Seasonal Variation of Solar Atmospheric Tides at Meteor Heights

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Systematic observation of the Kyoto meteor radar (35°N, 136°E) has been continuing since the end of 1977. A seasonal variation of diurnal and semidiurnal solar atmospheric tides at meteor heights has been studied by using meteor radar data. Monthly average behaviours of these tidal components have been summarized for the period from March 1979 to November 1980. Vertical profiles and harmonic dials of these components have been investigated in comparison with other meteor radar data. Complicated behaviour of diurnal tide can be explained by an interference between propagating and evanescent modes. The evanescent mode becomes dominant in summer, while the propagating mode appears in winter. As for semidiurnal tide, the $S_2$, $2$ mode is fundamental in summer, and the $S_{2,4}$ mode becomes apparent in winter.

1. Introduction

Studies on atmospheric tides have been extensively done in recent years (Kato, 1980). One reason is development in numerical computations of tides (e.g. Forbes and Garrett, 1979), and another is the improvement in observation techniques. Among those techniques, the meteor radar observation has been proven to be important, especially for the regular wind component such as tides.

Radio waves at HF and VHF frequencies are reflected by a meteor trail which is formed by a passage of a meteoric particle in the lower ionosphere. The doppler shift in the received echo signal provides a measure of a radial velocity of the meteor trail which is drifting with the surrounding atmosphere. The meteor radar method for measuring upper atmospheric winds was first applied by Manning et al. (1950) at Stanford University. In the last three decades, a number of meteor radars have been constructed, and are organized as an observational network named GRMWSP (Global Radio Meteor Wind Study Project). By collaborative works of this worldwide radar network, international campaigns of the CTOP (Cooperative Tidal Observation Program) have been done to clarify the global pattern of tides (Roper and Salah, 1978).

Kyoto meteor radar has been constructed in 1977 (Aso et al., 1979), and continuing observations regularly (Tsuda et al., 1980; Aso et al., 1980). Observation
periods of the Kyoto meteor radar for the last three years are shown in Fig. 1. Continuous observations prolonged over ten days were done seven times as in July 1978, March and August in 1979 and January, March, June and July in 1980, and some periods corresponded to the CTOP. The total length of observation periods were 44, 81 and 104 days in 1978, 1979 and 1980, respectively. More than 300,000 meteor echoes have been detected during 230 days of observation.

Kyoto meteor radar is a pulse doppler type one whose basic design is a duplication of the Stanford Mark II system (NOWAK, 1967; NOWAK et al., 1970). Improvements of the system have been done both in echo discrimination and height resolution. A small computer is incorporated into the system for the purpose of an automatic data collection, real time data reduction, echo validation and immediate feedback to the radar operation. The presence of the computer proved of great benefit to the Kyoto meteor radar in making the system efficient and intelligent. Another improvement is an installation of a digitally controlled phase sequenced interferometer originally developed at University of New Hampshire (RUDMAN et al., 1970). The interferometer being set in operation since March 1979 determines a direction of the arrival echo from phase differences between signals received at three antennas. Although the resolution of the interferometer is approximately one degree in elevation angle measurement, the over-all accuracy in determining the geographical coordinates of the meteor trail is affected by an antenna alignment, characteristics of antennas and configuration. Calibration of these factors was roughly done in October 1979, and the present accuracy of the system is enough to delineate the synoptic height profile of the northward tidal wind. This paper concerns with an average behaviour of northward component of diurnal and semidiurnal tides, and qualitative explanation of their seasonal variation by overlapping of classical tidal modes.

Fig. 1. Observation periods of the Kyoto meteor radar. A figure to the line denotes the length of the observation period in days.
2. Results

Monthly average behaviours of diurnal and semidiurnal tidal wind at Kyoto are analysed in this section. The northward component of tides has been deduced by the Groves' algorithm (1959) which was applied to the Kyoto meteor radar by adopting a cubic polynomial for an approximation of a height profile (TSUDA et al., 1980). All the data in those periods are separated according to four seasons; spring; March, April, summer; May, June, July, August, autumn; September, October, winter; November, December, January, February.

Figures 2–5 show the height profiles of the northward tidal winds in the periods from March 1979 to November 1980 except for those in May 1979 and August 1980 when we had little observations. By using these results, the seasonal variation of diurnal and semidiurnal tides will be discussed in the following. Phase corresponds to the hour of maximum northward wind velocity in local solar time. Considering the reliable height

Fig. 2. Northward tidal wind at Kyoto in spring. Top: amplitude and phase of the diurnal component, bottom: those of the semidiurnal component.
ranges of the analysis, results are illustrated at altitudes from 86 to 104 km (Tsuda et al., 1980).

2.1 Diurnal tide
(a) Height profile

Figures 2–5 show characteristic feature of the vertical profile for the northward component of diurnal tide. Except for the result in April 1980, the wind amplitude in spring varies in a similar manner such that it becomes minimum at around 90 km and increases up to 15 m/sec at 100 km. The phase varies gradually above 90 km, although it shows a complicated profile below 90 km. In April, 1980, the altitude of the minimum wind velocity is shifted upward by several kilometers, and the phase is around 15 hrs local time below 95 km and changes abruptly above 95 km. Generally, the phase in April at lower altitudes progresses toward noon in comparison with that in March. As for summer months, the wind amplitude varies from 5 m/sec to 25 m/sec. In May and June the amplitude decreases with altitude, while it gradually increases in July and August. The phase is around 12 hrs local time in the whole altitude region, and slightly delays with altitude. The phase variation sometimes follows a curved line with altitude.
This phenomenon will be explained later in terms of an interference between an evanescent mode and a propagating one. The amplitude variation in autumn is fairly well repeated in 1979 and 1980. It ranges from 10 m/sec at approximate altitude of 90 km to 5 m/sec at 100 km. Except for the result in September 1980, the phase variation in autumn shows similar feature with each other such that the phase is about 6 hrs local time below 95 km, and progresses linearly to 12 hrs local time above 95 km. In September, 1980, the phase delays from 10 hrs to 2 hrs local time in this altitude region suffering a slight fading.

In winter months, the amplitude tends to increase with altitude, which corresponds to the behaviour of the propagating mode. The phase lies around 0 hrs local time, and is nearly reversed to those in summer. Figure 6 shows height profiles of tidal winds observed in January, 1980. Above 95 km the phase variation is similar among different days except for that in 27–29 January, and indicates an appearance of the short vertical wavelength in the range from 25 km to 30 km; which corresponds to \( S_{1,1} \) mode. The median of the phase value seems to lie around 0 hrs local time. Although the monthly mean profile of the phase variation in Fig. 5 shows gradual change with height, it seems to be caused by cancellation among the waves with short vertical
wavelength at different phase value. This suggests that the \( S_{1,1} \) mode is not always in phase so that it is not stable.

In summary, the amplitude is largest in summer and smallest in equinoxes. The phase in summer and winter solstices lies at local noon and midnight, respectively. That is, they are different from each other by 12 hrs. In equinoctial months, the phase lies in between.

(b) Seasonal variation at 95 km

Amplitudes and phases at 95 km altitude are plotted in Fig. 7 for the northward component of diurnal tide. Note that determinations by using the decay height method are also shown in Fig. 7 in the period from April 1978 to January 1979. There is a slight annual variation in the amplitude such that it is enhanced in summer months. The phase is around 12 hrs local time in June, July and August in 1978 and 1980. In winter months the phase becomes about 0 hrs local time, which is most clearly seen in the period from November 1979 to March 1980. A gradual phase decrease can be seen in late summer every year. It seems that the annual variation is clearer in phase than in amplitude.

Seasonal variation of diurnal tide is replotted on a harmonic dial shown in Fig. 8 to investigate the repeatability of the annual variation. A hatched region in Fig. 8
includes all the monthly average for each season. Results for four seasons are clearly separated from each other. In spring, the triangular region contains the origin, and lies mostly in the first quadrant ranging up to 10 m/sec in amplitude. There is a large spread for summer months: the amplitude varies from about 10 m/sec to 20 m/sec, and the phase is widely distributed from 9.5 hrs to 15.5 hrs. The extent, however, is located in the fourth quadrant except for the two extremes determined in August, 1979 and May 1980. As for autumn, determinations are concentrated around a point whose coordinates are 6 hrs local time and 10 m/sec. The region for winter months lies on the opposite side to that for summer months, although it does not spread so widely as that in summer, and has the center of the region at coordinates of 0 hrs and 10 m/sec.

2.2 Semidiurnal tide
(a) Height profile

Seasonal variation of semidiurnal tide can be investigated by using Figs. 2–5. In spring, the amplitude ranges from 5 m/sec to 15 m/sec. Although it does not vary largely with altitude, it seems to be suffering from an amplitude modulation. Below 95 km, the phase retains constant at around 5 hrs local time, while it ranges from 4 hrs to 7 hrs above 95 km showing a gradual variation. As for summer months, the
Fig. 7. Monthly average of the amplitude and phase of the diurnal wind velocity at an altitude of 95 km. An open circle corresponds to the result in 1978 determined by using the decay height method.

Fig. 8. Harmonic dial for the diurnal wind velocity at an altitude of 95 km. Data are separated into four seasons as described in the text. A figure to a circle indicates a month.

Amplitude is largest among four seasons, and is generally increases with altitude. In May and June 1980, the phase is almost constant at 5 hrs local time in the whole altitude range. The phase variation is similar to results in July, August 1979 and July 1980 such that it delays by two hours while it changes linearly from bottom to top of the
altitude range. In autumn, the amplitude changed abruptly from September to October in 1979. The phase variation in September resembles that in summer months, while it shows phase reversal at around 95 km in October, 1979. In winter, the amplitude variation is classified into two types: one is that it increases monotonously with altitude and the other is that it decreases below 95 km and then increases. Phase variation does not show systematic characteristics, although its central value seems to be located at around 9 hrs local time.

(b) Seasonal variation at 95 km

Figure 9 shows the amplitude and phase of semidiurnal wind at an altitude of 95 km. An annual variation can be seen in the amplitude with maximum occurring in summer months, and is repeated for the consecutive three years. The phase value lies at around 5 hrs local time during the period from late spring to early autumn. The phase slightly increases from March to September in both 1979 and 1980. In other seasons, the phase is mostly determined in the range from 8 hrs to 10 hrs, although a considerable spread of the value can be recognized.

Harmonic dials are drawn in Fig. 10 for the northward component. Each determination is separated into four regions according to corresponding seasons in a similar manner as in Fig. 8. Generally, most of regions on the harmonic dial are located in the fourth quadrant. For summer months, the amplitude ranges from 10 m/sec to 25 m/sec. On the other hand, the region for winter months includes the origin, and the amplitude does not exceed 8 m/sec. In the equinoctial period, values fall between those in summer and winter. A smooth seasonal variation for the semidiurnal tidal wind will be examined later.
3. Discussion

3.1 Interference due to higher modes

Height profiles of diurnal and semidiurnal tides can be explained by a simple examination on interference and overlapping of the classical modes. FELLOUS et al. (1974, 1975) studied the vertical structure of tidal winds by means of modal analysis. KATO et al. (1982) examined that fluctuations of wind profiles are attributed to interference among multiple modes, although they considered only a simple case in which amplitude of each wave does not vary with altitude. Their idea will be expanded below in such a case that the wind amplitude increases as \( \exp (z/2H) \) with height for the propagating mode, and decreases exponentially for the evanescent mode.

(a) Diurnal tide

As for the diurnal tidal wind, \( v \), interference between the evanescent \( S_{1,-2} \) mode and the propagating \( S_{1,1} \) mode is considered as a function of an altitude, \( z \):

\[
v = A_1 \exp (ik_1z) + A_2 \exp (i(k_2z + \psi))
\]

\[
A_1 = -\exp (-z/60)
\]

\[
A_2 = -R \cdot \exp (z/12)
\]

\[
k_1 = 0
\]

\[
k_2 = -2\pi/30
\]

where subscripts 1 and 2 correspond to \( S_{1,-2} \) and \( S_{1,1} \) modes, and \( R \) and \( \psi \) are an amplitude ratio and a phase difference between the two, respectively. The evanescent
mode is assumed to become maximum at noon. Amplitude and phase are plotted as functions of vertical distance in Fig. 11 for cases $R = 0.03, 0.05, 0.07$ and $0.1$ for $\psi = \pi/2$. As the ratio $R$ becomes large, the minimum amplitude which occurs at around 22.5 km in vertical distance decreases, while the amplification above that level is enhanced. The phase variation shows a folding feature at an altitude corresponding to the minimum amplitude, although above and below the phase converges to the same value. The profiles are shown in Fig. 12 in cases $R = 0.05$ and $\psi = 0, \pi/2, \pi, 3\pi/2$. In the range from 0 to 40 km in vertical distance, the amplitude is modulated by a wave with vertical wavelength of 30 km, and sometimes becomes very small. As the vertical distance increases from 0 km to 30 km, the fluctuation of phase becomes large at around 12 hrs local time due to interference by the propagating mode. Above 30 km the phase tends to vary linearly at the vertical wavelength of 30 km. At 30 km in vertical distance, the amplitude ratio between $A_1$ and $A_2$ becomes approximately one, so that the propagating and the evanescent modes are dominant above and below the level, respectively.

Amplitude variation in spring shown in Fig. 2 except for April, 1980 can be fairly well reproduced by the curve (a) in Fig. 12, when the altitude of 90 km in Fig. 2 is converted to the vertical distance of 20 km. This suggests that the amplitude of the evanescent mode exceeds that of the propagating mode below the altitude of 100 km. As for summer months, variation of amplitude and phase shown in Fig. 3 can be explained by curves (a), (b) and (d) in Fig. 12, when the altitude of 90 km is converted to 10–15 km in the vertical distance. The evanescent mode seems to be dominant in the meteor region in summer. The height profile in autumn resembles the curve (b) in Fig. 12 in the range of 10–30 km in vertical distance. Amplitude variation in winter months

![Fig. 11. Amplitude and phase profile of the diurnal wind velocity calculated according to a manner outlined in the text. (a): $R = 0.03, \psi = \pi/2$ (solid line). (b): $R = 0.05, \psi = \pi/2$ (chained line). (c): $R = 0.07, \psi = \pi/2$ (long broken line). (d): $R = 0.1, \psi = \pi/2$ (short broken line).](image-url)
can be reproduced by curves (a) and (b) in Fig. 12 when the altitude of 90 km is set equal to 20–25 km in vertical distance. The phase variation in January, 1980 as shown in Fig. 6 is similar to curves (a) and (b) in Fig. 12 in the same height range for the amplitude profile, although the central value of the phase is shifted by 12 hrs. Above about 95 km, the propagating mode exceeds the evanescent mode in winter. It is suggested that the evanescent mode in winter corresponds to higher order modes, because the phase variation is reversed to the curve shown in Fig. 12 where the fundamental evanescent mode with maximum occurring at noon is assumed.

In summary, the meteor region includes transition from the evanescent mode to the propagating one for diurnal tide, and the transition height in summer would be raised by 10 km with respect to that in winter. This is attributed to that the evanescent mode affects up to higher altitudes in summer than in winter. The characteristics of the propagating mode are apparent in winter, not because it is enhanced, but the evanescent mode becomes weak. So that, the amplitude of the diurnal tide does not become larger than that in summer. At the equinoctial conditions, the amplitude is the smallest, because severe interference between the evanescent mode and the propagating one takes place in the meteor region. The feature agrees with the seasonal variation of the northward wind on a harmonic dial for diurnal tide at an altitude of 95 km shown in Fig. 8.

(b) **Semidiurnal tide**

Interference for semidiurnal tide due to $S_{2,2}$ and $S_{2,4}$ mode is investigated by the same manner with that for diurnal tide, and is shown in Fig. 13 by adopting parameters listed below:
where subscripts 1 and 2 correspond to $S_{2,2}$ and $S_{2,4}$ modes, and R is varied as 0.2, 0.5, 0.8, 1.1 and 2.0, and $\psi$ is set equal to $3\pi/2$. As a property of the propagating mode, the amplitude increases with altitude, so that $S_{2,2}$ mode is not modulated so largely by $S_{2,4}$ mode, which is different from the case of diurnal tide that contains the evanescent mode. The amplitude, however, fluctuates when the higher order mode is added out of phase to the fundamental modes as shown in Fig. 13. The phase variation tends to follow the characteristics of the dominant mode when its amplitude exceeds the other by a factor of two. When the amplitude ratio ranges from 0.5 to 2, the phase variation shows either an abrupt change or a folding feature. Figure 14 corresponds to cases for $R = 0.5$, and $\psi = 0, \pi/2, \pi$ and $3\pi/2$. Variation of the amplitude with altitude shows different features for various value of $\psi$. The average phase variation corresponds to the downward phase velocity with vertical wavelength of 150 km, although slight fading can be seen. The variance of the phase value is one hour in the whole height range. Note that the meaningful discussion can be done not on the absolute value of the phase but the shape of the phase variation with altitude for Figs. 13 and 14, that is, the horizontal axis can be shifted appropriately.

The height profile of semidiurnal tide in spring shown in Fig. 2 can be compared to curves (b) and (c) in Fig. 13. It seems that the $S_{2,4}$ mode is contained in this season, and its amplitude ratio to the $S_{2,2}$ mode ranges from 0.5 to 0.8. Height profiles in summer shown in Fig. 3 agree fairly well with curves (a) and (b) in Fig. 13, so that the $S_{2,2}$ mode is dominant in summer. Spread in the phase is about one hour, and is attributed to the...
The amplitude of the $S_{2,4}$ mode is larger in October than in September. As for the result in winter, some profiles resemble curves shown in Fig. 13, but systematic explanation could not be done. The general feature of semidiurnal tide is summarized as that the $S_{2,2}$ mode is clearly dominant in summer, while higher order modes contaminates in other seasons.

3.2 Comparison of height profiles with Adelaide meteor radar data

Adelaide meteor radar (35°S, 139°E) is located at a conjugate point of the Kyoto radar with respect to the equator. Height profiles of the northward tidal winds obtained at these stations are compared with each other, although the observation periods did not coincide. ELFORD (1973) studied both diurnal and semidiurnal northward winds at Adelaide from June 1966 to June 1973 which are reproduced in Fig. 15. The phase variation shows that the evanescent mode is dominant in summer, and the central value of the phase is around 0 hrs which is different from ours by 12 hrs. That for winter indicates appearance of the propagating mode, and the phase is also reversed to ours. Thus, the average behaviour of diurnal tide in solsticial periods at these stations agree well with each other.

As for semidiurnal tide, the phase variation in summer at Adelaide corresponds to the wave with a long vertical wavelength. This feature is consistent with our results except for that the phase is reversed. The phase shift of 6 hrs, however, agrees with the latitudinal structure of the symmetric $S_{2,2}$ mode. Height profiles in winter show similar
behaviour to ours except for that the mean value of the phase differs by 6 hrs. At
equinoctial periods, clear correlation cannot be deduced between the two. The central
value of the phase in spring at Adelaide is approximately equal to that at Kyoto, which
could not be explained by symmetric modes.

3.3 Average seasonal variation of semidiurnal tide

The seasonal variation of semidiurnal tide at Kyoto can be investigated by using a
harmonic dial at 95 km altitude. Figure 16 shows an average annual variation of the
northward component of the semidiurnal tidal wind. A full circle in Fig. 16
corresponds to the bimonthly average of the northward component calculated from
the results shown in Fig. 9. The northward wind vector rotates anticlockwise annually
on an ellipse whose major axis points at around 4.5 hrs local time. During summer
months, semidiurnal tide is characterized by stable phase and large amplitude. On the
other hand, the amplitude becomes the smallest in winter, and the phase is reversed to
that in summer. In two equinoctial periods, results are located at the opposite side on
the ellipse with respect to the major axis. Considering the seasonal variation of the
northward component, we could imagine a rapid change in the structure of semidiurnal
tide during winter and spring.

MÜLLER (1966) deduced an idealized pattern for systematic seasonal variation of
semidiurnal tide as shown in Fig. 17 by using meteor radar data obtained at Sheffield
(53°N), Kharkov (50°N) and Jodrell Bank (53°N). Our results in summer and spring
agree well with the Müller's pattern in both amplitude and phase. Because our mean
vector for autumn in Fig. 16 contains the results for both September and October, it
corresponds to the average value of these two months in Müller's pattern. Individual
monthly average shown in Fig. 10 is included in the corresponding region in Fig. 17,
although the amplitude detected in September at Kyoto is rather small. In November,
December, January and February the amplitude is as small as a few m/sec at Kyoto,
while it ranged from 10 m/sec to 30 m/sec at European stations. The phase in January
and February at Kyoto roughly agrees with that in winter shown in Fig. 17.

These discrepancies in the behaviour of semidiurnal tide in winter could be
explained by the difference in latitudes among these meteor radar stations besides the
difference in observation periods. If the $S_{2,4}$ mode is enhanced in winter, the
discrepancy mentioned above would be solved, because it has a latitudinal structure
such that the amplitude of the northward wind is much larger at around 50°N than that
at around 35°N. Harmonic dials at Kyoto and European stations do not show large
difference in summer, so that a fundamental mode with a simple latitudinal structure
seems to be dominant.

3.4 Latitudinal structure of tides

We have shown that the average behaviour of the atmospheric tides at meteor
heights are fairly well characterized in each season when observation period is
elongated enough. So that, we could expect to obtain the fundamental horizontal
structure of tides in each season. To investigate latitudinal variation of the tidal wind at
a specified height is one of the fruitful way to identify the dominant Hough mode.
a

SUMMER

AUTUMN

WINTER

SPRING

ALTITUDE (km)

AMPLITUDE (m/sec)

PHASE (hrs)

0 10 20 30

8 12 16 20 24 28

6/7 7/8 8/9 6/7 6/9

6 - 1966
7 - 1967
8 - 1968
9 - 1969

0/1 3/2 3/2 0/1

9 - 1969
9 - 1969
0 - 1970
1 - 1971
2 - 1972
3 - 1973
Fig. 15. Meridional component of the tidal wind velocity at Adelaide (ELFORD, 1973). (a): diurnal component. (b): semidiurnal component.
Fig. 16. Seasonal variation of the semidiurnal wind velocity at an altitude of 95 km observed at Kyoto in 1979–1980. A full circle corresponds to a bimonthly average.

Seasonal Variation of Solar Atmospheric Tides at Meteor Heights

Table 1. A list of meteor radar data.

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Observed periods</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheffield</td>
<td>53 N</td>
<td>1 W</td>
<td>1964–1965</td>
<td>MÜLLER (1966)</td>
</tr>
<tr>
<td>Kharkov</td>
<td>50 N</td>
<td>36 E</td>
<td>1964–1965</td>
<td>KASHCHEYEV and LYSENKO (1968)</td>
</tr>
</tbody>
</table>

TSUDA and KATO (1980) have theoretically studied the seasonal variation of diurnal tide due to ozone heating. They compared the computed northward diurnal wind with meteor radar observations obtained in the last two decades at many other stations listed in Table 1. The results are reproduced in Fig. 18 for June and December solstices, where a seasonal mean is calculated by taking a vector average. Open circles are added as averages of the observation carried out at Kyoto in June and July in both 1979 and 1980 for summer, and in December, 1979 and January, 1980 for winter. As for the wind amplitude we find a good agreement between theory and observation. Especially, in the northern mid-latitude region where many meteor radars exist, the agreement is fairly well at June solstice. An enhancement of the wind amplitude at mid-latitude in summer is attributed to the dominance of the evanescent mode which has large wind amplitude outside the equatorial region (e.g. KATO, 1980). Observed phase value generally indicates 12 hrs local time in summer in the northern hemisphere, and agrees with the theoretical curve. As for winter results, phases spread largely. This might be attributed to the presence of the propagating mode with short vertical wavelength whose phase considerably varies from day to day in the meteor region as shown in Fig. 6. Seasonal variation of diurnal tide described in section 3.1 (a) seems to be confirmed in terms of the latitudinal structure.

As for semidiurnal tide, TSUDA et al. (1980) investigated the latitudinal structure of the northward component in both summer and spring. Their conclusion was that the $S_{2,2}$ mode dominates in summer and the $S_{2,4}$ mode in spring. Examination done in the present work on the wind profile suggests a similar conclusion. We had better inquire the latitudinal variation in winter to show the dominance of the $S_{2,4}$ mode, because the discrepancy between Kyoto and European stations was largest in winter. Figure 19 shows the latitudinal structure of the northward wind velocity in winter. At around 40° in colatitude, semidiurnal tide is enhanced, while it becomes small at Kyoto. This can be explained by the dominance of higher order modes in winter than the fundamental mode (TSUDA et al., 1980).
Fig. 18. Amplitude and phase of the northward diurnal wind velocity with colatitude. Theoretical results (Tsuda and Kato, 1990) are shown as solid lines. Observations are plotted as circles for (a) summer and (b) winter on the northern hemisphere, respectively.
Fig. 19. The latitudinal variation of amplitude and phase of the northward semidiurnal wind velocity in winter.

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