Journal of the Meteorological Society of Japan, Vol. 73, No. 3, pp. 737–746, 1995

Creation of a Zonally Symmetric Tide due to the Interference of the Migrating Diurnal Tide and a Quasi-Stationary Wave

By Yuhji Kuroda and Masaru Chiba

Meteorological Research Institute, Tsukuba, Ibaraki 305, Japan

(Manuscript received 2 August 1994, in revised form 18 April 1995)

Abstract

An investigation was conducted into the effect of the interference of the migrating diurnal tide and a quasi-stationary wave of zonal wavenumber 1 to produce a zonally symmetric diurnal tide, making use of a general circulation model. It was found that the new zonally symmetric tide is created at the upper stratosphere in the winter hemisphere when the quasi-stationary wave amplifies. The amplitude of the new tide was found to be comparable to or larger than that of the tide propagating from the surface. This creation is expected to occur when the forced Rossby waves of zonal wavenumber 1 have large amplitude and the polar night jet-shift or warming event occurs.

1. Introduction

The zonally symmetric tide is the tidal wave with zonal wavenumber 0. This wave is unique in the sense that it is detected only through its temporal variation, and the usual zonal-mean field contains this wave. It is known that this tide is mainly excited by the inhomogeneity of sea-land contrast of solar heating. Lieberman (1991) first analyzed global structure of this tidal wave by using observed satellite data. Chiba and Shibata (1992) have analyzed preliminary results of the 10-year simulation of a general circulation model (GCM) of the Meteorological Research Institute (referred to as MRI-GSPM hereafter), and found that the zonally symmetric tide is well simulated in comparison with the observed tide (Lieberman, 1991), resulting in excitement at the surface.

In the real atmosphere, many types of waves coexist simultaneously. These waves may influence each other. Among the influences, the interference of waves is especially important. It is well known that, at times, interference between waves plays an important rôle in the general circulation of the atmosphere. Hirooka (1986) and Salby and Garcia (1987) have reported the vacillation of the zonal-mean zonal wind due to the interference between the normal-mode Rossby wave and the quasi-stationary wave. Kuroda *et al.* (1994) have reported the influence of the interference between the normal-mode Rossby waves and that between the normal-mode Rossby wave and the migrating diurnal tide.

In this paper, we would like to report on the effect of the interference between the migrating diurnal tide and quasi-stationary wave with wavenumber 1 to produce the zonally symmetric diurnal tide in a realistically simulated atmosphere. This is done through the analysis of the simulated data of a GCM as in Chiba and Shibata (1992), because there is not sufficient temporal resolution for the global observational data.

In the next section, mean features of the zonally symmetric tide and the activity of the forced Rossby waves in the model are introduced. Section 3 describes the effect of the interference on the zonally symmetric tide. Section 4 is devoted to conclusions and remarks.

2. Zonally symmetric tide and the activity of the forced Rossby wave.

2.1 Outline of the GCM and the data

The GCM used in this study is the R24L23 version of the MRI-GSPM. The model has 23 layers in the vertical, extending from the surface to 0.05 hPa and uses the spectral transformation method at a rhomboidal truncation of 24. Standard physical processes are included in the model. Effect of gravity-wave drag is replaced by a Rayleigh friction. The diurnal cycle of solar radiation is explicitly calculated, as well as the seasonal cycle. The details of the model, including its performance, can be found in Chiba *et al.* (1994), and in Shibata and Chiba (1990) for the R13L23 version of this model. The time integration

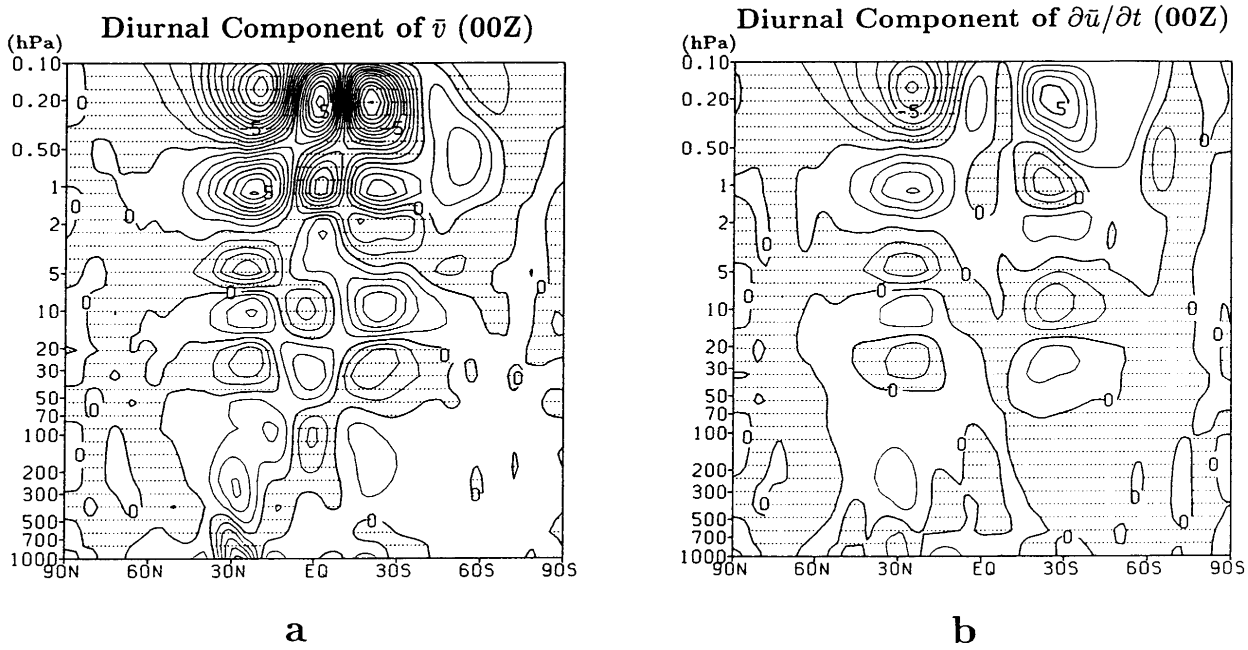

Fig. 1. Latitude-height cross section of the seasonal mean feature of (a) the zonal-mean meridional wind velocity and (b) the zonal-mean zonal wind acceleration of the zonally symmetric diurnal tide at 00Z extracted from June to August of the 6th model year. The contour intervals are 0.1 m/sec for (a), and 1×10^{-5} m/sec^2 for (b). Shaded regions denote negative values.

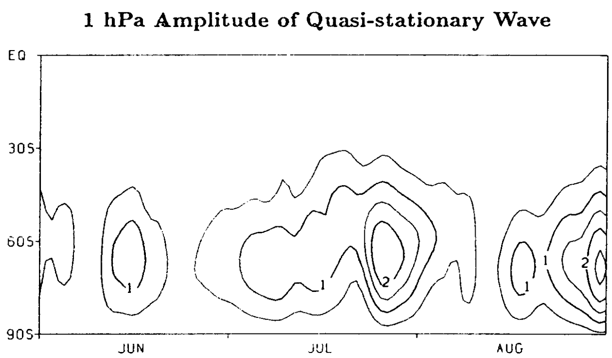

Fig. 2. Time-latitude cross section of the amplitude of the geopotential height of the quasi-stationary waves at the 1 hPa level. The contour intervals are 500 m.

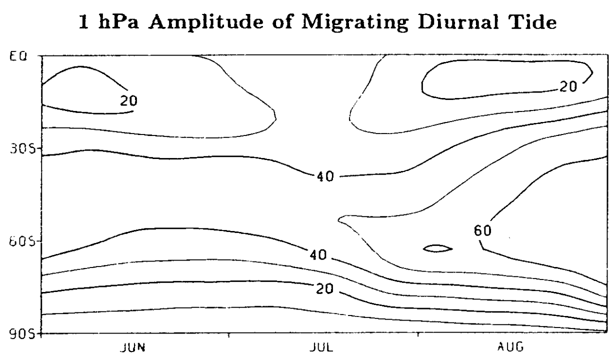

Fig. 3. Time-latitude cross section of the amplitude of the geopotential height of the migrating diurnal tide at the 1 hPa level. The contour intervals are 10 m.

has been performed for a period of 10 years, data were sampled every 2 hours.

Use is made of the simulated data from the 6th model year when the forced Rossby wave amplifies in the Southern Hemisphere in late July.

2.2 Mean feature of the zonally symmetric tide

The spectral analysis of the zonal-mean zonal wind acceleration shows that there exists a fairly broad diurnal peak as well as a semi-diurnal peak in the spectrum. To extract the zonally symmetric diurnal tide from June to August, we have filtered the zonally averaged data to select periods from 20 hours to 30 hours. To see the mean feature of the zonally symmetric diurnal tide, we have averaged the same hourly data of these filtered data from June to August. The mean profile for the meridional wind $\bar{v}$ and the zonal wind acceleration $\partial\bar{u}/\partial t$ of the zonally symmetric tide at 00Z are shown in Figs. 1a and 1b, respectively. It can be shown that these components are approximately related by the expression $\partial\bar{u}/\partial t = f\bar{v}$, where f is the Coriolis parameter. Note that this relation is exactly satisfied in the idealized zonally symmetric tide. It was also found that the phase moves downward in the ver-

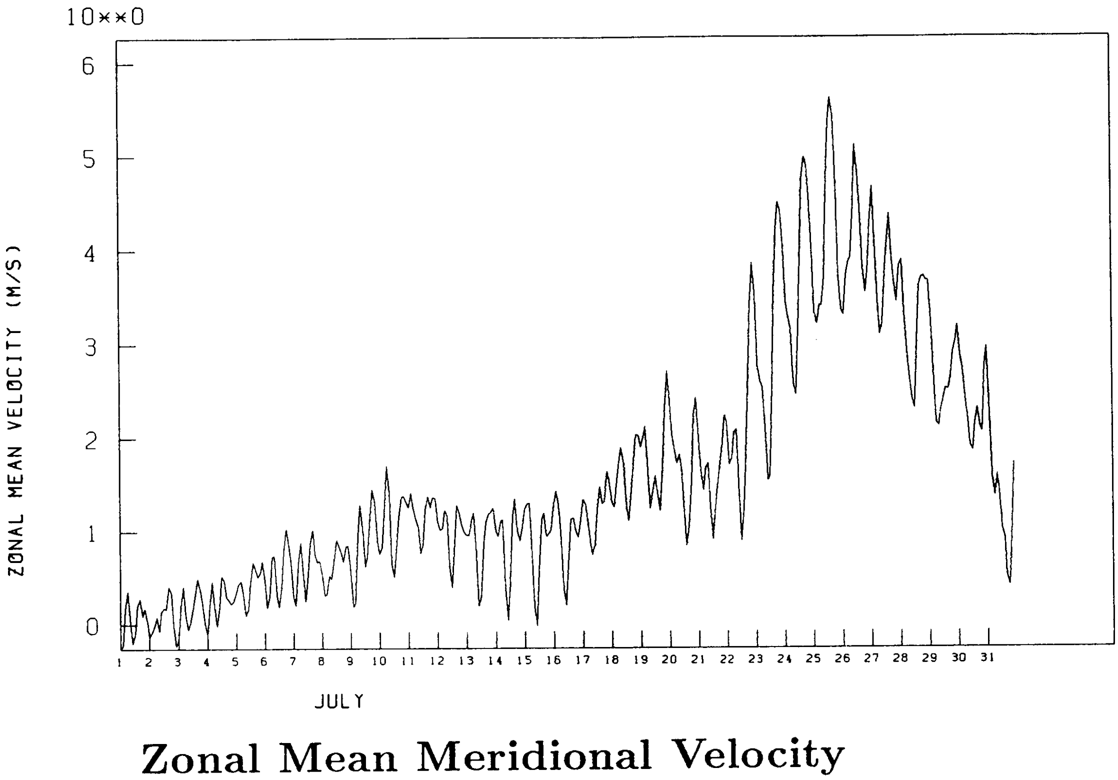

Fig. 4. Temporal variation of the zonal-mean meridional wind at 60°S for the 1 hPa level in July.

tical direction with time (not shown). This means that the wave is excited roughly at the surface.

It can be seen that the vertical wavelength is about 15 km and the meridional velocity component has two nodes in the latitudinal direction. It was found that these features are closely described by the 3rd Hough mode. A dominant Hough mode of the zonally symmetric tide in the model is different for every season, and the dominant mode is the 2nd Hough mode in winter of the Northern Hemisphere as was shown in Chiba and Shibata (1992). The large seasonal variation of the dominant Hough mode for the tide is also found in observed tide (Lieberman, 1991).

2.3 Situation of the quasi-stationary wave and the diurnal tide

Figure 2 is the time-latitude cross section of the amplitude of the geopotential height of the quasi-stationary wave (with zonal wavenumber 1) at the 1 hPa level in the Southern Hemisphere. Here, we have defined the quasi-stationary wave as the wave whose period is longer than 4 days. It can be seen that the wave is amplified late in July. When the wave is amplified, the polar night jet shifts in a poleward direction and there occurs sudden warming in the Southern Hemisphere (not shown). The analysis of this jet-shift event and comparison with observations was made in Kuroda and Yamazaki (1995).

The amplitude of the quasi-stationary wave with zonal wavenumber 2 was relatively small except for the first half period of August when the amplitude had a maximum value of 1200 m at 10 August. The amplitudes of the quasi-stationary waves with the wavenumber higher than 3 were at most 300 m, which is smaller than those of wavenumber 1 or 2.

The migrating diurnal tide with zonal wavenumber 1 has a large amplitude in the stratosphere. It exists as an external mode poleward of 30° and as an internal mode equatorward of 30°. The external mode is mainly excited by the absorption of solar ultraviolet radiation by atmospheric ozone in the upper stratosphere where ozone heating is maximized, and the internal wave is mainly excited by the water vapor in the troposphere (Chapman and Lindzen 1970). Spectral analysis shows that the migrating diurnal tide has a sharp peak at a 1 day period. Figure 3 shows the time-latitude cross section of the amplitude of the geopotential height of the migrating diurnal tide in the Southern Hemisphere. Here, the migrating diurnal tide is filtered from the original wavenumber 1 data by taking a westward-traveling wave with a period from 23 hours to 25.5 hours. It can be seen that the amplitude is almost steady during the time scale of a month, though it changes slowly as a seasonal march. As the ozone distribution has been prescribed by the data based on the observation in the model, the small variation of the amplitude poleward of 30° will be caused

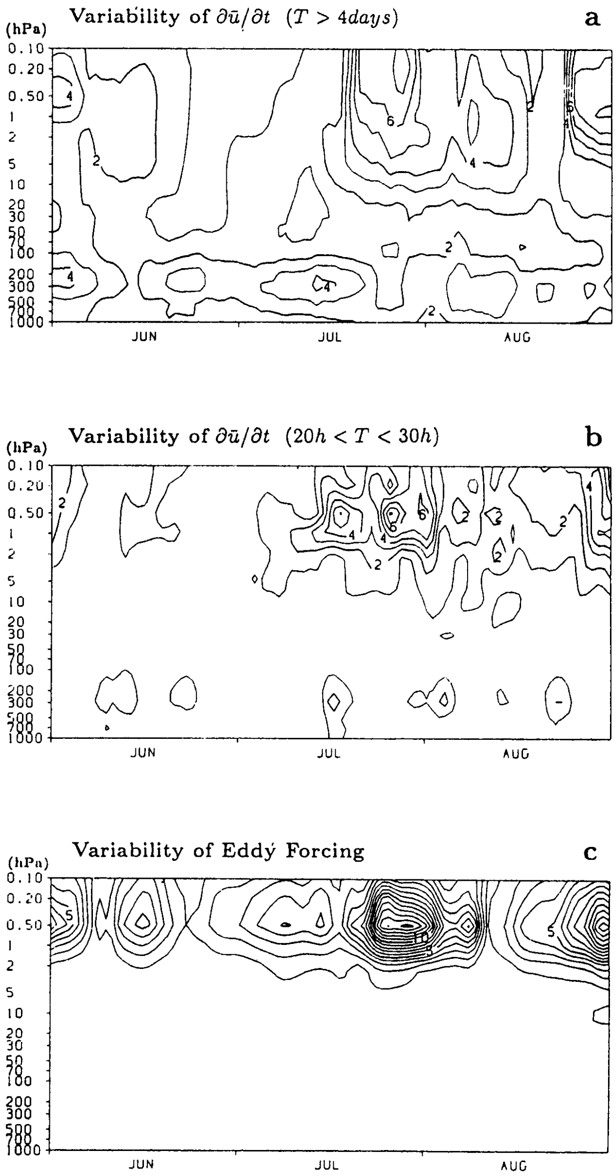

Fig. 5. Time-height cross section of the variability of the zonal-mean zonal wind acceleration for (a) the quasi-stationary component, (b) the diurnal component and (c) that for the eddy forcing. The contour intervals are 1×10^{-5} m/sec^2 in all figures.

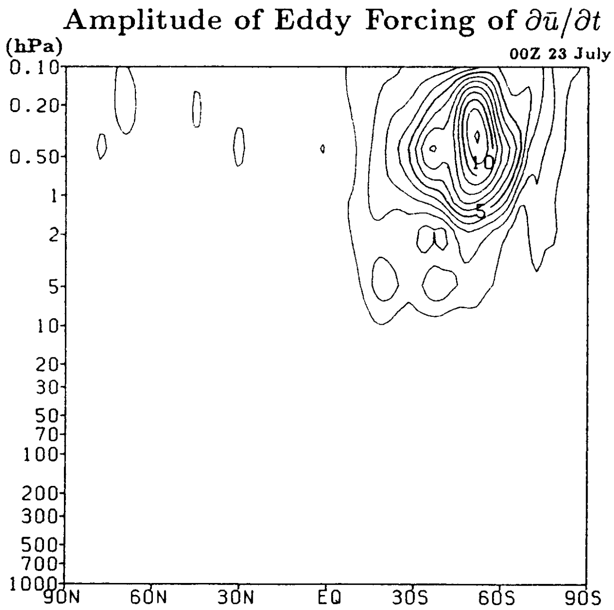

Fig. 6. Time-height cross section of the variability of the forcing due to the quasi-stationary wave and the migrating diurnal tide at 00Z of July 23. The contour intervals are 1×10^{-5} m/sec^2.

mainly by the seasonal changes of the ozone distribution. The feature of the migrating diurnal tide in this model and the comparison with the observation can be seen in Kuroda *et al.* (1994).

3. Creation of the zonally symmetric tide

There may always exist interference between any two atmospheric waves and creation of new waves in the real atmosphere. However, this secondary wave will not be so important except when the waves have sufficiently large amplitudes. Generally, a secondary wave has a large amplitude when the source waves have large amplitudes. In the real atmosphere, there exist several large-amplitude atmospheric waves. The quasi-stationary wave with zonal wavenumber 1 in the winter hemisphere is one such example. The migrating diurnal tide with zonal wavenumber 1 is another example in the upper stratosphere. Thus, when these two waves interfere, there will appear a large amplitude secondary wave with zonal wavenumber 0 as well as that with zonal wavenumber 2. This secondary wave has a period of approximately 1-day. The secondary wave with wavenumber 0 is somewhat similar to the zonally symmetric diurnal tide, because both waves have the same wavenumber and nearly the same period. In this sense, these waves cannot be distinguished from each other. Thus we shall call this secondary wave also a zonally symmetric diurnal tide.

We expect that the large interference and corresponding large-amplitude zonally symmetric tide are made when the quasi-stationary wave has a sufficiently large amplitude, because the amplitude of the diurnal tide is nearly steady. In the simulated data, this condition is satisfied in late July in the model when the forced Rossby wave with zonal wavenumber 1 is amplified in the stratosphere.

Figure 4 shows the temporal variation of the zonal-mean meridional velocity at 60°S in July. It is noteworthy that the amplitude of the tide is very large and it is comparable to that of the long term tendency which accompanies the amplification of the

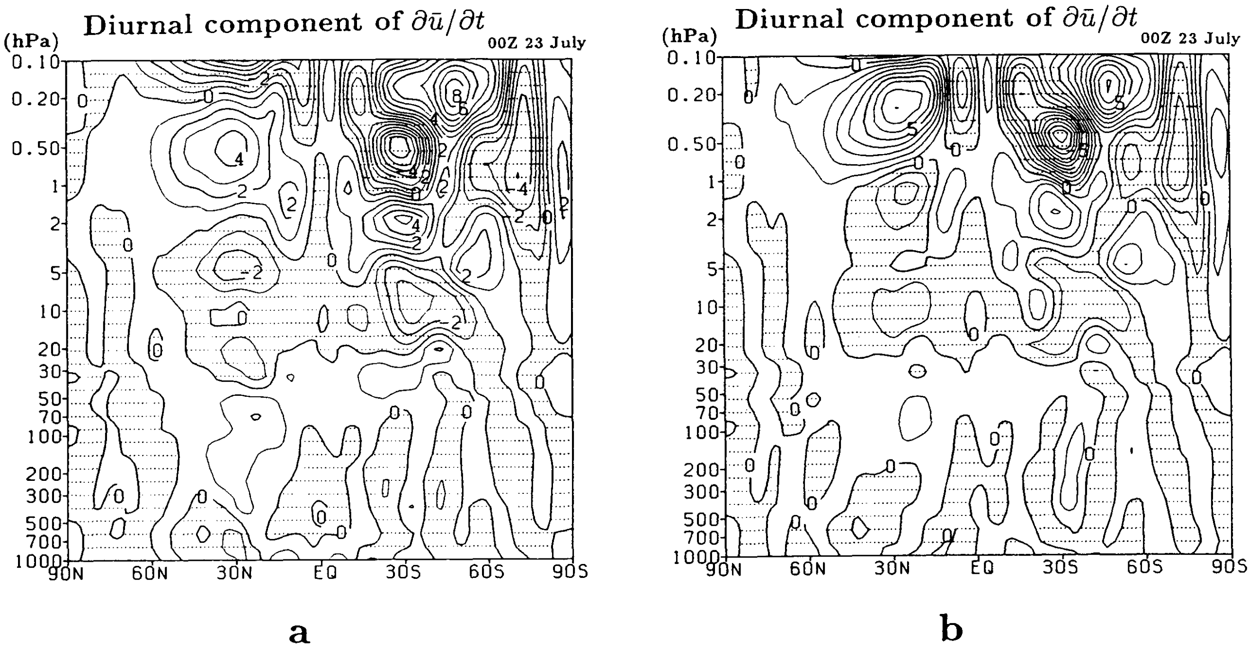

Fig. 7. Latitude-height cross section of the zonal-mean zonal wind acceleration due to (a) the zonally symmetric diurnal tide, and (b) that for only the tide due to the interference at 00Z of July 23. The contour intervals are 1×10^{-5} m/sec^2, and shaded regions denote negative values.

quasi-stationary wave in late July. This feature is also found in the zonal-mean zonal wind acceleration and the zonal-mean vertical velocity components. In this figure, it is also found that the amplitude of the tide becomes large with the activity of the quasi-stationary wave.

The long-term tendency of the variation of $\partial\bar{u}/\partial t$ is thought to be caused by the activity of the quasi-stationary wave, and the diurnal variation is directly related to that of the zonally symmetric tide. Then, to see the relation between the activity of the quasi-stationary wave and that of the zonally symmetric tide, we shall compare the variability of $\partial\bar{u}/\partial t$ for a long period and that for a diurnal period. Here, the variability $\sigma(t)$ of a function $A(t)$ is calculated by the standard deviation from the time mean state $m(t)$ and they are defined by the following equations:

$$m(t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} dt' A(t'),$$

and

$$\sigma(t) = \sqrt{\frac{1}{T}\int_{t-T/2}^{t+T/2} dt'[A(t') - m(t')]^2}, \qquad (1)$$

where T is a mean time. Figure 5a shows the time-height cross section of the variability of the zonal-mean zonal wind acceleration at 60°S whose period is longer than 4 days. Here, the variability is calculated from the mean time of 10 days. We have focused attention at 60°S, because the quasi-stationary wave has a large amplitude near this latitude. Figure 5b shows the same figure as Fig. 5a, except the wave with the period from 20 hours to 30 hours and used a mean time of 1 day. It can be seen that the amplitude of the zonally symmetric tide has a tendency to amplify with the activity of the quasi-stationary wave, as we have seen in Fig. 4.

To see the variation of the interference of the quasi-stationary wave and the migrating diurnal tide, we have calculated an eddy forcing F of $\partial\bar{u}/\partial t$ due to this interference. It is defined by

$$F = -\frac{1}{a\cos^2\phi}\frac{\partial}{\partial\phi}\left[\cos^2\phi(\overline{u_t'v_q'} + \overline{u_q'v_t'})\right] - \frac{1}{p}\frac{\partial}{\partial z}\left[p(\overline{w_t'u_q'} + \overline{w_q'u_t'})\right], \qquad (2)$$

where u_t' (v_q') is the zonal velocity component of the diurnal tide (the meridional velocity component of the quasi-stationary wave) etc. and other symbols are the same as usual conventions (see *e.g.* Andrews *et al.*, 1987). Figure 5c shows the time-height cross section of the variability of this forcing at 60°S. Here, it is calculated with a mean time of 1 day. It can be seen that the temporal variation of the eddy forcing coincides well with that of an amplitude of the zonally symmetric diurnal tide shown in Fig. 5b. The fact that the amplitude of the wave below the forcing is small is explained because the excited wave is mainly made of the external mode (see below). Thus we can conclude that the amplification of the zonally symmetric tide is mainly due to the forcing of the interference between the quasi-

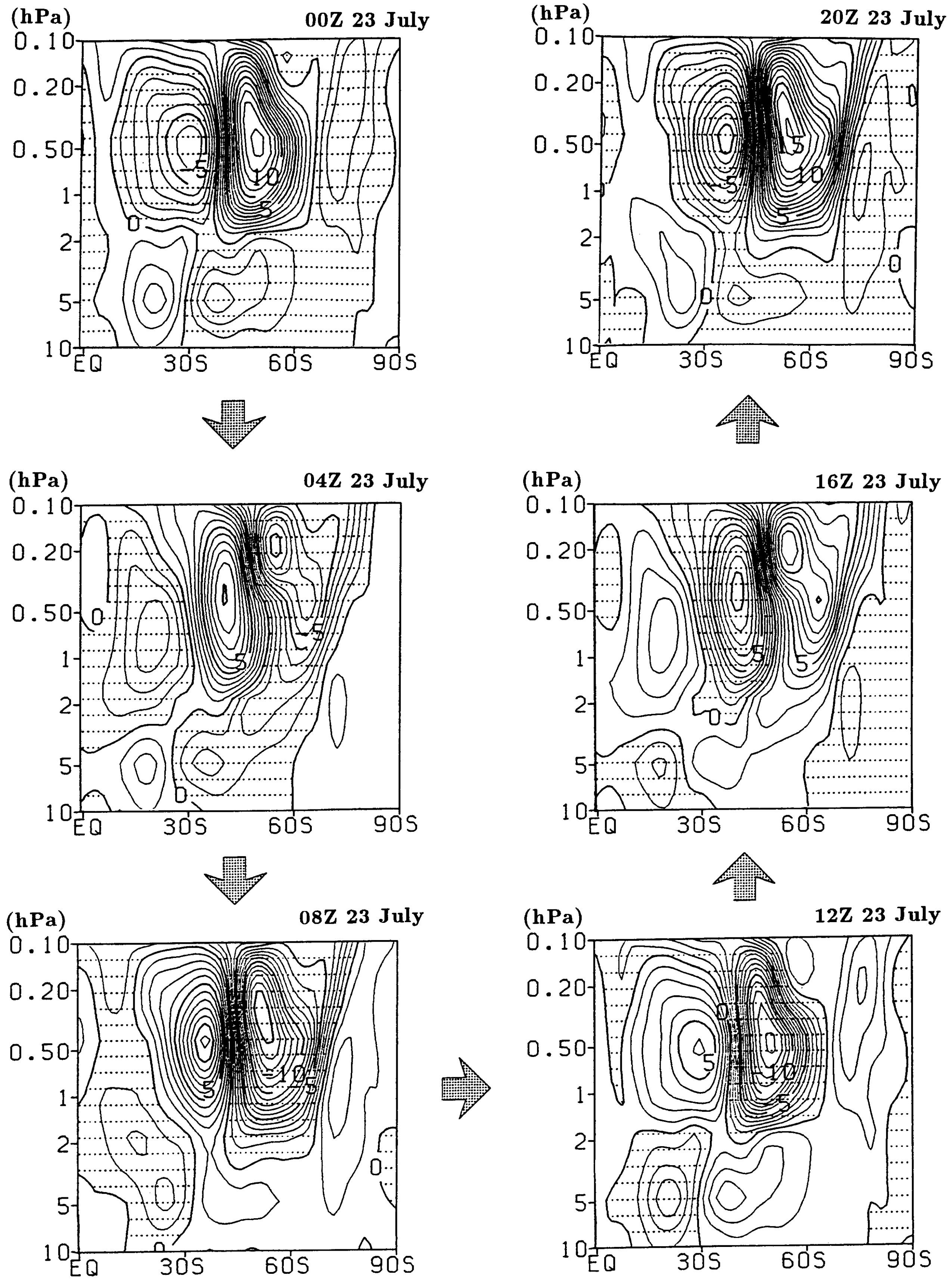

Fig. 8. Diurnal variation of the latitude-height cross section of the forcing due to the interference of the quasi-stationary wave and the migrating diurnal tide at July 23. The contour intervals are 1×10^{-5} m/sec^2, and shaded regions denote negative values.

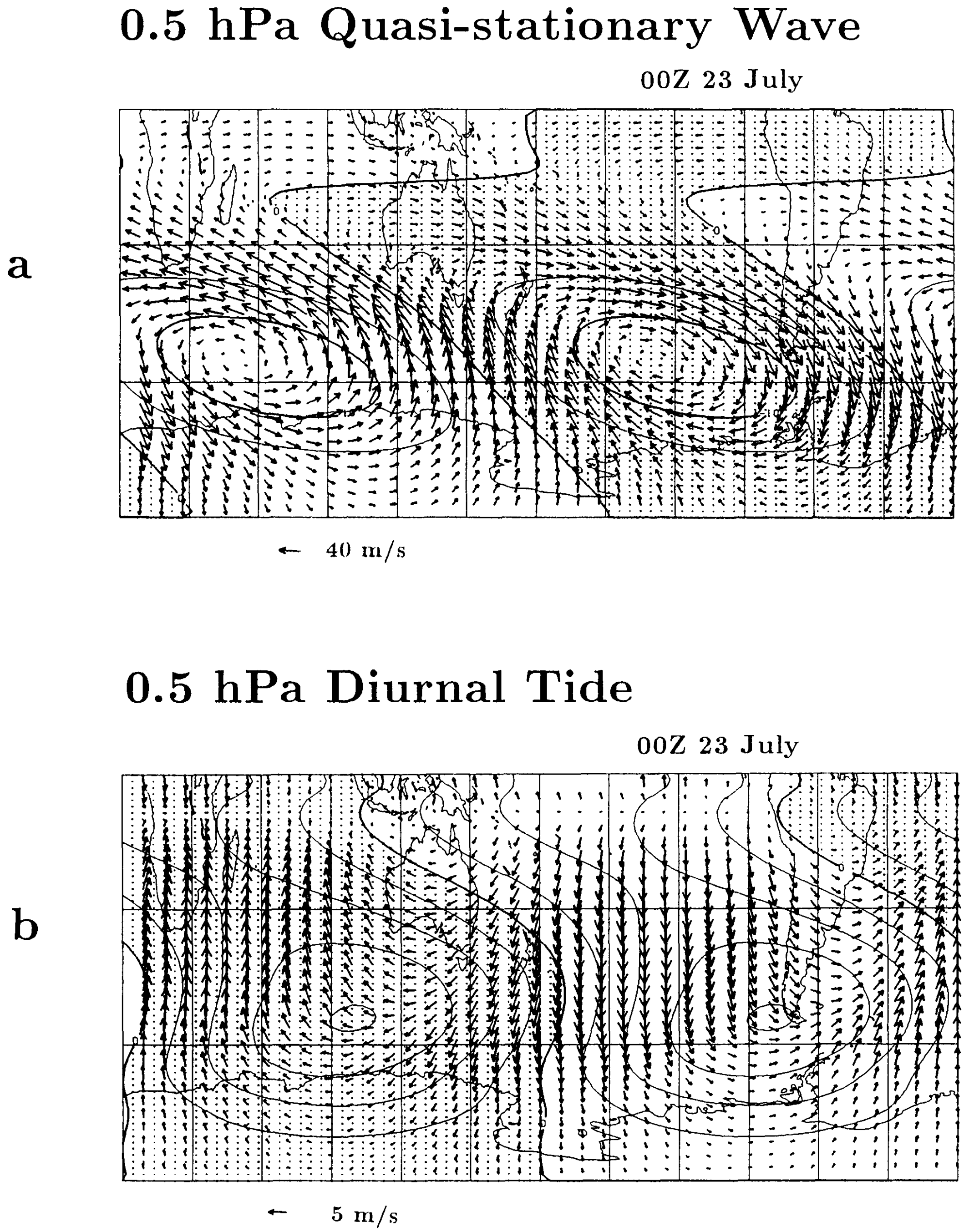

Fig. 9. Horizontal maps of (a) the quasi-stationary wave and (b) the diurnal tide in Southern Hemisphere at 0.5 hPa level at 00Z of July 23. The arrows indicate the wind, and the contours indicate the geopotential height. The contour intervals are 500 m for (a) and 20 m for (b). Shaded regions denote negative values.

stationary wave with zonal wavenumber 1 and the migrating diurnal tide.

Figure 6 shows the latitude-height cross section of the eddy forcing variability at 00Z of July 23 when the tide has a large amplitude. It can be seen that the eddy forcing is located at the region around 0.5 hPa level and 60°S. Figure 7a shows the latitude-height cross section of $\partial\bar{u}/\partial t$ for the zonally symmetric tide at the same time as in Fig. 6. It can be seen that the structure is perturbed from the mean state (shown in Fig. 1b), and it is mainly in the Southern Hemisphere where the forcing exists. Note that two types of tides coexist in this figure; one is a propagating tide from the surface and the other is created by the interference. To retain only the zonally symmetric tide due to the interference, we have removed the mean state of the tide from Fig. 7a and the result is shown in Fig. 7b. It is noteworthy that the amplitude is comparable to or larger than that from the surface (Fig. 1b) at the region above the upper stratosphere. On the other hand, the amplitude of the tide in the low altitude region seems to be relatively small. The internal mode of a tide with a 1-day period has generally a large amplitude only in the equatorial region (Andrews *et al.*, 1987). So a forcing in the poleward region is not an efficient means of exciting the internal mode of that wave. The forcing in the model exists in a relatively poleward region (Fig. 6). This means that the created wave is mainly an external mode and excitation of the mode to propagate downward is relatively small. This will explain the small amplitude in the low altitude region in Fig. 7b.

Next, let us examine how the forcing is formed by the interference. Figure 8 shows a time series of the latitude-hight cross section of the forcing on July 23. It can be seen that the forcing has changed its form in a fairly complicated way. It has a latitudinal structure as well as a vertical structure. One problem is to examine from where the structure originates. The quasi-stationary wave does not largely change its form on the time scale of a day, and the diurnal tide approximately travels around the earth without changing its form. Thus the variation of the forcing originates from the relative position of the quasi-stationary wave and the diurnal tide. Figure 9a (9b) shows the horizontal map of the quasi-stationary wave (the diurnal tide) at the 0.5 hPa level in the Southern Hemisphere. Here, the vector shows the wind and the contour shows the geopotential height. We have focused attention on the 0.5 hPa level where there exist maxima of the forcing (see Fig. 8). The main contribution of the eddy forcing comes from the first term of Eq. (2). The meridional structure of forcing (shown in Fig. 8) comes mainly from the wind variation of the quasi-stationary wave (Fig. 9a). Figure 10 shows the vertical phase variations of the meridional wind of the quasi-stationary wave (solid line) and the diurnal tide (dashed line) at 30°S at 00Z of July 23.[1] Here the phase angle is defined by the longitude where the meridional wind has a maximum value.

The westerly tilt of the quasi-stationary wave with height at the stratosphere is well simulated compared with the observations. The easterly tilt of the wave in the troposphere at this latitude also sometimes appears in the observational data. In the upper stratosphere, the vertical phase change of the diurnal tide agrees well with the observations at 30°N by Reed *et al.* (1969).[2] It is also similar to the theoretical calculation by Lindzen (1967) in the middle stratosphere and below. As the phase change of the quasi-stationary wave is relatively small compared with that of the diurnal tide, the vertical structure of the forcing is thought to be mainly due to to the vertical structure of the diurnal tide. As a result, it is found that the forcing pattern comes from the structure of these two waves.

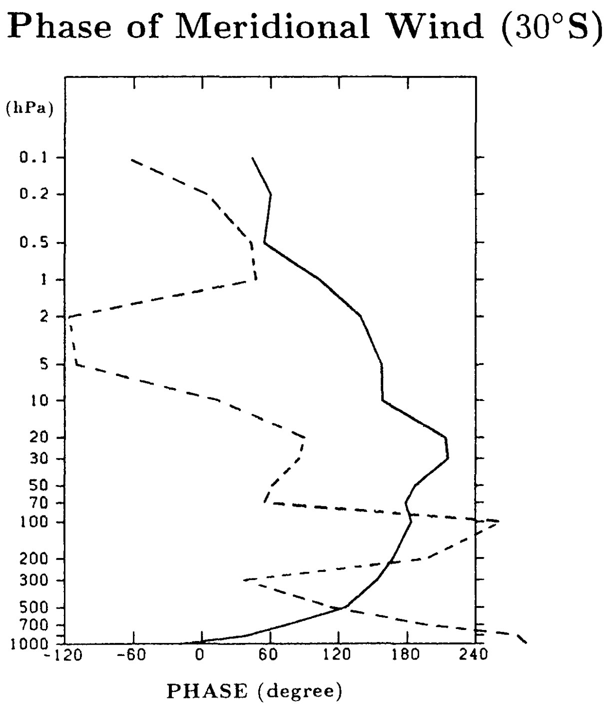

Fig. 10. Vertical variations of the phase of the quasi-stationary wave (solid line) and the diurnal tide (dashed line) at 30°S at 00Z of July 23.

4. Conclusion and Remarks

We have found in the simulated data of the GCM that an amplification and a large deformation of the zonally symmetric diurnal tide occur when the migrating diurnal tide and the quasi-stationary wave with zonal wavenumber 1 interact. This phenomenon is found to occur due to the generation of a new zonally symmetric tide in the upper stratosphere. The wave is made by the eddy forcing with approximately 1-day period in the upper stratosphere arising from the interference of the migrating tide and quasi-stationary wave. This phenomenon is prominent when the quasi-stationary forced Rossby wave is amplified and the polar night jet shift or sudden warming occurs, as the amplitude of the migrating diurnal tide is steady on timescales of a month. When the quasi-stationary wave is amplified, it is

1 Note the ambiguity in determination of the phase profile in the case of large phase changes because of the relatively poor vertical resolution of the GCM.

2 Note that the phase of the meridional wind component of the diurnal tide in the Southern Hemisphere is completely out of phase with that in the Northern Hemisphere.

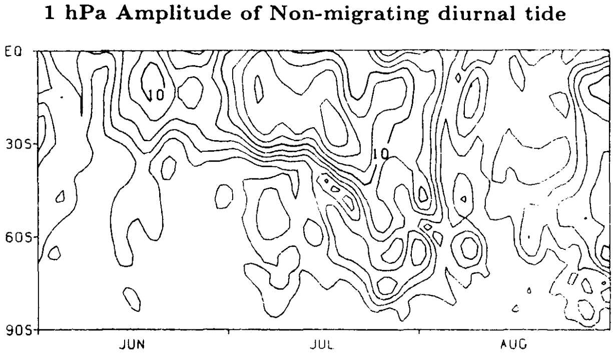

Fig. 11. Time-latitude cross section of the amplitude of the geopotential height of the westward traveling non-migrating diurnal tide with zonal wavenumber 2 at 1 hPa level. The contour intervals are 2 m.

found that the amplitude of the new zonally symmetric tide becomes comparable to or larger than that of the wave propagating from the surface.

We have focused our attention on the creation of the zonally symmetric tide due to the interference of the migrating diurnal tide and the quasi-stationary wave with wavenumber 1 in this paper. However, there may also exist the creation of the westward-traveling non-migrating diurnal tide with a zonal wavenumber 2 through this interference. Figure 11 shows the time-latitude cross section of the amplitude of that tide at the 1 hPa level. This wave is filtered from the zonal wavenumber 2 data with periods from 20 to 30 hours. It can be seen that the tide has a large amplitude at high latitudes when the quasi-stationary wave has a large amplitude (see Fig. 2). As the amplitude of the migrating diurnal tide is steady on timescales of a month, this shows that the tide is also created by this interference. Though the tide has a large amplitude also in the equatorial region, it is an internal mode and is propagating from below. The mode which can be seen at the high latitude, on the other hand, will be mainly an external mode, as we have explained before about the zonally symmetric tide. In fact, it can be seen that the amplitude rapidly decreases as the altitude decreases (not shown).

There may also exist the creation of the zonally symmetric semi-diurnal tide due to the interference between the quasi-stationary zonal wavenumber 2 wave and migrating semi-diurnal tide. However, the peak of the migrating semi-diurnal tide exists in the equatorial region and the maximum amplitude of the quasi-stationary wave with zonal wavenumber 2 exists poleward of that of the wave with zonal wavenumber 1. Thus the contribution of these waves to the creation of the zonally symmetric tide will be generally smaller than that of the zonal wavenumber 1 case.

Recently, Berger (1994, personal communication) has discussed the creation of the new waves due to the non-linear wave-wave interaction between the tidal wave and the stationary wave at the mesopause height by using a mechanistic model. His work is concerned with the experiment of the creation of the waves due to the non-linear wave-wave interaction. It will contain waves due to the higher order non-linear interactions as well as those due to simple interference. There may exist a similar mechanism for the creation of the new tide in our model. Creation of the tide due to the higher order non-linear interaction process is not discussed here.

The result in this paper is only obtained in the simulated data. However, this mechanism of the creation of a new tide is expected to work in the real atmosphere. It might occur in the winter hemisphere. We hope this phenomenon will be observed in the future.

Acknowledgments

The authors are grateful for Drs. K. Yamazaki, K. Shibata and H. Kondo for useful discussions and encouragement. We also thank anonymous reviewers for the critical reading of the manuscript. This research is partly supported by the Science and Technology Agency under the research program for the Arctic region. The simulation was performed with the HITAC S820 of Hitachi, Ltd.

References

Andrews, D.G., J.R. Holton and C.B. Leovy, 1987: *Middle Atmosphere Dynamics.* Academic Press, 489 pp.

Chapman, S. and R.S. Lindzen, 1970: *Atmospheric Tides.* Reidel, Dordrecht, Netherlands, 200 pp.

Chiba, M. and K. Shibata, 1992: Zonally symmetric diurnal tides simulated with a general circulation model. *J. Meteor. Soc. Japan*, **70**, 789–794.

Chiba, M., K. Yamazaki, K. Shibata and Y. Kuroda, 1994: The description of the MRI atmospheric spectral GCM (MRI-GSPM) and its mean statistics based on 10-year integration. Submitted to *Papers in Meteorology and Geophysics* .

Hirooka, T., 1986: Influence of normal mode Rossby waves on the mean field: Interference with quasi-stationary waves. *J. Atmos. Sci.*, **43**, 2088–2097.

Kuroda, Y., M. Chiba, K. Shibata and K. Yamazaki, 1994: Interference of the diurnal tide and normal-mode Rossby waves in the summer stratosphere. *J. Meteor. Soc. Japan*, **72**, 555–567.

Kuroda, Y. and K. Yamazaki, 1995: Poleward jet-shift in the southern hemisphere winter simulated with a general circulation model. Submitted to *Papers in Meteorology and Geophysics* .

Lieberman, R.S, 1991: Nonmigrating diurnal tides in the equatorial middle atmosphere. *J. Atmos. Sci.*, **48**, 1112–1123.

Lindzen, R.S, 1967: Thermally driven diurnal tide in the atmosphere. *Quart. J. Roy. Meteor. Soc.* **93**, 18–42.
Reed, R.J., M.J. Oard and M. Sieminski 1969: A comparison of observed and theoretical diurnal tidal motions between 30 and 60 kilometers. *Mon. Wea. Rev.*, **97**, 456–459.
Salby, M.L. and R.R. Garcia, 1987: Vacillations induced by interference of stationary and traveling planetary waves. *J. Atmos. Sci*, **44**, 2679–2711.
Shibata, K. and M. Chiba, 1990: A simulation of seasonal variation of the stratospheric circulation with a general circulation model. *J. Meteor. Soc. Japan*, **68**, 687–703.

日潮汐と準停滞波動の干渉による帯状対称潮汐の生成について

黒田友二・千葉　長
(気象研究所)

1日潮汐と波数1の準停滞性波動の干渉が帯状対称潮汐の生成に与える影響を大循環モデルを用いて調べた。その結果、波数1の準停滞性波動が増幅する時これらの波動の干渉によって上部成層圏で新しい帯状対称潮汐が生成される事が分かった。この新しい潮汐の振幅は地表面から伝搬してくる通常の潮汐の振幅よりもしばしば大きくなる。この新潮汐は波数1の強制ロスビー波が大きく増幅し極夜ジェットのシフトや突然昇温がおきる時に生成すると考えられる。