits up with height in summer, indicating the presence of two modes. Vertical wavelengths are short in summer and longer in autumn and winter.

Except for the phase behaviour, the results made at other latitudes partly differ from these observations, indicating a dependence of the TDT on latitude. At lower latitudes (43-45°N) the amplitude only shows one peak in winter and smaller values in summer, as well as significantly longer vertical wavelengths. At Arctic latitudes (68°N), a maximum in autumn occurred, but the other maxima were missing. There are also differences in phase and vertical wavelength.

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