NOTES AND CORRESPONDENCE

A Note on a QBO-Like Oscillation in a 1/5 Sector Three-Dimensional Model Derived from a GCM

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Abstract

A QBO-like oscillation has been obtained in a simulation using the 1/5 sector three-dimensional model, with moist convective adjustment, derived from a preliminary version of the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES) general circulation model. The basic structure of the oscillation is similar to that of the observed quasi-biennial oscillation (QBO). The amplitude of the oscillation is rather strong, about 30 ms^{-1} , which is comparable to the observed oscillation (25 ms^{-1}). However, the period of the oscillation is about 400 days, or half as long as that of the observed QBO in the lower equatorial stratosphere. Further, the height of the simulated oscillation is about 15 km higher than that of the observed QBO.

From a preliminary analysis of the wave behavior, it is suggested that gravity waves are important in the simulation of the QBO-like oscillation.

1. Introduction

The equatorial quasi-biennial oscillation (QBO) is an interesting long-term phenomenon observed in the lower stratosphere. Since the discovery of the QBO by Reed *et al.* (1961) and Veryard and Ebdon (1961) (see the observational review of Wallace (1973)), there have been many studies, both observational and theoretical of this phenomenon. The QBO was theoretically studied by Lindzen and Holton (1968) and in a slightly different form by Holton and Lindzen (1972). Holton and Lindzen (1972) explained the QBO using wave mean-flow interaction theory. Namely, Kelvin and Rossby-gravity waves, which propagate upward and are dissipated by Newtonian cooling, interact with the mean zonal wind. The Kelvin wave is associated with westerly wave momentum, while the Rossby-gravity wave has easterly wave momentum. These waves produce the westerly and easterly wind régimes, respectively, in the lower tropical stratosphere. The theory of these waves is supported by observational findings. Wallace and Kousky (1968) observed Kelvin waves of zonal wavenumber 1 and a period of about 15 days. Yanai and Maruyama (1966) discovered Rossby-gravity waves

of zonal wavenumber 4 and a period of about 4–5 days.

The model used in Holton and Lindzen's theory was a vertical one-dimensional model. Later, two-dimensional in the latitude-height plane (Plumb and Bell, 1982; Dunkerton, 1985; Takahashi, 1987) and three-dimensional (Takahashi and Boville, 1992) models were developed. The basic features of the QBO have been obtained using these mechanistic models; for example, a faster downward propagation of the westerlies than the easterlies, and the reproduction of the amplitude and period of the oscillation.

One problem in the mechanistic models, especially in the three-dimensional model (Takahashi and Boville, 1992), is the rather large wave amplitudes of the Kelvin and Rossby-gravity waves that must be forced to simulate the observed amplitude and period of the QBO (see also Dunkerton (1991) in the case of the two-dimensional model). In the model atmosphere, the zonal wind amplitude associated with the Kelvin wave is almost 15 ms^{-1} or more in the lower stratosphere, while the wave amplitude of the meridional wind associated with the Rossby-gravity wave is about 10 ms^{-1} . On the other hand, the observed Wallace-Kousky Kelvin wave amplitude is about 8 ms^{-1} (Wallace and Kousky, 1968),

Fig. 1. Time-height section of the simulated zonal-mean zonal wind over the equator. The time coordinate is from Day 0 to Day 1060 of the model simulation. The contour interval is 8 ms^{-1} .

Fig. 2. Latitude-height section of the zonal-mean zonal wind for Day 750. The contour interval is 10 ms^{-1} . The solid lines represent westerlies, the dashed lines easterlies.

and the Yanai-Maruyama Rossby-gravity wave amplitude is about 2 ms^{-1} (Randel, 1992; see also Boville and Randel (1992) for GCM wave amplitudes). The model Kelvin wave amplitude is about 1.5 times larger than the observed Wallace-Kousky wave amplitude. It should be noted that the wave momentum flux is twice as large. Recently, Maruyama (1994) found an eastward-propagating wave with a two-day period that had a larger wave momentum flux than the Wallace-Kousky wave. Sato *et al.* (1994) also observed a short-period gravity wave signal (see also Tsuda *et al.*, 1994).

The deficiency in the effective easterly momentum of the Rossby-gravity waves has been previously discussed by Lindzen and Tsay (1975). They suggested that the candidate for the deficiency is the meridional mode number $n = 1$ equatorial gravity wave which could not be resolved in their analysis. Takahashi and Holton (1991) showed that the $n = 1$ westward-moving equatorial gravity wave can produce a QBO-like oscillation. Recently, Takayabu (1994a, b) discovered $n = 1$ westward-propagating equatorial gravity wave signals in satellite cloud data. The gravity waves had about a 2-day period (also see Cadet and Teitelbaum, 1979). These observational results suggest an important role of the westward-moving gravity waves as a source of easterly momentum.

It is of interest that the lower stratospheric equatorial QBO has not been simulated using general circulation models (GCM). Cariolle *et al.* (1993) mentioned that a QBO was obtained in a French GCM. However, it is difficult to discern the QBO in the original time-height section presented in their technical report (Teyssedre, 1993). Also, the amplitude of this oscillation was much too weak, being about 2 ms^{-1} .

On the other hand, two-dimensional models in which waves are generated internally (like GCMs) have easily simulated a QBO-like oscillation. Takahashi (1993) produced a QBO-like oscillation with the use of a two-dimensional model in the longitude-height plane derived from a GCM. The model used the Kuo's cumulus parameterization in order to produce wave disturbances. The period, however, was found to be less than 100 days. A similar oscillation was obtained in a two-dimensional convection model by Held *et al.* (1993).

The present note is a report on the QBO-like oscillation found in a three-dimensional model in which waves are generated internally, even though the model is a $1/5$ sector which means 72 degrees wide with wavenumber 5 symmetry. The model has a rather high resolution in the horizontal, as well as in the vertical direction.

2. Model

The model used is derived from a preliminary version of the Center for Climate System Research/National Institute for Environmental Studies (CCSR/NIES) general circulation model (GCM). The basic features of the model have been described in the paper by Numaguti (1993).

The horizontal resolution is T106, however a $1/5$ sector is employed in the zonal direction. The number of grid points, therefore, is 64 in the zonal direction and 160 in the meridional direction. In the vertical, the domain has 45 layers, with a resolution of about 1 km in the stratosphere, being the same as the two-dimensional model discussed by Takahashi (1993). The top level is located at about 0.5 mb (the σ level is 0.0005).

A moist convective adjustment scheme is used for convective parameterization in the present paper. When the Kuo scheme was used in this model as in Takahashi (1993), the amplitude of the oscillation was weak. Since the QBO is considered to be a dynamical phenomenon, the radiation used in the model is the simple scheme employed by Takahashi (1993). The long-wave radiation is the same as that in Numaguti (1993). In the model there is no contribution from ozone, and the simulation day is fixed at March 15th, *i.e.*, there is no seasonal march.

The bottom boundary condition is that of an aqua-planet. The maximum temperature is 302 K over the equator, and gradually decreases toward the poles. The initial condition is an isothermal atmosphere at rest.

3. Results

Figure 1 shows a time-height section of the simulated mean zonal wind over the equator. A QBO-like oscillation can be clearly seen, though there is a westerly bias in the stratosphere and an easterly bias in the troposphere. The amplitude of the oscillation is about 30 ms^{-1} (the maximum westerly is about 45 ms^{-1} , the maximum easterly is about -15 ms^{-1}) in the time-mean westerly wind. The amplitude is sufficient, in comparison with the observed QBO. However, the simulated oscillation occurs at a height about 15 km higher than that actually observed. The period also differs from the actual QBO, being almost half as long as that observed.

No QBO-like oscillation appears in the lower stratosphere. Several experiments were attempted, such as the use of a smaller minimum vertical eddy viscosity, and an annual oscillatory SST boundary condition. However, the basic features of the oscillation are almost the same for these cases (not shown).

Figure 2 shows a latitude-height section of the zonal-mean zonal wind during Day 750 of the sim-

Fig. 3. Time-height section of the zonal-wind wave disturbance (the zonal-mean component has been removed) at 0° longitude over the equator. The time coordinate is from Day 730 to Day 740. The contour interval is 6 ms⁻¹. Westerlies are shaded.

Fig. 4. The vertical distribution of the time-averaged (from Day 730 to Day 740) wave momentum flux $\overline{u'w'}$ over the equator (m²s⁻²).

ulation. The figure exhibits westerlies near the upper stratosphere and easterlies in the middle stratosphere in the equatorial regions, which corresponds to the phase of downward propagation of westerlies in the QBO-like oscillation.

The westerlies around the middle- and high-

latitudes in the upper stratosphere are rather strong, having amplitudes of about 100 ms⁻¹. The Rayleigh friction is not included in the simulation. An interesting feature appears around the sub-tropical jet: a separation of the sub-tropical jet and polar night jet. This may be due to the high horizontal resolu-

Fig. 5. Power spectrum of the wavenumber 1 component of the zonal wind around the 10 mb level (the σ level is 0.01) over the period from Day 730 to Day 760 at the equator. The units are m^2s^{-2} . Positive (negative) frequencies mean eastward-(westward-)propagating waves.

tion of the model. A detailed analysis will be given in a following paper.

4. Wave analysis

Figure 3 shows a time-height section of the eddy component (the zonal-mean component has been removed) of the zonal wind at 0° longitude over the equator. The time domain is from Day 730 to Day 740 of the simulation, and exhibits the downward phase propagation or equivalent upward energy propagation of the waves. The propagation can be seen from near the 10 mb level to the 1 mb level, which is the height of the QBO-like oscillation. The waves have a period of about 2 days and a vertical wavelength of about 5 km. This signal appears to be gravity waves (see below). In the lower stratosphere, other waves appear which have a longer vertical wavelength (about 15 km) and longer period.

Figure 4 shows the vertical distribution of the total vertical wave momentum flux $\overline{u'w'}$, averaged over Days 730 to 740 over the equator. The vertical wind w can be approximated by the following equation:

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

where H is the scale height (a value of 7 km is assumed). In the lower and middle stratosphere,

an easterly momentum flux can be seen. A westerly momentum flux appears near the upper stratosphere, which produces the upper stratospheric westerlies. On the other hand, around Day 1005, which corresponds to the phase of downward propagation of easterlies in the QBO-like oscillation, an easterly momentum flux appears in the stratosphere (not shown).

Figure 5 shows a power spectrum of the zonal wind wavenumber 1 (5 in the global domain) around the 10 mb level over the period from Day 730 to 760 at the equator. The maximum signal occurs at a westward-moving period of 2.5 days corresponding to an $n = 1$ equatorial westward-propagating gravity wave, found in the latitude-frequency distribution of the meridional wind component (not shown). The structure is similar to that obtained by Takayabu (1994a, b). The vertical wavelength of an $n = 1$ equatorial westward-propagating gravity wave with a period of 2.5 days is theoretically 7.7 km in the case of no mean zonal wind. The value is consistent with that in Fig. 3. A faster eastward-propagating wave signal appears in the upper stratosphere around Day 750. The waves exhibit gravity wave-like behavior (not shown). The westward-moving $n = 1$ equatorial gravity wave in the easterly phase and eastward-moving gravity waves in the

westerly phase are responsible for the model oscillation. A more detailed wave analysis will be presented in a future paper.

5. Concluding remarks

A QBO-like oscillation has been obtained in a three-dimensional model derived from the CCSR/NIES GCM, even though it is a 1/5 sector model. The basic structure of the oscillation is similar to that observed. The amplitude of the oscillation is rather large (30 ms^{-1}), but comparable to the observed values (25 ms^{-1}). The period, however, is half (400 days) as long as that observed. The oscillation occurs around 15 km higher than that observed. A preliminary analysis of the wave behavior suggests an important role of gravity waves in the model oscillation.

The height of the oscillation is similar to that of the semi-annual oscillation (SAO), but the period of the oscillation is 400 days which is different from that (180 days) of the SAO. There is no annual forcing in the present model. It is therefore difficult to decide whether the simulated oscillation is a QBO-like or SAO-like oscillation. A further test, including the annual forcing in the model, is needed to examine the problem. However, the oscillation obtained in the three-dimensional model with cumulus parameterization and without mechanistic forcing of equatorial waves is interesting by itself.

There is a strong signal with around a 2.5 day period in the model. The phase speed $\sim 30 \text{ ms}^{-1}$ is reasonable for interaction in the stratosphere. If the model were extended to the full sphere and the response were at the 2.5 day period, the phase speed of the wave with zonal wavenumber 1 would be $\sim 150 \text{ ms}^{-1}$, which is too large for interaction in the stratosphere. It should therefore be noted that the results from the sector model might be misleading. However, lower resolution GCMs could not produce the QBO. These results may suggest that the smaller-scale gravity waves are important to the QBO. The QBO problem of the GCM using higher horizontal and vertical resolution (for example, T106 with about 1 km vertical resolution; note that the GFDL GCM uses 2 km vertical resolution in the stratosphere) is still an open question which should be examined in the future.

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1/5 セクター・3次元モデルに現れた QBO 的な振動について

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1/5 セクターの 3 次元モデルを用いて、QBO 的な振動を再現した。モデルは気候システム研究センター/国立環境研究所 (CCSR/NIES) の大気大循環モデルの初期バージョンを変更した。再現された振動の構造は観測されている QBO によく似ている。振幅も 30 ms^{-1} と大きい。しかしながら、振動の周期は 400 日程度と実際の QBO に比べ半分くらい短く、また振動の高度も 15 km ほど高い。

波動の簡単な解析から、重力波がモデルの振動に重要な役割をはたしていることが示唆される。