Equatorial Waves in a General Circulation Model Simulating a Quasi-Biennial–Oscillation

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Abstract

The quasi-biennial oscillation (QBO) in the equatorial lower stratosphere has been well simulated in the first version of the Center for Climate System Research / National Institute for Environmental Studies (CCSR/NIES) atmospheric general circulation model (Takahashi, 1996). The model horizontal resolution is T21 with 60 layers of vertical resolution of about 500 m in the upper troposphere and lower stratosphere, with a moist convective adjustment scheme. The period of the simulated oscillation is 1.5 years, which is slightly shorter than that observed.

The equatorial wave behavior in the model is examined using the spectral analysis method. The westerly acceleration phase of the QBO-like oscillation in the model is due to Kelvin waves and eastward-propagating gravity waves. The easterly acceleration phase of the oscillation is due to westward-propagating $n = 1$ equatorial gravity waves, random westward-propagating gravity waves and Rossby waves propagating from the mid-latitudes in the northern winter hemisphere to the equatorial region. The Rossby-gravity wave has a role in the easterly acceleration of the QBO-like oscillation in the present general circulation model.

1. Introduction

The quasi-biennial oscillation (QBO) in the equatorial lower stratosphere is an interesting phenomenon, which is explained by Holton and Lindzen (1972) using a wave mean-flow interaction theory. In their theory, the Kelvin and Rossby-gravity waves, which propagate from the tropical troposphere into the lower stratosphere and are dissipated by Newtonian cooling, produce the westerly and easterly phases of the QBO, respectively. Yanai and Maruyama (1966) discovered Rossby-gravity waves of zonal wave number 4 and a period of about 4.5 days. Wallace and Kousky (1968) found Kelvin waves of zonal wavenumber 1 or 2 and a period of about 15 days.

Recently, Maruyama (1994) found a short period eastward-propagating wave of which the wave momentum flux is comparable to that of the so-called

Wallace-Kousky wave (see also Sato *et al.*, 1994). The observations suggest that the Wallace-Kousky wave is not alone in making a contribution to the westerly acceleration phase, but is aided by short-period Kelvin, inertia-gravity, and gravity waves.

On the other hand, the deficiency in the easterly momentum flux of the Rossby-gravity wave has already been mentioned by Lindzen and Tsay (1975). They suggested that another candidate is the meridional mode number $n = 1$ equatorial gravity wave which was not resolved in their analysis (see also Takahashi and Holton (1991) for a mechanistic model study). Recently, Takayabu (1994a, b) found $n = 1$ westward-propagating equatorial gravity wave signals in the satellite cloud data. The $n = 1$ equatorial gravity wave has about 2-day period. However, the $n = 1$ equatorial gravity wave behavior is not very clear in the stratosphere (*cf.* Maruyama, 1994; Sato *et al.*, 1994).

Concerning general circulation model (GCM)

studies, Hayashi and Golder (1994) demonstrated that the realistic N30 GFDL SKYHI general circulation model adequately produces both Kelvin and Rossby-gravity waves. They also suggested that the weakness of the QBO simulated in the model is due to small-scale gravity waves not being adequately produced.

Recently, a QBO-like oscillation in a three-dimensional mechanistic model has been obtained. The horizontal resolution is the same as T106, however, the model resolves 1/5 sector only in the zonal direction and has an aqua-planet condition on the surface (Takahashi and Shiobara, 1995; Takahashi and Kumakura, 1995). The downward-propagating structure and amplitude of the oscillation are similar to that of the observed QBO. However, the period of the oscillation is about 400 days, half as long as that of the observed QBO in the equatorial lower stratosphere. Further, the height of the simulated oscillation is about 15 km higher than that of the observed QBO. In the model, $n = 1$ westward-propagating equatorial gravity waves and random eastward-propagating gravity waves are responsible for the production of the QBO-like oscillation.

More recently, the QBO has been fairly well simulated by use of a T21 60-layer (T21L60) general circulation model with moist convective adjustment scheme (Takahashi, 1996). The damping time for the maximum wavenumber in the fourth-order horizontal diffusion was 20 days. The 20-day damping time is about one-order of magnitude less than that used in standard general circulation models (*cf.* Boville, 1991). The period of the simulated oscillation is 1.5 years, which is slightly shorter than that observed, and the height of the oscillation is slightly higher than that observed. On the other hand, an idealized T21L60 mechanistic model with an aqua-planet surface, no annual cycle and no mountains has about a 4-year QBO-like oscillation, as will be shown below.

In the present paper, equatorial wave behavior in the model is presented. The model used in the present work is briefly mentioned in Section 2. In Section 3, numerical results and spectral analysis of equatorial waves contributing to the QBO-like oscillation are presented. Finally, concluding remarks are given in Section 4.

2. Model

The model is the first version of the atmospheric general circulation model which was developed at the Center for Climate System Research / National Institute for Environmental Studies (CCSR/NIES). The basic features of the model can be found in a paper by Numaguti (1993). Newly implemented physical processes are discussed in Numaguti *et al.* (1995). A detailed description of the radiation scheme can be found in Nakajima *et al.* (1995).

The horizontal resolution is T21, which corresponds to a grid spacing of about 600 km. There are 60 layers in the vertical, having about 500 m vertical resolution in the upper troposphere and lower stratosphere. The top level of the model is located at about 0.5 mb (approximately 50 km, the 0.0005 sigma level).

Following previous experiments (Takahashi and Shiobara, 1995; Takahashi and Kumakura, 1995), the moist convective adjustment scheme is also used as the cumulus parameterization in this experiment, although the standard convection scheme of the CCSR/NIES GCM is the prognostic Arakawa-Schubert scheme (Numaguti *et al.*, 1995). The magnitude of the minimum vertical eddy viscosity coefficient is set to $0.1 \text{ m}^2 \text{ s}^{-1}$, even though the Mellor-Yamada level-2 closure scheme is used as the vertical eddy viscosity in the free atmosphere, as well as in the bottom boundary layer.

As mentioned in the Introduction, the damping time for the maximum wavenumber in the fourth-order horizontal diffusion is 20 days, being about one-order of magnitude less than that usually used in general circulation models. This small value of the horizontal diffusion is a necessary characteristic of the present GCM experiment of the QBO, as well as high vertical resolution. It is noted that there is no oscillation in the case of 4-day damping time (see Takahashi, 1996). The effects of orographically excited subgrid-scale internal gravity waves are included through McFarlane's parameterization (1987). The dry convective adjustment scheme is also applied in the stratosphere to represent wave breaking. The other processes and schemes are the same as those in the standard GCM experiments. For example, use is made of a climatological sea-surface temperature distribution and realistic mountains, among others.

The initial condition is an isothermal atmosphere at rest. The first day of the simulation is the 1st of January of the zeroth year (day=0), and 360 days constitutes one year. A strong Rayleigh damping (1-day damping time) near the top boundary is used during the first three months of the simulation. After three months, a smaller value (10 days near the top boundary) of Rayleigh friction is used.

3. Results

3.1 A QBO-like oscillation and net wave activity over the equator

Figure 1 shows the time-height section of the simulated mean zonal wind over the equator. A QBO-like oscillation in the equatorial middle stratosphere (about 15 mb) can be clearly seen in Fig. 1. The amplitude of the zonal-wind of the oscillation is about 20 ms^{-1} (maximum westerlies of about 20 ms^{-1} ; maximum easterlies of about -15 ms^{-1}). The westerly phase of the oscillation is, however, stronger

Fig. 1. Time-height section of the simulated mean zonal wind over the equator. The time coordinate is from day 0 (1 Jan. 0-th year) to day 1122.5. The contour interval is 6 ms^{-1} . The solid lines represent westerlies and the dashed lines easterlies. The vertical lines in the figure indicate the wave analysis time of days 375–405.

Fig. 2. Latitude-height section of the time-averaged mean zonal wind for days 375–405 (16 Jan. first year–16 February). The contour interval is 7.5 ms^{-1} . The solid lines are westerlies; dashed lines are easterlies.

than the easterly phase in the model simulation. This is the reverse of that observed (see Naujokat, 1986: the maximum easterlies are about -30 ms^{-1} ; the maximum westerlies 15 ms^{-1}). The height of the oscillation is slightly higher than that of the QBO. Mainly the easterly phase is too high. This is related to the general weakness of the easterly phase. The

period of the simulated oscillation is 1.5 years, being slightly shorter than that of the observed QBO. The simulated oscillation, in other respects, resembles the QBO very well.

Figure 2 shows the latitude-height section of mean zonal wind time-averaged over days 375–405 (northern hemisphere winter from Jan. 16 of the first year

Fig. 3. Latitude-height section of the time-averaged vertical wave momentum flux $\overline{u'w'}$ from days 375 to 405. The contour interval is $1.2 \times 10^{-2} \text{ m}^2 \text{ s}^{-2}$. The solid lines represent westerly upward momentum flux, and the dashed lines easterly upward momentum flux. The easterly acceleration phase of the QBO is in the middle stratosphere at days 375–405.

to Feb. 16). The basic structure is similar to that of the observed January-mean zonal wind, even though the westerlies in the winter hemisphere are stronger than that observed. This may be due to the weaker 10-day Rayleigh damping near the top boundary. There are easterlies at $\sigma=0.001$ (about the 1 mb level) over the equator. This is the easterly phase of the semiannual oscillation around the stratopause level. But there are no westerlies of the semiannual oscillation at the equinoxes in the model simulation, as shown in Fig. 1. Around the $\sigma=0.015$ (about 15 mb) level over the equator, the easterly phase of the QBO is seen, and there are westerlies of the QBO around the $\sigma=0.05$ (about 50 mb) level. The meridional extent of the QBO is approximately 1500 km. The value is comparable to that observed (*cf.* Wallace, 1973). In the next sub-section, a wave analysis is performed in this time period. There are westerlies in the equatorial middle and upper troposphere. This is a defect of the low-resolution CCSR/NIES GCM.

Figure 3 shows a latitude-height section of the time-averaged vertical wave momentum flux $\overline{u'w'}$ for days 375–405. As noticed from Fig. 1, this time corresponds to the easterly phase of the QBO in the middle stratosphere and westerly phase in the lower stratosphere. The vertical wind w is approximated by the following equation as in our previous paper (Takahashi and Kumakura, 1995):

$$p\left(\frac{\dot{\sigma}}{\sigma} + \frac{d \ln p_s}{dt}\right) = \omega = \frac{dp}{dt} \approx -\frac{p}{H}w \quad (3-1)$$

where H is the scale height (a value of 7 km is as-

sumed). There is westerly momentum flux upward in the lower and middle stratosphere, and easterly momentum flux upward in the troposphere over the equator. Note here that the part of the vertical Eliassen-Palm (EP) flux

$$\frac{(2\Omega \sin \phi - \frac{\partial(\bar{u} \cos \phi)}{a \cos \phi \partial \phi})}{N^2} \frac{R}{H} \frac{v'T'}{v'T'}$$

(this is an approximate form; see Takahashi and Holton, 1991) is much smaller than $\overline{u'w'}$ near the equator (not shown). Therefore, the acceleration of the mean zonal wind over the equator can be estimated from the divergence of $\rho u'w'$.

Figures 4a and 4b show the vertical distributions of density weighted momentum flux $\rho u'w'$ and the convergence of momentum flux $-\frac{1}{\rho} \frac{d(\rho u'w')}{dz}$ over the equator, respectively. As suggested from Fig. 3, the westerly momentum flux is positive in the whole stratosphere and negative in the upper troposphere. The convergence of wave momentum flux (the solid line in Fig. 4b) induces westerly acceleration in the upper stratosphere and lower stratosphere. The magnitude is approximately $4 \times 10^{-6} \text{ ms}^{-1}$ ($\sim 10 \text{ ms}^{-1}/\text{month}$). The value is rather high but realistic. There is easterly acceleration in the middle stratosphere. The magnitude of easterly acceleration is about $-1 \times 10^{-6} \text{ ms}^{-2}$ in the middle stratosphere. The magnitude is slightly small to produce the QBO-like oscillation at these altitudes. The westerly acceleration is stronger than the easterly acceleration. This produces a stronger westerly than easterly in the oscillation, as mentioned above.

Fig. 4. (a) Vertical distribution of the density-weighted vertical wave momentum flux $\overline{\rho u'w'}$ meridionally averaged from -8°S to 8°N . The unit is $10^{-3} \text{ kg m}^{-1} \text{ s}^{-2}$. (b) Same as Fig. 4a, except for momentum flux convergence $-\frac{1}{\rho} \frac{d(\overline{\rho u'w'})}{dz}$ (solid line) and non-linear advection term $-\overline{w} \frac{\partial \overline{u}}{\partial z}$ (dashed line). The unit is 10^{-6} m s^{-2} .

The non-linear advection term $-\overline{w} \frac{\partial \overline{u}}{\partial z}$ has a rather complicated structure (the dashed line in Fig. 4b). Note, however, that the upwelling term has positive maxima in each of the descending shear zones. Also, the magnitude is relatively less than the wave momentum flux convergence (the maximum amplitude is at most $1 \times 10^{-6} \text{ ms}^{-2}$ in the middle and lower stratosphere, and the vertical scale is small). The vertical advection term could still play a significant role in the present simulation.

Figures 5a and 5b show the meridional momen-

tum flux $\overline{u'v'}$ at days 375–405 (from Jan. 16 of the first year to Feb. 16) in the northern hemisphere winter and the convergence of momentum flux $-\frac{1}{\cos^2 \phi} \frac{\partial}{\partial y} (\overline{u'v'} \cos^2 \phi)$ vertically averaged from sigma 0.1 to 0.01, respectively. The magnitude of the easterly acceleration is approximately $-2 \times 10^{-6} \text{ ms}^{-2}$ over the equator. The value is almost the same as that estimated by Dunkerton (1983). This value is also larger than the easterly acceleration in the middle stratosphere due to the convergence of vertical wave momentum flux $\overline{\rho u'w'}$ (see

Fig. 5. (a) Latitude-height section of the time-averaged horizontal wave momentum flux $\overline{u'v'}$ from days 375 to 405. The contour interval is $5 \text{ m}^2\text{s}^{-2}$. There is the southward easterly wave momentum flux from the winter hemisphere in the middle stratosphere. (b) Meridional distribution of mean zonal wind (solid line) and the convergence of horizontal wave momentum flux $-\frac{1}{\cos^2 \phi} \frac{\partial}{\partial y} (\overline{u'v'} \cos^2 \phi)$ (dashed line) vertically averaged from $\sigma=0.1$ to 0.01 . The unit is ms^{-1} for mean zonal wind and 10^{-6} m s^{-2} for the convergence of momentum flux, respectively.

Fig. 4b). The horizontal wave momentum flux from the mid-latitude in the northern winter hemisphere, therefore, has a role to play in the easterly acceleration of the model QBO. In the other seasons, there is a small contribution of the easterly acceleration phase of the equatorial QBO. Low horizontal resolution may allow laterally propagating Rossby waves to influence the QBO more than would be found in a high-resolution experiment. This problem, however, is still open to question.

It is noted here that a mechanistic three-dimensional global model, which has the same resolution (T21L60) and the same damping time of fourth-order horizontal diffusion, but without mountains and having no annual cycle, has a QBO-like os-

cillation in the middle and lower stratosphere with period about 4 years, as shown in Fig. 6. Note that the easterly phase descent is slower, and that this is largely responsible for the longer QBO period. On the other hand, the period of oscillation in the GCM simulation is 1.5 years, as shown in Fig. 1, about half of that in the mechanistic model result. A dominant dynamical difference of the two models may be Rossby waves propagating from the mid-latitudes to the equatorial region. The mechanistic 'no-mountains' experiment has much smaller Rossby waves from mid-latitudes due to the absence of topography, and therefore it is orographically excited waves that contribute to the QBO in the GCM experiment. On average, the contri-

Fig. 6. Time-height section of mean zonal wind over the equator in the case of a T21L60 mechanistic model. The time coordinate is from day 0 to 3000. The contour interval is 8 ms^{-1} . The solid lines represent westerlies and the dashed lines easterlies.

bution of the easterly acceleration due to Rossby waves from the mid-latitudes is probably about half ($-2 \times 10^{-6} \text{ ms}^{-2}/4\text{seasons} \approx -0.5 \times 10^{-6} \text{ ms}^{-2}$) the vertical wave momentum flux.

Conclusively, the dominant contribution to the QBO-like oscillation in the present model is the vertical wave momentum flux convergence $-\frac{1}{\rho} \frac{d(\rho u'w')}{dz}$. The magnitude of the easterly flux is smaller than the westerly flux. The meridional momentum flux convergence by Rossby waves from the mid-latitudes into the equatorial region adds to the contribution from the smaller easterly vertically upward momentum flux. The non-linear advection term has a contribution to the acceleration of the QBO-like oscillation.

The spectral analysis of equatorial waves in the model is shown in Subsection 3.2.

3.2 Wave analysis

In this subsection, equatorial wave behavior in the general circulation model simulating the QBO-like oscillation is examined. As mentioned above, the wave analyses are performed around days 375–405 of the simulation (the easterly acceleration phase of the QBO-like oscillation in the middle stratosphere and the westerly acceleration phase in the lower stratosphere, as shown in Fig. 1). The calendar time is the northern hemisphere winter from January 16 to February 16 of the first year. The sampling time interval is 6 hours, so the Nyquist time is 12 hours, as in the T106S5 model (see Takahashi and Kumakura, 1995).

3.2.1 Precipitation

Figure 7 shows the time-longitude section of precipitation at 3°S at days 375–405. The precipitation is strong around 150°E longitude. Similar structures are also around 60°E and 60°W . There is a steady component and moving component. These structures are similar to those in a mechanistic T21L45 model with larger horizontal diffusion by one order, with an aqua-planet surface boundary condition as in the previous paper (Takahashi and Kumakura, 1995). But the precipitation is more confined to localized regions in the present case.

The spectral analysis of the precipitation does not show a clear wavenumber 1 signal. It has a rather scattered wavenumber distribution. The dominant wavenumbers are 1, 3 and 6 (not shown). The dominant signal in frequency is the steady component which is usually seen in the standard GCM simulation (*cf.* Hayashi and Golder, 1994). From the precipitation it is difficult to see the high-frequency signal corresponding to fast gravity waves.

3.2.2 Wave signals in the middle stratosphere

Before the spectral analysis, a time-latitude section of the eddy component of zonal wind at $\sigma=0.03$ (about the 30 mb level) at days 375–405 is shown in Fig. 8. The position is the zero longitude in the model. Complicated structures are shown, having many time scales from about 10 days to a 1-day period. The meridional structure is also very complicated. It has some modal structures and an asymmetric structure about the equator.

Fig. 7. Longitude-time section of the precipitation at 3°S from days 375 to 405. The longitude is from 0 to 360 degrees. The contour interval is 500 Wm^{-2} (about 500 mm/month).

Fig. 8. Time-latitude section of eddy-component of zonal wind from days 375 to 405 at longitude 0 degree. The contour interval is 4 ms^{-1} . The solid lines represent westerlies and the dashed lines easterlies.

1) Westward-propagating waves

Figure 9a shows a frequency-latitude section of the vertical wave momentum flux $\overline{u'w'}$ at $\sigma=0.03$ (about 30 mb level) at days 375–405. This level corresponds to that of the minimum density-weighted westerly upward wave momentum flux (see Fig. 4a). The zonal wavenumber is integrated from 1 to 5. Around the stationary com-

ponent, the easterly upward momentum flux dominates in the northern winter hemisphere. The waves of zonal wavenumbers 1–3 are dominant. These signals correspond to Rossby waves propagating from mid-latitudes to equatorial regions, because the signal is stronger in higher latitudes of the northern hemisphere. As mentioned above, the horizontal wave momentum flux convergence due to Rossby

Fig. 9. (a) Latitude-period distribution of the power of the wave momentum flux $\overline{u'w'}$ at sigma level 0.03 (middle stratosphere) from days 375 to 405. The contour interval is $2.0 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$. The zonal wavenumber is from 1 to 5. The solid lines represent westerly upward momentum flux and the dashed lines easterly upward momentum flux. The shaded regions correspond easterly upward momentum flux. (b) Same as Fig. 9a, except for zonal wavenumbers from 6 to 10. The contour interval is $1.0 \times 10^{-4} \text{ m}^2 \text{ s}^{-2}$.

waves contributes to the easterly acceleration of the QBO-like oscillation.

At off-equatorial latitudes there is a signal around 4–5 days in the westward-propagating waves. The vertical wave momentum flux $\overline{u'w'}$ is positive. The dominant zonal wavenumber is 5. The signal of the meridional component of the 5-day wave is symmetric about the equator (not shown). This signal, therefore, corresponds to an $n = 0$ Rossby-gravity wave. The phase speed of the zonal wavenumber 5 wave is -20 ms^{-1} , corresponding the Yanai-Maruyama wave (Yanai and Maruyama, 1966). However, the vertical EP flux of this wave has a negative value, so the Rossby-gravity wave makes a contribution to the QBO-like oscillation.

There is a signal around 2 days in the westward-propagating waves at the equator. The dominant zonal wavenumber of this wave signal is 3. From the meridional structure of the zonal and vertical wind, the wave is an $n = 1$ westward-propagating gravity wave. This signal is similar to that of a very strong zonal wavenumber 5 wave of period 2.5 days in the T106S5 model. These short-period 2–3 day wave signals are also seen in the T21L45 model with stronger horizontal diffusion (Fig. 14a of Takahashi and Kumakura (1995)). The signals in Fig. 9a are stronger than those in the previous stronger horizontal diffusion case. These short-period $n = 1$ gravity waves make a strong contribution to produce the easterly of the QBO-like oscillation in the model.

There is also a faster westward-propagating wave signal at 1 day. The dominant zonal wavenumber is 1. A zonal wavenumber $s = 1$ tidal wave contributes about a third of the wavenumber 1–5 momentum flux around a 1-day period. Other waves of period 1 day have a complicated structure and asymmetry.

Figure 9b shows a frequency-latitude section of the vertical wave momentum flux $\overline{u'w'}$ from zonal wavenumber 6 to 10 at the same level. There are comparable or stronger signals around 1–3 days of westward-propagating waves with a short period. However, the meridional structures of these waves are very complicated and asymmetric. But their combined signal, to some extent, is symmetric about the equator. These waves are like ensembles of westward-propagating $n = 1$ equatorial gravity waves and random gravity waves. Note that there is no signal corresponding to a stationary component or Rossby-gravity component from zonal wavenumbers 6 to 10.

2) Eastward-propagating waves

There is a strong signal of 10-day period in eastward-propagating waves whose zonal wavenumber is 1. This wave corresponds to the so-called Wallace-Kousky Kelvin wave, though the period is slightly faster than that observed. This wave makes a dominant contribution to the westerly acceleration. There are also strong signals around 2.5 days.

The dominant zonal wavenumber is 4, and the phase speed is 46 ms^{-1} . It is noted that these waves are somewhat asymmetric about the equator. There are also short-period waves of higher zonal wavenumber with asymmetric structure about the equator. Evidently the waves behave like Kelvin waves and eastward-propagating gravity waves. These Kelvin waves and short-period gravity waves make a significant contribution to the westerly acceleration of the QBO-like oscillation.

4. Concluding remarks

The equatorial QBO in the lower stratosphere has been well simulated in a CCSR/NIES T21L60 general circulation model. The character of the present model is as follows. The vertical resolution is about 500 m in the upper troposphere and lower stratosphere. We also adopted a smaller fourth-order horizontal diffusion coefficient by one order of magnitude than that used in standard general circulation models. The period of the simulated oscillation is 1.5 years, which is slightly shorter than that observed. The height of the oscillation is slightly higher than that of the real QBO. It seems that mainly the easterly phase is too high. This is related to the general weakness of the easterly phase. The amplitude of the model oscillation is 20 ms^{-1} .

An equatorial-wave analysis has been done. The westerly phase of the simulated QBO-like oscillation is due to Kelvin waves and eastward-propagating gravity waves. This result does not differ from recent observational studies (*cf.* Maruyama, 1994; Sato *et al.*, 1994). The easterly phase of the oscillation is due to $n = 1$ equatorial gravity waves and higher zonal wavenumber ($k = 5$ –10) random gravity waves. The role of the Rossby-gravity wave is smaller in the easterly acceleration of the present model. Further, Rossby waves propagating from the mid-latitude northern winter hemisphere have a role in the easterly acceleration of the simulated QBO-like oscillation.

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準2年振動を再現した大循環モデルにおける赤道波について

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気候システム研究センター／国立環境研究所(CCSR/NIES)・大気大循環モデル(AGCM)の第1バージョンにおいて準2年振動が再現された(Takahashi, 1996)。モデルは、湿潤対流調節のスキームを使っている。水平分解能がT21で鉛直分解能は約500 mの60層モデルである。得られた振動の周期は1.5年と少し早い。

モデル中の赤道波の振舞いを調べてみた。モデルでは、QBO的振動の西風はKelvin波と東向きの重力波が生成している。一方、東風は $n = 1$ の西向き重力波、ランダムな西向き重力波や冬の北半球から伝播してきたRossby波が作っている。このモデルではRossby-重力波はQBO的振動の東風生成に少しの役割を果たしている。