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The terdiurnal tide in the mesosphere and lower thermosphere over Wuhan (30°N, 114°E)

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Winds measured by an all-sky meteor radar have been used to investigate the terdiurnal tide in the mesosphere and lower thermosphere (MLT) region over Wuhan (30.6°N, 114.4°E). We present a climatology of the terdiurnal tide at low-mid latitude site during the period of April 2002 to December 2004. The terdiurnal peak is distinct in the long-term power spectrum of the wind. The monthly and seasonal mean maximum amplitudes have values of 7 m/s and 5 m/s, respectively. The short-term amplitudes can occasionally reach up to 30 m/s, and at times the terdiurnal tide is as large as the diurnal and semidiurnal ones. It seems that the meridional component is more regular than the zonal one. An obvious annual variation is observed in the meridional phases with a phase leading in winter than that in summer. The annual variation for the terdiurnal tidal amplitude is not obvious, and is variable from year to year in our observations. This seasonal trend is slightly different from earlier studies at other locations.

Key words: Meteor radar, terdiurnal tide, mesospheric dynamics, nonlinear interaction.

1. Introduction

Ground-based and satellite-based measurements and theoretical studies have greatly enriched our knowledge on the diurnal (24-hour) and semidiurnal (12-hour) tides in the mesosphere/lower thermosphere (MLT) region (e.g., Burrage *et al.*, 1995; Hagan *et al.*, 1999; Manson *et al.*, 1999). However, there are still very limited studies on the terdiurnal (8-hour) tide in the MLT region, partly because of the relatively small amplitude of the terdiurnal tide compared to the diurnal and semidiurnal ones, as generally expected. However, some workers have shown that the amplitude of the terdiurnal tide is often comparable to that of the diurnal and/or the semidiurnal tides (Manson and Meek, 1986; Cevolani, 1987; Reddi *et al.*, 1993; Teitelbaum *et al.*, 1989). Midlatitude observations suggest that the amplitude of the terdiurnal tide is largest in winter or near winter months (Manson and Meek, 1986; Teitelbaum *et al.*, 1989; Thayaparan, 1997; Smith, 2000; Namboothiri *et al.*, 2004). The latest modeling studies of the terdiurnal tide also exhibit the maximum amplitudes in winter (e.g., Akmaev, 2001; Smith and Ortland, 2001). However, the polar meteor radar observations at Esrange (68°N, 21°E) show the maximum amplitude in autumn (Younger *et al.*, 2002).

The origin of the terdiurnal tide is still uncertain. Some authors think that the terdiurnal tide cannot be completely explained by the solar thermal driving. They found a more irregular phase variation and shorter wavelength in summer than in winter, and that the short vertical wavelength in summer was not consistent with solar driven modes (Glass and Fellous, 1975; Manson and Meek, 1986; Cevolani, 1987; Teitelbaum *et al.*, 1989). However the phase variations in summer can be explained by a nonlinear interaction between the diurnal and semidiurnal tides (Glass and Fellous, 1975; Teitelbaum *et al.*, 1989). At some certain times, the observed short-term terdiurnal tidal amplitudes are correlated to those of the diurnal and semidiurnal tides, and its vertical wave number is equal to the sum of the vertical wave numbers of the diurnal and semidiurnal tides (Cevolani, 1987; Thayaparan, 1997; Younger *et al.*, 2002), which supports the interpretation of nonlinear interaction. Furthermore, some researchers presented that interactions between the diurnal tide and gravity waves can also produce near 8-hour and 12-hour oscillations (Miyahara and Forbes, 1991; Thayaparan *et al.*, 1995).

In this study, the meteor radar wind data recorded at Wuhan (30.6°N, 114.4°E) over the interval of April 2002 to December 2004 are analyzed to determine the terdiurnal tide. The meteor radar system and data analysis are described in Section 2. Then we present the short-term variations, monthly and seasonal amplitudes and phases of the terdiurnal tide in Section 3. And the discussions and conclusions are made in Section 4.

2. Wuhan Meteor Radar and Data Analysis

An all-sky interferometric meteor wind radar began to be operated at Wuhan (30.6°N, 114.4°E), China, with a peak power of 7.5 kW, a duty cycle of 10% at a frequency of 38.7 MHz, a pulse repetition frequency of 1980 Hz and a height resolution of typically <2 km since January 2002. This system is almost identical to the Buckland Park meteor radar in Australia (Holdsworth *et al.*, 2004). A mean daily meteor count recorded by the Wuhan meteor radar is about 2500–3000, and almost all meteor echoes appear in the altitude region from 70 km to 110 km with the peak echo counts near 91 km. Continuous observations have been carried out from March 2002 to December 2004, apart from a data gap of 56 days from February 26 to April 22 in 2003.

The observed meteor echoes are divided into five height ranges 79–84, 84–88, 88–92, 92–96 and 96–101 km. Considering the mean height of all meteors recorded over the entire period, the five height ranges are centered on 81.4, 86.1, 90.0, 93.9 and 98.5 km, respectively. The measured radial velocities, azimuths, zeniths and ranges in each height range are used to infer zonal and meridional wind components in a 1-hour window by applying a least-squares fitting algorithm (Hocking *et al.*, 2001). Then two methods are used to analyze the terdiurnal tide. The Lomb periodogram analysis (Lomb, 1976) was used to verify the existence of evident peaks with periods near 8 hour. And a harmonic analysis based on a least-squares fit was performed to retrieve the amplitudes and phases of the terdiurnal tide. In the harmonic analysis, the hourly mean data were fitted to mean, 24-, 12- and 8-hour components. We used a 2-days window, stepped by 1 day, and a fit for a given height interval is performed only if there are data for at least 32 hours in the 2 day data set.

3. Results

3.1 Existence of the terdiurnal tide

Figure 1 gives the amplitude spectrum calculated from the entire time series of meridional winds measured at 90.0 km in the period of April 2002 to December 2004. The 24-, 12- and 8-hour period peaks are clearly evident. The 24- and 12-hour peaks represent the well-known diurnal and semidiurnal tides. But we should be aware of that the 8-hour oscillation in Fig. 1 can also be used to address other waves with periods near 8-hour, such as gravity waves and Lamb waves. Although the gravity waves play an important role in oscillations in period band between 5 and 10 hours, the peak at 8-hour rises markedly above the gravity-wave background. And that any gravity waves with period near 8-hour may have random phases, so they would self-cancel or submerge in a spectrum analysis using a so long time series. This suggests that the 8-hour signal in Fig. 1 is not primarily gravity waves.

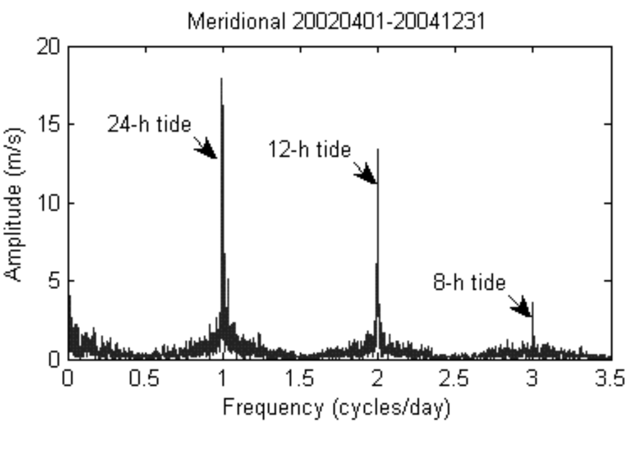

Fig. 1. The Lomb periodogram of meridional winds at 90 km in the interval from April 2002 to December 2004.

The intradiurnal Lamb waves are observationally and theoretically studied at polar region in the last two decades (Hernandez *et al.*, 1995; Forbes *et al.*, 1999; Portnyagin *et al.*, 2000). Among them, the second symmetric mode with period near 8.6 hours and the second antisymmetric mode with period near 7.2 hours have similar periods to the terdiurnal tide. Forbes *et al.* (1999) suggested that the Lamb waves may exist at middle latitudes by numerical simulations, and it would be easy to confuse these waves with terdiurnal tide for its limited lifetime. The 8-hour peak in Fig. 1 should be interpreted as a terdiurnal tide rather than Lamb waves for two factors (Younger *et al.*, 2002). First, Fig. 1 indicates a motion whose period is exactly 8 hours, but the Lamb waves only have similar periods to tides. Second, the Lamb waves are not permanent atmospheric phenomena and their lifetimes are limited, so they can be easily concealed in a spectrum calculation using a time series longer than two years. These factors suggest that a terdiurnal tide really exists and it ought to be a permanent phenomenon in the atmosphere, as most authors suggested (Thayaparan, 1997; Smith, 2000; Younger *et al.*, 2002; Namboothiri *et al.*, 2004). We should note that the gravity waves and Lamb waves may be as significant as terdiurnal tide in short terms, and may affect the day-to-day variation of the terdiurnal tide by the superposition with the terdiurnal tide.

3.2 Short-term variations

Although the terdiurnal tide seems to be a persistent motion, the strong terdiurnal tide activity only appears from time to time and usually last from 2 to 10 days. In this part, we would show some examples of short-term daily amplitude variations of this strong terdiurnal tide activity. Four 16-day continuous data sets of the terdiurnal tidal amplitude at 93.9 km are presented on the left panel in Fig. 2. For the purpose of comparison, the amplitudes of diurnal and semidiurnal tides over the same period are also given. The amplitude spectra, obtaining from Lamb periodogram analysis (Lomb, 1976), for the corresponding period are plotted on the right panel of Fig. 2.

In these figures, the short-term daily amplitudes of the terdiurnal tide can reach values as large as 20–30 m/s, and that the terdiurnal tide occasionally has comparable amplitude with the diurnal and semidiurnal ones. Amplitude spectra also show the existence of significant peaks at periods near 8 hours. Large day-to-day variability is found in the tidal amplitudes. The amplitude variations of the terdiurnal tide in December 10–25, 2003 (bottom panel) are correlated to those of the diurnal and semidiurnal tides, with correlation values of 0.64 and 0.73, respectively, which supports the suggestion that the terdiurnal tide could be partially generated by nonlinear interaction between the diurnal and semidiurnal tides (Teitelbaum *et al.*, 1989; Thayaparan, 1997). But in other three examples, the correlation values are quite low. Furthermore, this amplitude variation may also be affected by the superposition of the terdiurnal tide with gravity waves of comparable period, or result from the resonant interaction among the diurnal, semidiurnal and

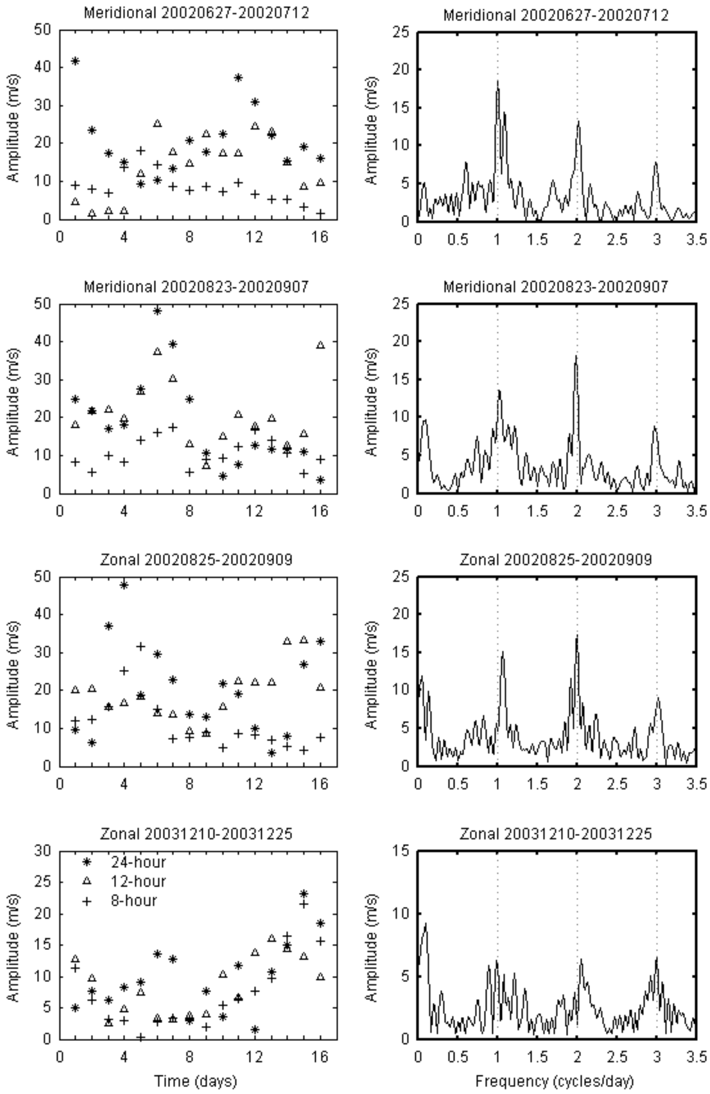

Fig. 2. Daily amplitude variations of the diurnal, semidiurnal and terdiurnal tides (left panel) and the corresponding amplitude spectra (right panel) for the 16 days time series at 93.9 km.

terdiurnal tides at the mesopause region.

3.3 Monthly mean and annual variations

Figure 3 gives the monthly mean amplitudes and phases of the terdiurnal tide obtained at 86.1, 90 and 93.9 km from April 2002 to December 2004. The phase of the terdiurnal tide is defined as the local time in hours after midnight when the amplitude is maximal. The monthly tidal averages are calculated by taking a vector average of the daily tidal values. The monthly amplitudes display that the meridional component is generally stronger than the zonal one. The meridional terdiurnal tidal amplitudes are 2–7 m/s, and the zonal ones are usually 1–5 m/s. There is not an obvious season pattern in the zonal amplitudes. In 2003, the zonal amplitudes seem to be slightly larger in winter and smaller in summer. For the meridional amplitudes, the annual variation manner is variable from year to year. Obvious amplitude maximums are found during late winter of 2003 and early spring of 2004 (January–March). But in 2002, there are not obvious seasonal pattern with comparative amplitudes in most months. In 2004, enhanced meridional amplitude appeared in August. The larger meridional amplitude in April 2003 may be partly come from that a vector average we have used to calculate the monthly mean and only eight daily tidal values are obtained in that month for a data gap. This season pattern is some different from most early observations in mid-latitudes those reported large amplitudes in or near winter months and small amplitudes in summer (Manson and Meek, 1986; Teitelbaum *et al.*, 1989; Thayaparan, 1997; Smith, 2000; Namboothiri *et al.*, 2004), and also different from the polar region results at Esrange (68°N, 21°E), where the amplitudes reach a peak in September/October (Younger *et al.*, 2002). The observed differences may be geographical reasons because our observations are made at a lower latitude station compared to others.

The phases of the meridional component are more regular than those of the zonal one. An obvious annual variation appears in the meridional phases with a phase in winter leading that in summer. The phases are usually stable in the summer and winter with phase transition in March and September. This pattern is repeated in three years shown here. The meridional phases for the three heights show

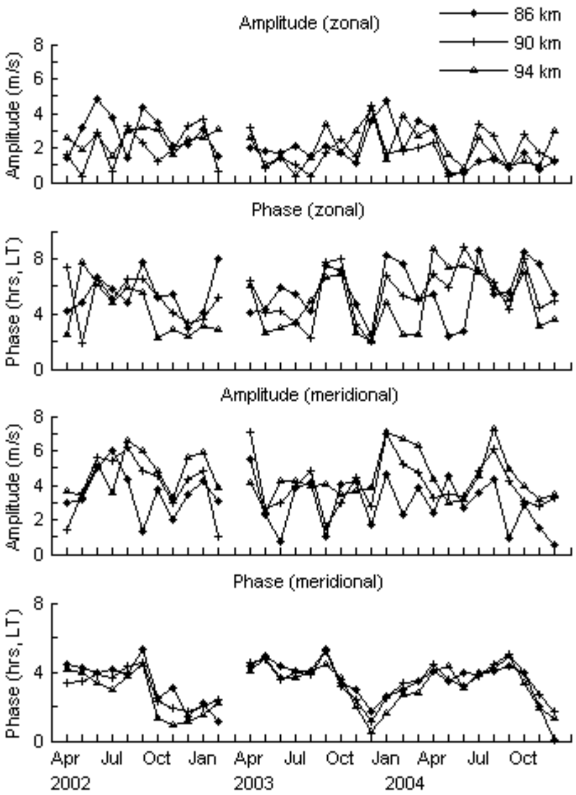

Fig. 3. Monthly mean amplitudes and phases of the terdiurnal tide at altitudes of 86, 90, 94 km, respectively.

a roughly similar behavior, but this feature is less obvious in the zonal phases. The regular annual variation in meridional phases and the similar behavior at three separate heights support the interpretation that the terdiurnal tide is a real and permanent motion in the atmosphere. Under most conditions, the phases of three heights only undergo a little change, indicating large vertical wavelengths.

The similar phase variation manner has also been observed at Wakkanai by Namboothiri *et al.* (2004). But at London, no obvious phase annual variation is observed (Thayaparan, 1997). At Esrange, a distinct season variation in phases is visible in both the zonal and meridional components, but the season pattern seems to consist of relatively constant equinoctial values separated by solsticial transitions (Younger *et al.*, 2002), which is contrary to our result with relatively constant solsticial values separated by equinoctial transitions. Furthermore, the phases of meridional component are less organized than the zonal ones at Wakkanai and London. But in our results, the zonal phases are more regular than the meridional ones.

3.4 Seasonal variations

Figure 4 presents the season behavior of height variations of the terdiurnal tide at Wuhan for four seasons. In this analysis, the data from 2002–2004 were classified into spring (March, April and May), summer (June, July and August), fall (September, October and November) and winter (December, January and February). The seasonal averages of tide are calculated by taking a vector average of the monthly mean values. We present the amplitudes and phases in the top and bottom panels, respectively.

The zonal amplitudes are usually less than 3 m/s except at 98.5 km in winter. The amplitudes in winter are slightly larger than those in other three seasons above 90 km, and the minimum amplitude appears in fall. Above 90 km, the winter amplitudes show an abrupt increase with height, changing velocity from $\sim$1 m/s below 90 km to near 4 m/s at 98.5 km. The fall amplitudes are usually less than 1m/s except at 81.4 km with a little larger value. It is noticeable that the spring amplitudes decrease with height below 90 km and increase above this height, reaching a minimum value (near 0 m/s) at 90 km, and a phase jump appears at the same height.

The meridional amplitudes are in the range of 2–5 m/s, and are larger than the zonal one in all seasons. This may be partly resulted from a vector average we have used, because the meridional phases are more regular than the zonal ones (see Fig. 3). The meridional amplitudes in winter, spring and summer have comparable values in our results. Many observations at mid latitudes show that the winter amplitudes are obviously larger than the summer amplitudes (Thayaparan, 1997; Namboothiri *et al.*, 2004). But this characteristic is not distinct at Wuhan. In fact, the summer amplitudes of the meridional component at Wuhan are larger than the winter ones at most heights except near 94 km. The fall amplitudes are again the smallest one at heights above 85 km (about 2 m/s) for the meridional component. It is noted that a phase transition from summer to winter appears between September and November (see Fig. 3), which can affect the seasonal average amplitudes by taking a vector average. The height dependence of the fall amplitudes is not obvious, but the amplitudes in other three seasons generally increase with height (the winter amplitudes attain maximum at 94 km and decrease above this height).

The phase of the terdiurnal tide is presented at the bottom panel of Fig. 4. The meridional phase profiles are more regular and smooth than the zonal ones, and phase jumps are often found in the zonal phases, especially a big phase jump appears at 90 km in spring. For both the zonal and meridional components, the winter phases are earliest. Furthermore, the meridional phases are generally earlier than the zonal phases. The mean phase differences are about 2 hours in spring, summer and fall, and become smaller in winter. A downward phase propagation is found in most cases. A linear trend is evident in the spring and summer phases of the meridional component, corresponding a vertical wavelength of $\sim$150 km.

4. Discussions and Conclusions

In this paper, we have presented a general picture of the terdiurnal tide in the MLT region over Wuhan (30.6°N, 114.4°E). The terdiurnal tide seems to be a permanent feature of the mid-latitude MLT region. Although the monthly and seasonal mean values of the terdiurnal tide are significantly smaller than the diurnal and semidiurnal tides, the short-term amplitudes are comparable to the diurnal and semidiurnal ones at times. Strong day-to-day variations exist in the present study, and large amplitudes can occasionally reach up to 30 m/s. To specify the mechanisms producing short-time variations is difficult, probably due to the

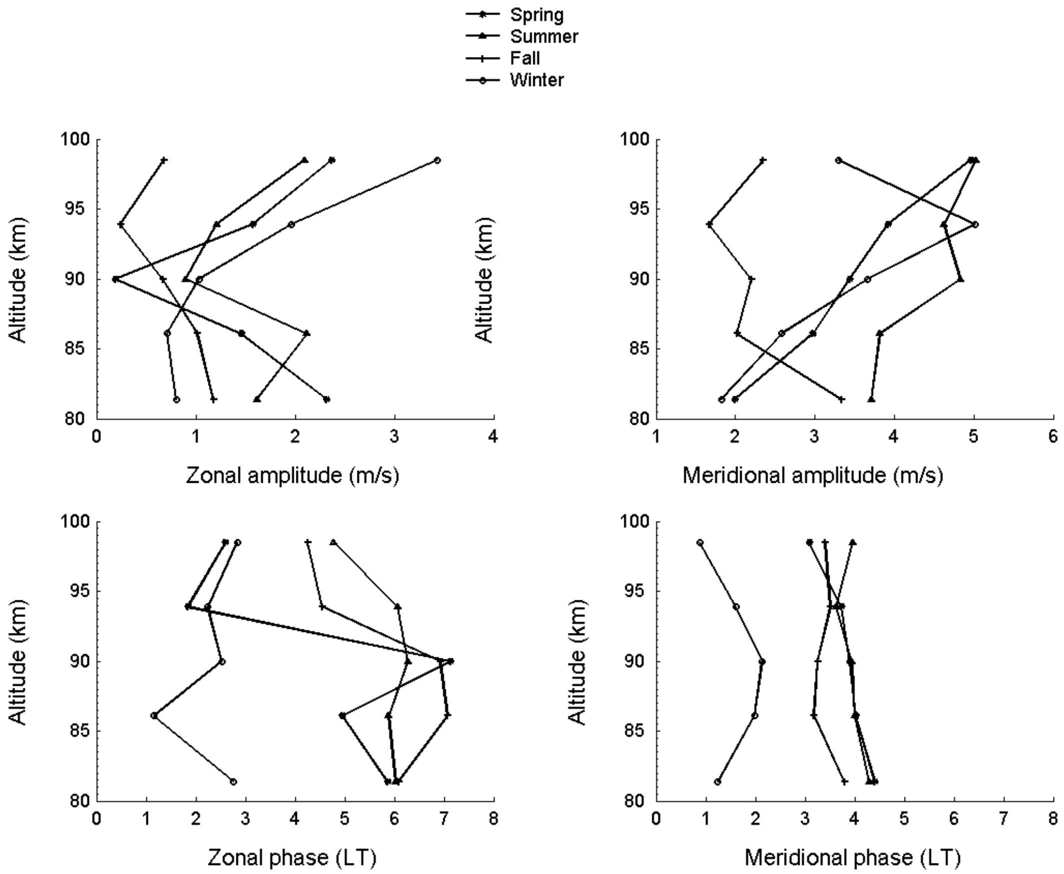

Fig. 4. Seasonal mean amplitudes and phases of the terdiurnal tide measured over Wuhan.

existence of several mechanisms involved: direct thermal excitation by solar heating; non-linear interaction between the diurnal and semidiurnal tides; tidal and gravity wave interaction; wave propagation characteristics; and tidal amplitude modulation by planetary waves.

The nonlinear interaction between the diurnal and semidiurnal tides is suggested as an important mechanism to cause the terdiurnal tide by several authors (Glass and Fellous, 1975; Teitelbaum *et al.*, 1989; Thayaparan, 1997). The observational evidence for tide interactions involve that the short time amplitude variations are correlated to those of the diurnal and semidiurnal tides, and that the vertical wavelengths of the terdiurnal, semidiurnal and diurnal tides meet the relation . In our observation, we also find some examples of short time amplitude variations correlation, such as the bottom panel of Fig. 2 (more examples are not shown here). Interaction between diurnal tide and gravity waves was considered to be another origin to produce oscillations near 8-hour (e.g., Miyahara and Forbes, 1991; Thayaparan *et al.*, 1995). Thayaparan (1997) surmised that such interaction might explain at least some of the large amplitudes observed over London. Together with the direct thermal driven mechanism by solar, each one of these mechanisms may play an important role at certain times of year, and they can also coexistent at some time.

Some authors reported a phase jump associated with a minimum in the amplitude, and they explained that this phenomenon is the result of the superposition of two waves of different origin (Teitelbaum *et al.*, 1989; Thayaparan, 1997). Two such examples in our research are presented in Fig. 5. For these two cases, we can see the minimum amplitude at 90 km accompanied by a phase jump at the same height. Further, Younger *et al.* (2002) found that some of the amplitude fluctuations of the terdiurnal tide appear quasi-periodic in character. They also gave an example that the 8-hour tidal amplitudes vary with a quasi-2-day period, and explained this as a result of a nonlinear coupling between tides and planetary waves.

The monthly mean amplitudes of the terdiurnal tide are ∼2–7 m/s for the meridional component and ∼1–5 m/s for the zonal component, which are similar to the results at London (Thayaparan, 1997). But another midlatitude observation at Wakkanai (45.4°N, 141.7°E) has given monthly amplitudes up to 15 m/s. The annual variation for the terdiurnal tidal amplitude is not obvious, and is variable from year to year in our observations. A more long term observation is needed to understand well the season pattern of the terdiurnal tide at Wuhan. An obvious annual variation appears in the meridional phases with relatively constant solsticial values separated by equinoctial transitions, and this pattern is repeated in the years shown here.

Compared to other studies at higher latitudes stations, the season pattern of the terdiurnal tide at Wuhan revealed some significant differences. For example, the amplitudes during winter are larger than those during summer, as many mid latitude observations reported (Manson and Meek, 1986; Teitelbaum *et al.*, 1989; Thayaparan, 1997; Smith, 2000; Namboothiri *et al.*, 2004), which is not clear at Wuhan.

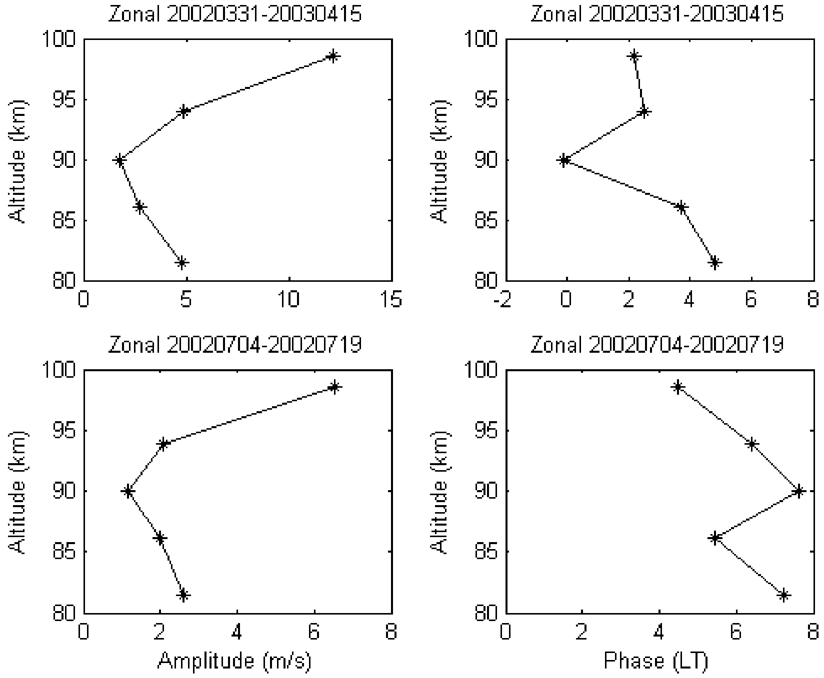

Fig. 5. Height profiles of the amplitude and phase of the terdiurnal tide during March 31 to April 15, 2002 (top panel), and July 4–19, 2002 (bottom panel).

Such differences may result from the different observational sites, observational period and observational manner.

In general, we only give a primary picture of the terdiurnal tide at mid-low latitude. More observations are needed to investigate the season pattern in our site and more comparisons with other stations are also needed to understand the latitude and longitude difference of the terdiurnal tide in the future.

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