NOTES AND CORRESPONDENCE

Zonally Symmetric Diurnal Tides Simulated with a General Circulation Model

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Abstract

A large zonally symmetric diurnal variation is found in temperature and wind fields in a model general circulation of the middle atmosphere. This variation has a vertical wavelength of about 25 km and shows similar structures to those of the basic mode of zonally symmetric diurnal tides. The zonal component of diabatic heating projected to the horizontal structure function of this mode shows a prominent diurnal change with large amplitudes near the surface. The simulated zonally symmetric diurnal variation therefore is the basic mode of the upward propagating tides thermally excited in the lower troposphere, the amplitude of which mode becomes appreciably large in the middle atmosphere due to the density effect.

1. Introduction

Numerous observational and theoretical studies on the atmospheric thermal tides have been made over many decades, their major concern being the migrating diurnal and semi-diurnal components (*e.g.*, Kato, 1966a, b; Chapman and Lindzen, 1970; Forbes, 1982). On the other hand, on non-migrating diurnal and semi-diurnal tides, which are induced by localized diabatic heating, only a few studies (*e.g.*, Haurwitz, 1965; Chapman and Lindzen, 1970) were made until the late 1970's. Giwa and Hussain (1978) showed that the differential heating between land and sea generates non-migrating zonally symmetric semi-diurnal tides. Kato *et al.* (1982) studied non-migrating diurnal tides excited by localized heat sources near the equator. Tokioka and Yagai (1987) simulated non-migrating diurnal tides of westward-moving wave number 5 and eastward-moving wave number 3 with a general circulation model, following which Yagai (1989) found these non-migrating diurnal tides in the analysis of the FGGE data. Tsuda and Kato (1989) calculated the amplitudes and vertical structures of the non-migrating diurnal tides due to an assumed heating distribution of the eddy heat transfer near the ground, using a linear combination of the eigen-modes of the diurnal tides.

There can be a zonally symmetric mode as one

of the non-migrating diurnal atmospheric tides, if an appropriate exciting force is added to the atmosphere (Chapman and Lindzen, 1970). Observational and theoretical studies showed that such a mode has significant amplitudes in the surface pressure variation (Haurwitz, 1965; Yagai, 1989; Tsuda and Kato, 1989).

Recently, we have developed a spectral general circulation model which includes the upper stratosphere and the lower mesosphere. In the model simulation we found that there is an appreciably large diurnal variation in the zonal mean fields of the upper atmosphere. In this short paper we will show that the variation comes from zonally symmetric diurnal tides, which are thermally excited near the ground and propagate upward in the middle atmosphere.

2. Outline of the model and data

The model used in this study is a spectral atmospheric general circulation model, which is almost the same as the extended version (Shibata and Chiba, 1990) of the model originally developed by Chiba *et al.* (1986), using an accurate calculation scheme of the long-wave radiation process (Shibata and Aoki, 1989). The model is rhomboidally truncated at wavenumber 24 (R24) and has 23 layers from the surface to the topmost level of 0.05 mb as shown in Fig. 1. The physical processes are almost

the same as those of the original version except for the radiation processes. The solar radiation process is coded following Lacis and Hansen (1974) with a slight modification for the treatment of cloudy skies. The cloud used in the radiation processes is diagnosed as a function of relative humidity.

The Rayleigh damping is used to decelerate the air flow in the upper atmosphere as a crude parameterization of the internal gravity wave breaking. Figure 2 shows the profile of damping coefficient, the magnitude of which is about a half of that used by Holton and Wehrbein (1980).

Data used in this study are sampled every 2 hours over 5 days during December 10–14.

Fig. 2. Vertical profile of the Rayleigh friction coefficient (1/sec).

Fig. 3. Zonal mean fields of temperature (upper; contour interval 5 K) and zonal winds (lower; contour interval 10 m/sec) averaged over 5 days.

3. Results

3.1 Zonal mean basic states

The simulated zonal mean fields are shown in Fig. 3. Zonal winds are strong in both westerly and east-

Fig. 4. Zonal mean meridional winds averaged over 5 days at 00Z (upper), at 12Z (middle), and the difference between 00Z and 12Z (lower). The contour interval is 1 m/sec.

erly components compared with observed winds (see *e.g.*, Randel, 1987). This is due partly to the fact that the Rayleigh damping coefficient is too small. The simulated temperature distribution has almost the same features as those of the observed one, in spite of being about 5 K lower in the stratosphere.

3.2 Difference between 00Z and 12Z

Figure 4 shows the zonal mean meridional winds at 00Z (upper panel) and 12Z (middle panel), and the difference between them (lower panel). We can see from this figure that the difference is significant and systematic in the stratosphere and above. In the

Fig. 5. Differences in zonal winds (upper; contour interval 1 m/sec) and temperature (lower; contour interval 0.5 K).

horizontal the difference is anti-symmetric about the equator, and it takes extreme values in the subtropics with a node near the equator. In the vertical the difference shows wavelike stratification (about 25 km wavelength), and it increases with altitude. Note that the vertical scale in winds shear (1/2 wavelength) is much larger than the two-grid spacing in the model. There is no significant difference in the troposphere except near the ground.

The difference in the zonal winds (upper panel in Fig. 5) shows similar vertical and horizontal structures to those in the meridional winds except for the symmetry about the equator. On the other hand, though symmetric, the difference in the temperature (lower panel in Fig. 5) shows the largest amplitude on the equator, and the latitudes of its node approximately coincide with those of the extrema of meridional and zonal winds. It is worthwhile to point out that the amplitude of the meridional winds is nearly the same as that of the zonal winds. Figures 4 and 5 also show that the vertical phase lag between winds and temperature is about 1/4 wavelength, which relation is expected to hold from the hydrostatic assumption.

According to the tidal theory (see Longuet-Higgins, 1968), zonally symmetric modes of diurnal atmospheric tides have positive eigenvalues, indicating that they can vertically propagate in the atmo-

Fig. 6. Time variation of the total diabatic heating projected to the basic mode of the zonally symmetric diurnal tides.

sphere. The eigen-mode corresponding to the second largest equivalent depth of 629 m has a vertical wavelength of about 26 km in an isothermal atmosphere of 250 K. Meridional structures of u (zonal winds), v (meridional winds), and Φ (geopotential height) of this mode have quite similar characteristics to those shown in Figs. 4 (lower panel) and 5, where u and Φ are symmetric about the equator, and v anti-symmetric (we will refer to this mode as the basic mode of zonally symmetric diurnal tides).

Recently, zonally symmetric diurnal tides in the middle atmosphere have been revealed by the analysis of the data from the the Nimbus-7 Limb Infrared Monitor of the Stratosphere (LIMS) (Lieberman, 1991). The meridional and vertical scale and structure of the temperature perturbation (shown in Fig. 3a in his paper) are almost same to those shown in Fig. 5 except for amplitude.

Inertial instability, which is induced due to the strong meridional gradient of the zonal winds, is another mechanism producing zonally symmetric oscillations (see *e.g.*, Charney, 1973). But the growth rate of the perturbation due to this instability becomes larger for shorter vertical scales. Hence, the inertial instability, if any, is expected to occur with the least vertical scale such as a two-grid scale in the model. In fact, it appeared so in the simulation by Hunt (1981). In addition, the inertial instability occurs only in either hemisphere. As mentioned above, the simulated zonally symmetric diurnal variation extends in both hemispheres, and its vertical scale is larger than the two-grid spacing in the model. Hence it is evident that the simulated diurnal variation is not induced through the inertial instability.

Fig. 7. The relative amplitude of the diabatic heating by radiation, condensation and turbulent heat exchange processes which contribute to the total heating shown in Fig. 6.

3.3 Diabatic heating

Some thermal exciting forcing is needed to produce the basic mode of zonally symmetric diurnal tides. In this model the ozone density is zonally given from the climatological distribution of Klenk *et al.* (1983). Thus diabatic heating due to the solar flux absorption by ozone can not have a significant diurnal variation in the zonal mean component. On the contrary, diabatic heating due to the surface physical processes could have many kinds of horizontal pattern because of the complexity of the land-sea distribution and various ground conditions.

Figure 6 shows the time variation of the coefficient of the total diabatic heating rate projected to the horizontal structure function of the basic mode. This figure shows that there is a diurnal oscillation with large amplitudes in the lower troposphere (0.3–0.4 K/day at 1000 mb) and that it is decreasing with altitude. The relative contribution of four diabatic heating processes (radiation(short and long wave), condensation and vertical turbulent heat exchange) to the total diabatic heating is shown in Fig. 7 scaled by the diabatic heating of the turbulent heat exchange process in the lowest layer. Diabatic heating due to the turbulent heat exchange process is dominant and other processes negligibly contribute to the total heating. Thus heating due to the turbulent heat exchange may be identified as the exciting force of the basic mode of zonally symmetric diurnal tides in this simulated atmosphere. As not shown here, the exciting forces mainly come from the zonal component of localized sensible heat fluxes on the subtropical continental surfaces over Africa, India, Australia, and South America.

Fig. 8. Fourier components of the diurnal surface pressure oscillation averaged over all latitudes for observations (dashed line, Haurwitz and Cowley, 1973) and the present study (full line).

Fourier coefficients of the diurnal surface pressure oscillation are shown in Fig. 8 compared with those estimated from the observed data (Haurwitz and Cowley, 1973). Each wave component in the model has a comparable amplitude to that of the observation except for the dominant mode of wave number 1 propagating westward. As mentioned by Tokioka and Yagai (1987) and Yagai (1989), westward-propagating wave number 5 and eastward-propagating wave number 3 component also have large amplitudes, as shown here. Note that Tsuda and Kato (1989) also diagnosed the zonally symmetric diurnal tides in the surface pressure, though they assumed a localized heating force of much more simple shape.

In summary, the basic mode of zonally symmetric diurnal tides is excited by the diabatic heating near the ground and propagates upward into the upper atmosphere, where its amplitude becomes appreciably large because of the density effect.

4. Summary and conclusion

A large zonally symmetric diurnal variation is found in temperature and wind fields in the model of the general circulation of the middle atmosphere. The u and Φ components of this variation are symmetric about the equator and the v component is anti-symmetric. The vertical wavelength is about 25 km. These structures are similar to those of the basic mode of zonally symmetric diurnal tides, whose equivalent depth is about 630 m.

The zonal component of total diabatic heating projected to the horizontal structure function of this mode shows a prominent diurnal change with large

amplitudes near the surface (0.3–0.4 K/day at 1000 mb). The major part of this heating is due to the turbulent exchange process between the atmosphere and ground and other processes contribute very little to this mode.

The simulated zonally symmetric diurnal variation, therefore, is the basic mode of the upward-propagating zonally symmetric tides which is thermally excited in the lower troposphere, and the amplitude of this mode becomes appreciably large in the middle atmosphere due to the density effect.

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大気大循環モデルにみられた帯状平均場の1日周期潮汐

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大気大循環モデルで再現された中層大気の温度と風の場に波数0の1日周期の変動がみられた。この変動は鉛直波長が約25 kmで、南北の構造は波数0の1日周期の大気潮汐の基本モードとよく似ている。非断熱加熱の帯状平均のうち基本モードを同じ南北構造の成分を取り出してみると、地表付近で顕著な1日周期変動をしており、その大部分は地表面からの乱流熱輸送による加熱であった。

このようなことからモデルに現れた中層大気の帯状平均場の1日周期の変動は、下部対流圏で熱的に誘起され、上方に伝搬し、密度効果により中層大気で顕在化した波数0の1日周期の大気潮汐の基本モードである。