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MF radar observations of the diurnal tide over Syowa, Antarctica (69° S, 40° E)

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Abstract. Characteristics of the diurnal tide in the Antarctic mesosphere and lower thermosphere (MLT) are investigated using 10 years of medium frequency (MF) radar data from Syowa Station (69° S, 39.6° E). Seasonal variations and height dependence of the diurnal amplitude and phase of zonal and meridional winds are mostly consistent with previous studies using the other Antarctic station data. The meridional momentum flux due to the diurnal tide shows a seasonal variation clearly different between above and below 90 km, which has never been reported in the literature. Finally, a cause of some discrepancy in the characteristics of the diurnal tide between the observation and simulation (i.e., GSWM-02) is discussed. It implies that the realistic representation of gravity waves in the simulation is crucial for realistic modeling of the diurnal tide.

Keywords. Meteorology and atmospheric dynamics (Middle atmosphere dynamics; Waves and tides)

1 Introduction

A number of scientific research activities have been conducted in the Antarctic by the Japanese Antarctic Research Expedition (JARE) since the International Geophysical Year (IGY) in 1957–1958. Syowa Station is the mother station of JARE, which is located on East Ongul Island (69° S, 39.6° E) near the coast of Antarctica. Recently, a new research project exploring coupling processes between the lower, middle, and upper atmosphere due to the vertical transport of momentum, energy, minor constituents, and energetic particles has started as a special project of JARE. For this project, several instruments observing the mesosphere and lower thermosphere (MLT) are in operation or will be installed at Syowa Station (cf. Ejiri et al., 1999). One of them is the medium frequency (MF) radar, which measures zonal and meridional winds in the MLT region. In this paper, basic features of the atmospheric diurnal tide in the Antarctic MLT region obtained by the MF radar observations at Syowa Station are reported.

Atmospheric tides are one of dominant waves observed in the MLT region. They vertically transfer zonal momentum through their vertical propagation, and maintain the background wind distribution and meridional circulation in the MLT region, in conjunction with gravity waves. Temperature perturbations associated with the tides reach 30 K in the equatorial MLT region (Hagan and Forbes, 2002) and influence the radiation balance and chemistry there.

Fluid dynamical theory of atmospheric tides has been intensively investigated since the pioneering work by Laplace, and was reviewed by Chapman and Lindzen (1970). The theory predicts that the atmospheric tides in the polar MLT region are primarily composed of a vertically-propagating semidiurnal tide and a vertically-evanescent diurnal tide. They are excited by insolation absorption due to water vapor in the troposphere and ozone in the stratosphere and mesosphere. Thus they propagate westward coincident with the sun, which are called migrating tides. On the other hand, recent studies have shown that nonmigrating (i.e., sun-asynchronous) tides also exist in the polar MLT region. The westward-propagating semidiurnal tide with a zonal wavenumber 1 was observed at the South Pole throughout the year (Hernandez et al., 1993; Forbes et al., 1995; Portnyagin et al., 1998). Murphy et al. (2006) divided semidiurnal components of zonal and meridional winds into migrating and nonmigrating tides with zonal wavenumbers 0–3 using data from several Antarctic stations. However, the nonmigrating diurnal tide with significant amplitude in the polar region has never been reported, so that the diurnal tide observed in the Antarctic MLT region is regarded as migrating.

Avery et al. (1989) described basic features of the diurnal tide in the Antarctic MLT region based on the MF and

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Fig. 1. Coverage of MF radar data recorded at Syowa and used in this study.

meteor radar data at three Antarctic stations. The meridional amplitude of the diurnal tide is larger than the zonal one and their amplitudes maximize at about 85 km in austral summer. The phase of the diurnal tide is nearly constant with height except during austral winter. The phases of the zonal and meridional components of the diurnal tide are not necessarily in quadrature with each other. These features are consistent with recent analyses of single station data at Scott Base (78° S, 167° E) (Baumgaertner et al., 2005) and Rothera (67° S, 68° W) (Hibbins et al., 2007).

This paper first describes height and seasonal dependence of zonal and meridional diurnal tides observed in the MLT region over Syowa Station using the MF radar data covering 10 years. Since the zonal and meridional diurnal tides are not in quadrature with each other, they have a significant meridional momentum flux. Its height and seasonal dependence are also shown and compared with the simulation (GSWM-02; see Sect. 2.3 for details). The differences between the observations and results from a simulation will be discussed.

The remainder of this paper is organized as follows. Details of the MF radar observations at Syowa Station and the analysis procedure to compute amplitude and phase of the zonal and meridional diurnal tides are given in Sect. 2. Characteristics of the diurnal tide and the accompanying momentum flux estimated by the observations are shown in Sect. 3. Section 4 discusses how to explain the difference between the observation, theory, and simulation. Summary and concluding remarks are given in Sect. 5.

2 Data and analysis method

2.1 Syowa MF radar system

The Syowa MF (medium frequency) radar system was installed on East Ongul Island (69° S, 39.6° E), located near the coast of Antarctica, and started its operation in March 1999 (Tsutsumi et al., 2001). The radar measures zonal and meridional winds in the mesosphere and lower thermosphere (MLT) using a conventional spaced antenna technique. The radar operates at a frequency of 2.4 MHz with a transmitter power of 50 kW and a 99% power bandwidth of 60 kHz. This configuration corresponds to a height resolution of about 4 km sampled at 2 km height intervals in a height region of 50–100 km. The following analysis is applied to hourly data in a height region of 70–94 km, above which the MF radar is susceptible to group retardation (Namboothiri et al., 1993) and E-region echo contamination (Hocking, 1997). Below 70 km, the acquisition rate of hourly data is less than 90%, which is probably related to low electron density. The data covers nearly one solar cycle from March 1999 to December 2008 (Fig. 1). More details of the Syowa MF radar system are described in Tsutsumi et al. (2001).

2.2 Analysis procedure

In order to obtain amplitude and phase of diurnal variations of zonal and meridional winds, a Lomb-Scargle periodogram (Lomb, 1976; Scargle, 1982; Hocke, 1998) is applied to the hourly data in a 3-day moving Hamming window with a shifting time step of 1 day. This calculation is performed only when the data missing is less than a half of 3 days in the window. The obtained vector amplitude of diurnal variations is averaged over one month, resulting in the monthly-mean amplitude and phase of the diurnal variations of zonal and meridional winds as a function of month and height for each year. The monthly-mean amplitude and phase averaged over 1999–2008 are also given by the average of the monthly-mean vector amplitude. The phase is expressed by time of maximum eastward or northward wind in local solar time.

2.3 GSWM-02 data

For comparison with the MF radar data, amplitude and phase of diurnal wind variations computed by the Global-Scale Wave Model-2002 (GSWM-02) are employed (Hagan et al., 1995, 1999, 2001, http://www.hao.ucar.edu/modeling/gswm/gswm.html). The GSWM-02 solves the linearized and extended Navier-Stokes equations in the background field obtained from the HRDI instrument onboard the UARS satellite (Hagan et al., 1999) and the MSISE-90 model (Hedin, 1991). Tidal forcing in the GSWM-02 includes only migrating sources excited by the absorption of solar radiation. A lack of nonmigrating sources such as latent heat release in the troposphere and wave-wave interaction is not crucial in this study, because the diurnal tide in the polar MLT region

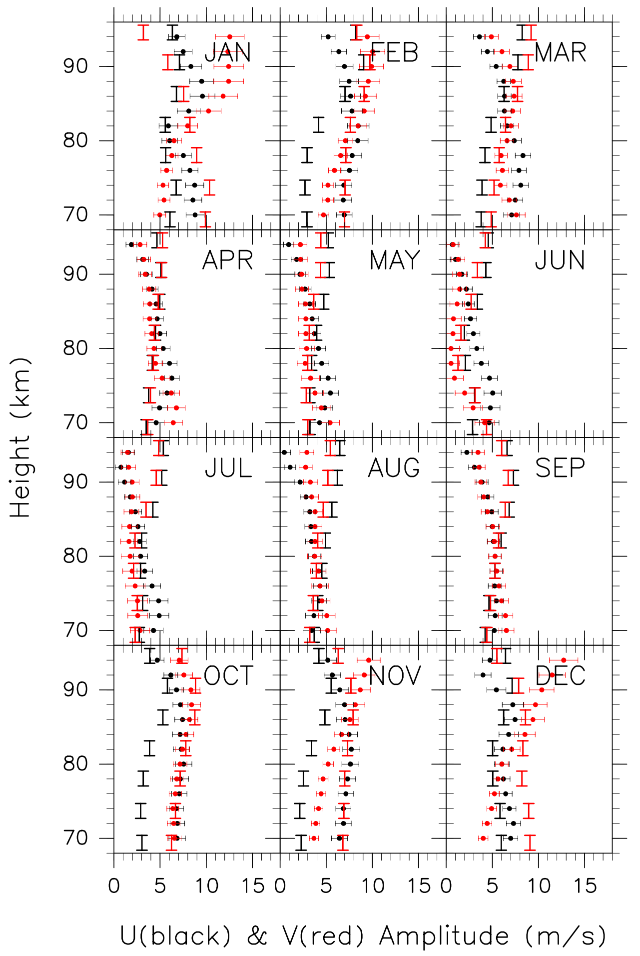

Fig. 2. Vertical distributions of diurnal amplitudes of zonal (black) and meridional (red) winds at Syowa for each month averaged over 1999–2008. Circles and "I" represent the MF radar and GSWM-02 data, respectively. 2σ error bars are plotted for the MF radar data.

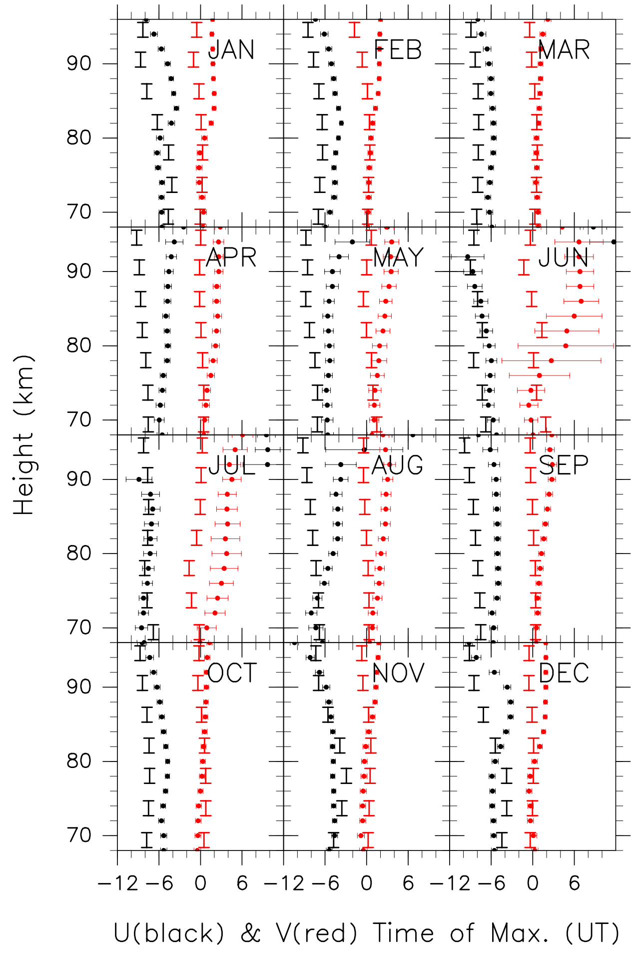

Fig. 3. Same as Fig. 2 except for diurnal phases in local solar time.

is considered to be composed of the migrating components alone.

3 Results

3.1 Seasonal variations and height dependence of the diurnal tide

Figure 2 shows diurnal amplitudes of zonal and meridional winds averaged over 1999–2008 at Syowa as a function of month and height. Both the zonal and meridional amplitudes have little height dependence and are smaller than 5 m s^{-1} throughout austral winter. The zonal amplitude has the largest value of 7–10 m s^{-1} around 85 km and the smallest value of 5–7 m s^{-1} around 80 km in austral summer. On the other hand, the meridional amplitude gets larger with height even above 85 km and has the largest value of 10–15 m s^{-1} during austral summer. As a result, the meridional amplitude is larger (smaller) than the zonal amplitude above (below) about 80 km in austral summer. Both of the zonal and meridional amplitudes represent a clear seasonal variation with summer maxima and winter minima (see also Fig. 4). Avery et al. (1989) showed that the zonal amplitude at Mawson (67° S, 63° E) maximized below 90 km with a maximum value of 5–10 m s^{-1} while the meridional amplitude reached 10 m s^{-1} around 90 km and maximized above 100 km in austral summer. These features are mostly consistent with those obtained at Syowa.

Vertical distributions of the phase of zonal and meridional diurnal winds for each month at Syowa are shown in Fig. 3. Both of the zonal and meridional phases mostly have little phase tilt with height and are approximately in quadrature with each other throughout the year. However, a closer inspection reveals that the zonal phase tilts eastward with height from 80 to 85 km and westward above 85 km compared to the meridional phase in austral summer, which results in zonal and meridional phases out of quadrature with each other.

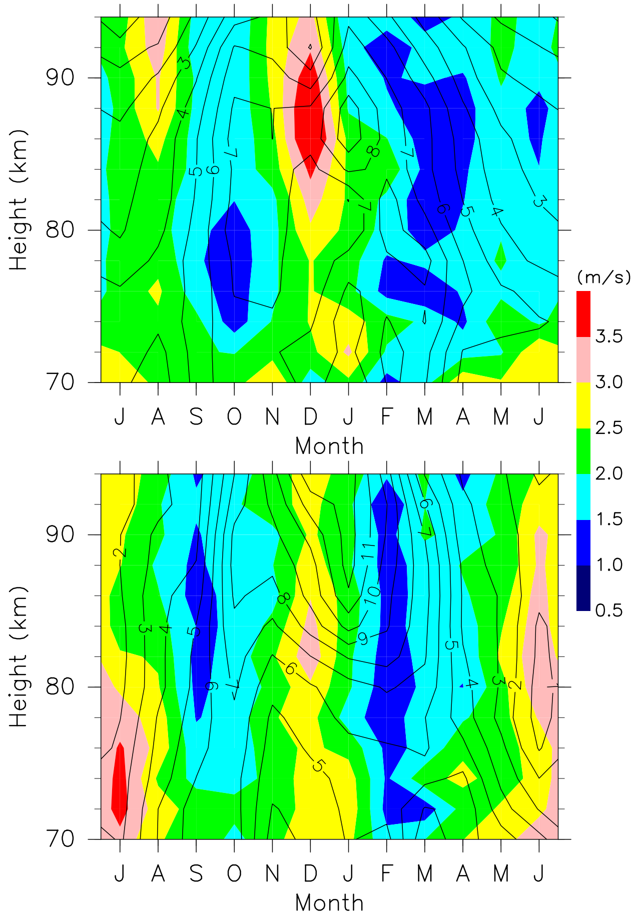

Fig. 4. Time-height sections of monthly-mean amplitudes (contours) of zonal (top) and meridional (bottom) winds with standard deviations (colors) of their interannual variations. Contour intervals are 1 m s^{-1}.

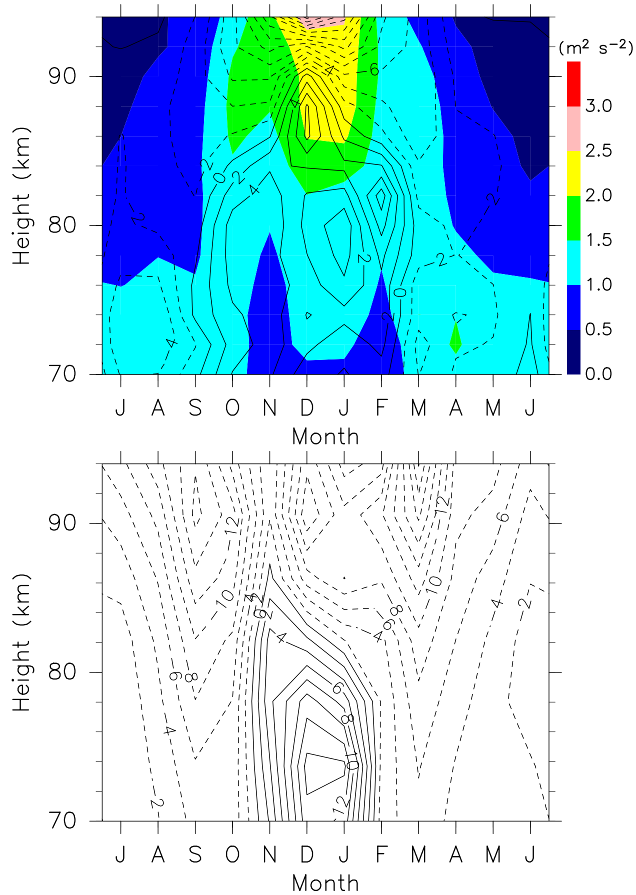

Fig. 5. Time-height sections of meridional momentum flux due to diurnal tide at the latitude of Syowa computed from the MF radar (top) and GSWM-02 data (bottom). Contour intervals are 2 $m^2\,s^{-2}$. Colors represent 1σ errors of meridional momentum flux.

The diurnal amplitude and phase at Syowa obtained by the GSWM-02 are represented by "I" in Figs. 2 and 3, respectively. The zonal and meridional amplitudes in the GSWM-02 are larger in austral summer than in winter. Their amplitudes are nearly equal and smaller than 5 m s^{-1} during austral winter, which is consistent with those of the MF radar data. On the other hand, the meridional amplitude is larger than the zonal one below 90 km and their height dependence is much variable with month during austral summer. These features in the GSWM-02 during austral summer are clearly different from those of the MF radar data. The phase in the GSWM-02 is in good agreement with that of the MF radar data in austral summer with larger amplitude than in winter. However, the eastward phase tilt between 80 and 85 km in the MF radar data during austral summer is not observed in the GSWM-02 data.

Seasonal variations of zonal and meridional amplitudes are more clearly shown in Fig. 4 with their interannual variations. The interannual variation is computed as a standard deviation of the vector amplitude, so that it reflects both of the amplitude and phase variations. While the zonal and meridional amplitudes are maximized in austral summer, their interannual variations are maximized in austral winter as well as summer. Since the phase has little interannual variation in austral summer (not shown), the large interannual variation in austral summer is due to that of the amplitude. On the other hand, the amplitude is small in every austral winter (not shown), so that the large interannual variation indicates that the phase is variable in austral winter.

3.2 Momentum transport due to the diurnal tide

As argued in Sect. 1, the diurnal tide in the polar MLT region is considered to consist of the migrating components alone. Thus the zonal and meridional winds of the migrating diurnal tide which are not in quadrature with each other induce nonzero meridional flux of zonal momentum (i.e., meridional momentum flux). If the diurnal wind variations at one location are composed of several modes of the migrating diurnal tides, daily average of a product of the diurnal zonal and meridional wind perturbations is equivalent to the zonal-mean meridional momentum flux ($\equiv \overline{u'v'}$) at the corresponding latitude (Hines, 1972; Elford, 1979). The meridional momentum flux of $-10\,\mathrm{m^2\,s^{-2}}$, which is close to the maximum negative value above 90 km in December, at the latitude of Syowa can uniformly accelerate the zonal-mean zonal wind in the latitude region poleward of Syowa by $1.5\,\mathrm{m\,s^{-1}\,day^{-1}}$ through its convergence (Andrews et al., 1987).

The meridional momentum flux due to the diurnal tide at Syowa computed from the MF radar and GSWM-02 data is shown in Fig. 5. The momentum flux in the MF radar data has a large negative value in austral summer and is nearly zero in austral winter above 90 km. On the other hand, the momentum flux has two positive maxima in November and February, and becomes weakly negative in austral winter below 90 km. The magnitude of the seasonal variations of the momentum flux is larger than its estimate error shown by colors. The height dependence of the momentum flux during austral summer in the GSWM-02 data is similar to that in the MF radar data, but the height where the sign changes is lower in the GSWM-02 (i.e., 80–86 km) than in the MF radar data (i.e., 86–90 km). Seasonal variations of the momentum flux with positive and negative values in austral summer and winter, respectively, below 90 km are common to the MF radar and GSWM-02 data. However, two positive maxima of the flux in the MF radar data are not observed in the GSWM-02 data.

Eastward or westward acceleration induced by the convergence of meridional momentum flux of the diurnal tide in the Antarctic MLT region is at most a few $\mathrm{m\,s^{-1}\,day^{-1}}$, which is much smaller than the gravity wave drag of several tens $\mathrm{m\,s^{-1}\,day^{-1}}$ (Brasseur et al., 2000), although it is close to the total tidal wave drag (i.e., smaller than $10\,\mathrm{m\,s^{-1}\,day^{-1}}$ (Miyahara, 1981)). On the other hand, the meridional momentum flux can influence the latitudinal distribution and seasonal variation of the background wind through latitudinal redistribution of the zonal momentum transported by vertically-propagating gravity waves and tides.

4 Discussion

Several features of the diurnal tide at Syowa obtained in Sect. 3.1 are mostly consistent with previous studies (Avery et al., 1989; Baumgaertner et al., 2005; Murphy et al., 2006; Hibbins et al., 2007) concerning the MLT diurnal tide over Antarctica as described in Sect. 1. On the other hand, the reversal of zonal and meridional amplitudes around 80 km in austral summer has not been discussed in detail in the previous studies, because most of them focused on the height region above 80 km. This feature and the departure of the phase difference from quadrature have an important implication for the structure of the MLT diurnal tide over Antarctica.

The classical tidal theory has predicted that the diurnal tide in the polar MLT region was composed of the vertically-evanescent migrating components alone (Chapman and Lindzen, 1970). The subsequent theoretical and model studies indicated that the vertical and meridional structure of the MLT diurnal tide could be affected by spatial inhomogeneity of the background wind and temperature distributions and dissipation processes such as molecular and turbulent diffusion and gravity wave drag (Forbes and Garrett, 1979; Forbes, 1982; Forbes and Hagan, 1988; Forbes and Vincent, 1989; Aso et al., 1987). Although the migrating sources of the diurnal tide are mostly attributable to insolation absorption by water vapor in the troposphere and ozone in the stratosphere and mesosphere with the (1, 1) and (1, −2) Hough modes (Chapman and Lindzen, 1970), the energy of the (1, 1) Hough mode is transferred to the (1, −1) and (1, −2) Hough modes through mode coupling associated with the nonseparability of the tidal equations (Forbes and Hagan, 1988; Forbes and Vincent, 1989). In addition, the dissipation which becomes effective around the mesopause could serve to change the phase relation and the amplitude ratio between the zonal and meridional diurnal winds. The vertical and meridional structure of the diurnal tide taking into account these effects is numerically obtained in a form of the Hough mode extension (Svoboda et al., 2005).

The zonal and meridional winds of the (1, −1) and (1, −2) Hough modes are in quadrature with each other and have a similar amplitude ratio (i.e., $|v'|/|u'|$) of 0.73–0.74 (Chapman and Lindzen, 1970). Thus a combination of the (1, −1) and (1, −2) Hough modes cannot explain the meridional amplitude larger than the zonal one above 80 km and the phase difference out of quadrature in austral summer. On the other hand, the dissipation could change the amplitude ratio and phase difference between the zonal and meridional tidal winds (Forbes and Vincent, 1989). The GSWM-02, taking into account both the inhomogeneity of the background field and the dissipation, roughly reproduces the phase structure of the diurnal tide up to 94 km. However, it does not reproduce the observed reversal of zonal and meridional amplitudes except above 90 km in January. Since the background temperature and zonal wind distributions are observationally provided, inconsistency between the observation and GSWM-02 might be attributable to unrealistic representation of the dissipation processes in the GSWM-02.

It should be noted that the GSWM-02 employs the Rayleigh friction as a gravity wave drag (GWD) parameterization (Miyahara and Forbes, 1991). The Rayleigh friction had been used as a simple and useful GWD parameterization in general circulation models (GCMs) to reproduce the realistic MLT wind structure such as weak zonal wind around the mesopause. However, the gravity wave drag in the real atmosphere significantly depends on its forcing distribution and propagation routes below the MLT region (Fritts and

Alexander, 2003). The interaction between gravity waves and tides could result in the tidal forcing different from the Rayleigh friction (Miyahara and Forbes, 1991; Liu et al., 2008; Watanabe and Miyahara, 2009). Additionally the gravity wave breaking in the MLT region induces nonuniform and intermittent turbulence (Fritts and Alexander, 2003), which might change the amplitude ratio and phase relation between the zonal and meridional diurnal tides in a different way from uniform turbulence in space and time. Thus the realistic representation of gravity waves in the model could be crucial for realistic modeling of the MLT tide. Recent advances in computer technology would enable the GCMs to explicitly resolve gravity waves and reproduce the realistic MLT tide (cf. Watanabe et al., 2008; Watanabe and Miyahara, 2009).

5 Concluding remarks

A climatology of the diurnal tide in the Antarctic MLT region was obtained by the MF radar observations at Syowa Station (69° S, 39.6° E) covering 10 years. Amplitudes of the diurnal tide maximize in austral summer. In austral winter, both the zonal and meridional amplitudes have little height dependence and are smaller than $5\,\mathrm{m\,s^{-1}}$. The zonal amplitude reaches 7–$10\,\mathrm{m\,s^{-1}}$ around 85 km and the smallest value of 5–$7\,\mathrm{m\,s^{-1}}$ around 80 km in austral summer, while the meridional amplitude gets larger with height even above 85 km and has the largest value of 10–$15\,\mathrm{m\,s^{-1}}$. As a result, the meridional amplitude is larger and smaller than the zonal one above and below about 80 km, respectively, in austral summer. Although the phase of the diurnal tide is mostly constant with height, slight westward and eastward tilts with height are observed above 80 km in austral summer. The zonal and meridional phases are not always in quadrature with each other, which results in some meridional momentum flux. These features are mostly consistent with the previous studies analyzing the diurnal tide in the Antarctic MLT region. However, the reversal of zonal and meridional amplitudes around 80 km has not been clearly documented.

The time-height section of the meridional momentum flux due to the diurnal tide at the latitude of Syowa Station was also obtained. Its seasonal dependence is clearly different between above and below 90 km. The momentum flux above 90 km has the largest negative value in austral summer and is nearly zero in austral winter. On the other hand, the momentum flux below 90 km has two positive maxima in November and February, and becomes weakly negative in austral winter. The largest negative momentum flux of about $-10\,\mathrm{m^2\,s^{-2}}$ above 90 km can accelerate the zonal-mean zonal wind in the Antarctic MLT region by $1.5\,\mathrm{m\,s^{-1}\,day^{-1}}$. This acceleration is much smaller than the wave drag due to vertically-propagating gravity waves, but might contribute to changing the latitudinal distribution and seasonal variation of the zonal wind.

Comparison of the MF radar results with the GSWM-02 was performed. Seasonal variations of the diurnal amplitude with summer maximum and winter minimum was reproduced in the GSWM-02. The phase structure of the diurnal tide in austral summer was well simulated by the GSWM-02. On the other hand, the vertical distributions of the diurnal amplitude in austral summer is significantly different between the MF radar data and the GSWM-02. The reversal of zonal and meridional amplitudes observed by the MF radar in austral summer was not captured by the GSWM-02. Such a difference of the ratio of zonal and meridional amplitudes implies that unrealistic representation of dissipation processes in the model may cause such a difference. The dissipation processes in the MLT region are closely related to the gravity waves, which interact with the tides through momentum deposition and induce turbulence by breaking. Although current GCMs cannot fully resolve the gravity waves, full representation of gravity waves in the model could be essential for realistic simulation of the MLT tides. At the same time, the reality of the gravity waves represented in the model needs to be confirmed by observations with resolution and precision high enough to capture the full spectrum of gravity waves. The MST (Mesosphere-Stratosphere-Troposphere) radar planned at Syowa Station (PANSY: Program of the Antarctic Syowa MST/IS radar; http://pansy.nipr.ac.jp/index-e.html) can measure the three-dimensional wind speeds in the troposphere, stratosphere, mesosphere, and thermosphere (ionosphere) with high temporal (∼1 min) and vertical (∼75 m) resolutions. In addition, the vertical momentum flux ($\equiv \overline{u'w'}$) mostly due to gravity waves can be directly estimated by the PANSY radar. It will make a huge contribution to understanding the behavior of gravity waves in the Antarctic MLT region.

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