# QBO–like Oscillations Induced by Local Thermal Forcing

*Zhang Daizhou* (张代洲)①and *Qin Yu* (秦 瑜)
Department of Geophysics, Peking University, Beijing 100871
Hiroshi Tanaka Institute for Hydrospheric–Atmospheric Sciences of Nagoya University, Nagoya 464–01, Japan
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ABSTRACT

A zonal–vertical two–dimensional equatorial model is used to study the possibility that the long period oscillation of the zonal mean flow occurring in the lower equatorial stratosphere (QBO) is caused by local thermal activities at the tropical tropopause. The model successfully reproduces QBO–like oscillations of the zonal mean flow, suggesting that the local heating or cooling at the tropical tropopause is probably the main reason of QBO's generation. The analysis of the dependence of the oscillation on the wave forcing indicates that the oscillation is not sensible to the forcing scale. The model can reproduce QBO–like oscillations with any forcing scale if the forcing period and amplitude take appropriate values, proving that the internal gravity waves generated by local thermal source take much important roles in QBO.

**Key words:** Quasi–biennial oscillation(QBO), Local thermal forcing, Forced wave, Wave–flow interaction

## I. *INTRODUCTION*

The quasi–biennial oscillation(QBO) is a phenomenon that the zonal mean flow alternates with easterlies and westerlies in the lower equatorial stratosphere at the averaged period of about 30 months (Reed et al., 1961; Veryard and Ebdon, 1961). Holton and Lindzen (1972) successfully simulated it by a one–dimensional model and explained its generation through wave–flow interaction mechanisms. On this basis, Dunkerton(1981a,b) and Tanaka et al. (1985, 1987) analyzed QBO further under the assumptions of wave saturation and self–acceleration. Two–dimensional models in the meridional plane were performed by Plumb and Bell (1982) and Dunkerton (1985). Later on Takahashi (1987), Takahashi and Boville (1992) applied two– and three–dimensional general circulation models to give more realistic elucidation of QBO, respectively. However, these models have only focused on the characteristics of Kelvin and mixed Rossby–gravity waves by using WKB approximation to estimate the mean flow acceleration and the phase speed of the two waves or assuming that they were steadily excited at the bottom boundary of the models.

In fact, most of the waves found in the tropical area are generated by local sources because global–scale sources of steady waves have not been found so far in the tropical stratosphere and troposphere. The equatorial troposphere is characterized by active cumulus convection, especially the area of Indonesia Archipielago where tall cloud clusters frequently appear, sometimes penetrate the tropopause transporting tropospheric air into stratosphere and affect the stratospheric flow(Newell and Gould–Stewart, 1981; Hess et al., 1993). The

①Present address: Center for Environmental Sciences of Peking University, Beijing 100871 equatorial Kelvin and mixed Rossby–gravity waves must be originated by such activities (Holton, 1972). Although the waves generated in the tropical troposphere do not contain much energy compared with the tropical weather disturbances, they dominate the wave activities in the equatorial stratosphere through their vertical energy and momentum transport.

The motivation of this study comes from the fact that the tropopause temperature over Indonesia shows approximately 15–20 day periodical variation (Tsuda et al., 1993). Holton (1972) suggested that oscillations of narrow longitudinal diabatic heat source could generate the global–scale waves observed in the equatorial stratosphere. Takahashi (1993) proved the possibility that internal gravity waves in the lower stratosphere are generated initially by convective activities in the troposphere. Therefore, we set up a zonal–vertical two–dimensional model to study the features of the zonal mean flow if there is a local thermal wave source at the bottom boundary of the model.

## II. MODEL DESCRIPTION

In the log–pressure coordinate for vertical direction defined as $z = -H\ln(p/p_s)$, where $H(=7\text{ km})$ is the constant mean scale height and $p_s$ is the surface pressure, if the latitude is assumed to be zero, the horizontal momentum equation, the thermodynamic equation, the continuity equation, and the hydrostatic approximation can be expressed, respectively, as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{\partial \Phi}{\partial x} + \nu_x\frac{\partial^2 u}{\partial x^2} + \nu_z\frac{\partial^2 u}{\partial z^2} \ , \tag{1}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + w\left(\frac{\partial T}{\partial z} + \frac{kT}{H}\right) + \frac{H}{R}N^2 w = -\alpha T + K_x\frac{\partial^2 T}{\partial x^2} + K_z\frac{\partial^2 T}{\partial z^2} \ , \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} - \frac{w}{H} = 0 \ , \tag{3}$$

$$\frac{\partial \Phi}{\partial z} = \frac{RT}{H} \ , \tag{4}$$

where $u(x, z, t)$ and $w(x, z, t)$ are the total zonal velocity and vertical "velocity" $(=dz/dt)$, $T(x, z, t)$ is the temperature deviation from the basic state temperature $T_0(z)$, $\Phi(x, z, t)$ is the geopotential deviation from the basic state geopotential $\Phi_0(z)$, $\nu_x$ and $\nu_z$ are the horizontal and vertical eddy viscosity coefficients and take 300 $m^2s^{-1}$ and 0.3 $m^2s^{-1}$, $K_x$ and $K_z$ are the horizontal and vertical eddy thermal conductivity coefficients and take 300 $m^2s^{-1}$ and 0.3 $m^2s^{-1}$, respectively, $R$ is the gas constant for dry air, $\kappa$ is the ratio of gas constant to specific heat at constant pressure $(=R/c_p)$, $N$ is the buoyancy frequency, and $\alpha$ is the Newtonian cooling coefficient which takes the same value as Holton and Lindzen (1972).

With respect to the zonal–vertical plane along the equator in the lower equatorial stratosphere, the simulation region is from 16 km to 35 km vertically with the increments of 500 m. The horizontal scale is 40000 km with the increments of 500 km. And the lateral boundary conditions are cyclic in zonal direction. The top boundary conditions are

$$\frac{\partial u}{\partial z} = \frac{\partial \Phi}{\partial z} = w = 0 \ . \tag{5}$$

The bottom boundary conditions for geopotential, zonal and vertical velocities are

$$\frac{\partial w}{\partial z} - \frac{w}{H} = \Phi = 0 \ . \tag{6}$$

The local temperature oscillation at the bottom boundary is the source of the internal gravity waves and is formulated as

$$T = \begin{cases} T_f[1+\cos\left(\frac{2(x-x_0)\pi}{L_f}\right)]\sin\left(\frac{2\pi t}{P_f}\right) & |x-x_0| \leqslant \frac{L_f}{2} \ , \\ 0 & |x-x_0| > \frac{L_f}{2} \ , \end{cases} \tag{7}$$

where $T_f$, $L_f$ and $P_f$ are the forcing amplitude, scale and period, respectively, and $x_0$ is the center of the forcing region and equals 20000 km. This local temperature oscillation at the bottom excites eastward– and westward–propagating internal gravity waves with the same frequencies but different wavenumbers. Such a mechanism is similar to the experiment performed by Plumb and McEwan (1978) but it has only one "segment" rather than 16 segments at the bottom.

Because the problem is completely symmetric about the forcing center $x_0$, the zonal mean flow will not be generated unless there is some initial bias. We apply

$$u(z) = \begin{cases} 30(z-16 \text{ km})/14 \text{ km} \quad \text{ms}^{-1} & 16 \text{ km} \leqslant z \leqslant 30 \text{ km} \\ 30 \text{ ms}^{-1} & 30 \text{ km} < z \leqslant 35 \text{ km} \end{cases} \tag{8a}$$

and

$$w = T = \Phi = 0 \tag{8b}$$

as the initial conditions.

The numerical model is based on the staggered scheme described by Pielke (1974). Equations (1) and (2) are integrated simultaneously by Runge–Kutta method, and then $w$ and $\Phi$ are calculated from (3) and (4), respectively. The time step of the integration is 15 minutes.

## III. FUNDAMENTAL FEATURES OF THE ZONAL MEAN FLOW

Changing the forcing amplitude $T_f$, scale $L_f$ and period $P_f$, we may obtain quite different results of zonal flow oscillations, or even fail to get periodical variations of the zonal flow.

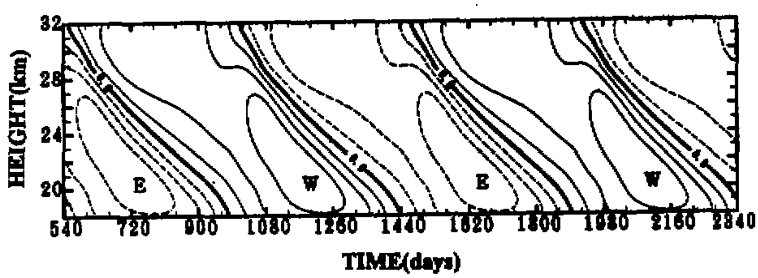


Fig. 1. Time–height cross section of 15–day averaged zonal mean flow from Day 360 to Day 2160. Contour intervals are 10 ms$^{-1}$. Regions of westerly (W) and easterly (E) are drawn by thin solid curves and dash curves, respectively.

In order to detect the possibility that the long period oscillation occurring in the low equatorial stratosphere is caused by local thermal activities at the tropical tropopause, first of all we use 15 K, 10000 km and 15 days for the forcing amplitude, scale and period in the present case. The dependence of the zonal mean flow oscillation on the forcing will be discussed in Section V.

The simulation is carried out for 2160 days. Fig. 1 shows the time–height cross section of the 15–day averaged zonal mean flow after 360–day adjustment calculation. The main feature of the mean flow is that easterly and westerly wind regimes alternate regularly with a constant steady period of about 900 days (30 months). The successive regimes first appear from the top boundary and descend at the speed of 1 km per month. The maximum of the wind speeds, 35 $ms^{-1}$, appears at 23 km whatever in easterly and westerly regions. All of these features relate to the wave activities. However in this paper, we focus on discussing the relationship between the zonal mean flow oscillation and the forcing. The wave properties will be examined precisely in another paper. This result proves that the zonal mean flow has periodical variations of westerly and easterly if there is a proper local thermal oscillation at the bottom.

## IV. INTERNAL GRAVITY WAVES INDUCED BY THE FORCING

The dependence of the zonal mean flow oscillation on the forcing is explained on the basis of forcing waves, which can be examined from (7). Through Fourier transform, (7) is changed to another form as

$$T = -\frac{1}{\eta} T_f \sin\left(\frac{2\pi t}{P_f}\right) + \sum_{k=1}^{\infty} \alpha_k \sin\left(\frac{2\pi t}{P_f}\right) + \cos\left(\frac{2k(x-x_0)}{L}\right) dx , \qquad |x - x_0| \leqslant L/2 \quad (9)$$

where

$$\alpha_k = \frac{T_f}{k\pi}\left(1 + \frac{k^2}{\eta^2 - k^2}\right) \sin\left(\frac{k}{\eta}\pi\right),$$

$\eta = L / L_f$ is the total horizontal scale of the domain (=40000 km) and $k$ is the non–dimensional zonal wavenumber. From (9), the generated internal gravity waves are symmetric about the forcing center ($x_0$ = 20000 km) and propagate eastward and westward at the same phase speed if the waves have the same wavenumbers. And also the phase speeds of the forced waves whose zonal wavenumber are 1, 2, 3 and 4 are approximately 31, 15, 10 and 7.5 $ms^{-1}$, respectively, if we assume the periods to be 15 days which, at least, is reasonable immediately after the waves are excited by the forcing. For the convenience of following discussion, the wave power corresponding to wavenumbers is shown in Fig. 2 for different forcing scales. The waves which have the main power are those whose zonal wavenumbers are less than 5. Short waves are relatively weaker. As a result, the vertical momentum flux is likely to be controlled by longer waves.

## V. DEPENDENCE OF THE OSCILLATION ON THE FORCING

### 1. *On the forcing period*

In order to detect the sensibility of the oscillation of the zonal mean flow to the forcing period, the forcing amplitude and scale are fixed at 15 K and 5000 km, respectively, and the

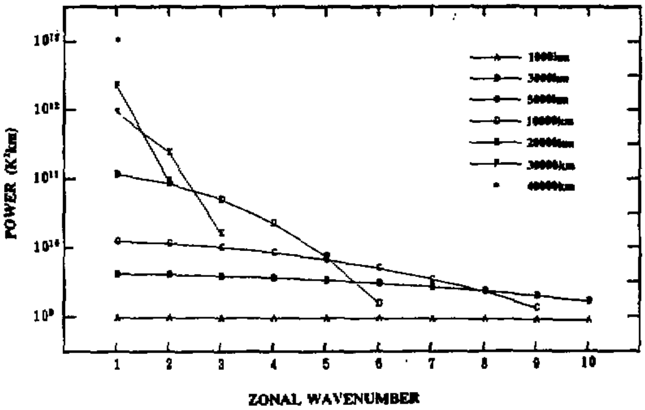


Fig. 2. Wave power (weighted by $k$) of the forced waves for different scales when the forcing amplitude and period are 15 K and 15 days.

period takes 3.75, 7.5, 10, 15, 17.5 and 20 days to make six experiments. When the forcing period is 20 days, the model failed to get a QBO–like oscillation of the zonal mean flow. The results of the other five experiments are shown in Fig.3. The oscillation periods are between 30 and 40 months except the case whose forcing period is 3.75 days.

The zonal wavenumber of the predominant internal gravity waves generated by the forcing are 1, 2, 3 and 4. The shorter scale forced waves can be ignored in momentum transport. The phase speeds of the forced waves are illustrated in Fig.4 for different forcing periods. The waves can easily deposit their momentum into the zonal mean flow if their Doppler–shifted speeds are small (Dunkerton, 1981a). When the forcing period is 3.75 days, the maximum wind speed of the zonal mean flow is about 22 $ms^{-1}$. The phase speeds of the four predominant waves are larger than 31 $ms^{-1}$ so that the waves hardly transfer their momentum into the zonal mean flow. On the other hand, the waves with zonal wavenumbers 2 and 3 play important roles in the wave–flow interaction when the forcing period is 7.5 days. Therefore, 7.5–day forcing is more effective to produce faster zonal mean flow oscillation than 3.75–day forcing. The oscillation features of 10–, 15– and 17.5–day forcing cases are not difficult to be explained in the same way. The reason that 20–day–forcing–period case failed to get a QBO–like oscillation seems to be the phase speeds of the forced waves are too small to interact with the zonal flow at appropriate levels to deposit sufficient momentum into the zonal flow if the periods of the forced waves are too long. It is not difficult to prove the largest phase speed of the forced waves is about 21 $ms^{-1}$ if the forcing period is larger than 20 days.

2. *On the forcing scale*

Seven experiments in which the forcing scales are 1000, 3000, 5000, 10000, 20000 and 40000 km, respectively, with the forcing periods and amplitudes equal to 15 days and 15 K, have been employed to examine the dependence of the zonal mean flow oscillation on the forcing scale. The periods and amplitudes of zonal mean flow oscillations of the simulation results are illustrated in Fig.5.

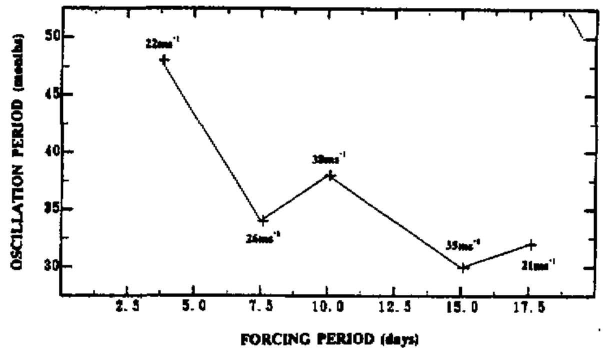


Fig. 3. Oscillation periods and amplitudes of the zonal mean flow for different forcing periods when the forcing scale and period are 5000 km and 15 K, respectively.

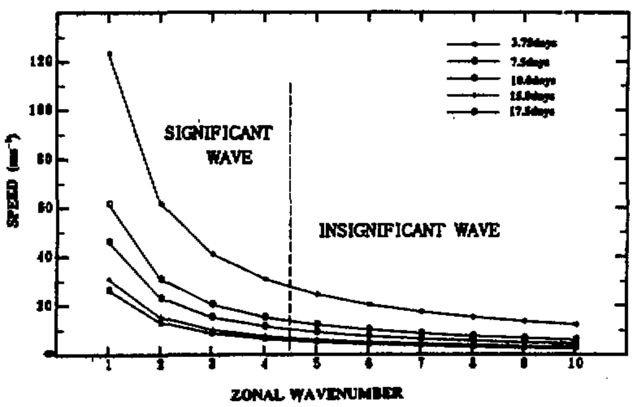


Fig. 4. Phase speeds of the forced waves for different forcing scale.

The figure shows a very peculiar but interesting feature. The zonal mean flow has a very slow oscillation when the forcing scale is 1000 km. When the scale is in the range from 3000 to 20000 km, all periods of the zonal mean flow oscillation are near 30 months. When the forcing scale is larger than 30000 km, the oscillation again becomes slow. Such a feature can be also explained through the interactions between the forced waves and zonal mean flow. We chose two cases, whose forcing scales are 1000 km and 3000 km as examples to explain this feature. The amplitudes of the zonal mean flow oscillations of the two cases are 15 $ms^{-1}$ and 31 $ms^{-1}$. As a result, the most available forced waves which can interact with the zonal mean flow in the two cases are those whose zonal wavenumbers are between 2 and 5 and between 1 and 4, respectively(refer to Fig.4). The wave power shown in Fig.2 reveals that the waves whose zonal wavenumbers are between 2 and 5 in the first case are much weaker than the waves whose zonal wavenumbers are between 1 and 4 in the second case. Hence the acceleration of easterlies or westerlies caused by the wave–flow interactions in the first case is

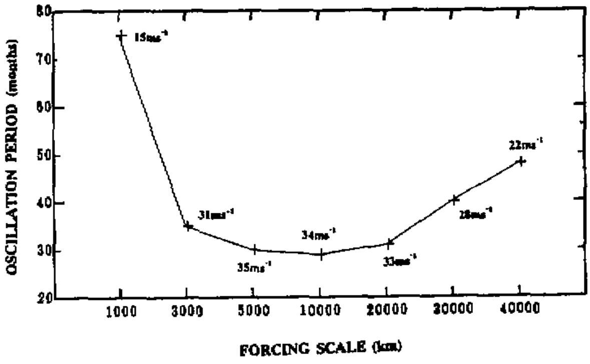


Fig. 5. Oscillation periods and amplitudes of the zonal mean flow for different forcing scales when the forcing period and amplitude are 15 days and 15 K, respectively.

smaller than that in the second case. Therefore, the oscillation of the second case is faster than the first case. It is noticed that the scale of 1000 km is the smallest forcing scale because the horizontal grid increment of this model is 500 km. We have ever conducted some other experiments with different forcing periods and amplitudes when the forcing scale is fixed at 1000 km and found that, with appropriate forcing amplitude, the model could reproduce QBO–like oscillations if the forcing period lain between 3 and 17.5 days. Upon this result, it may be concluded that, with appropriate forcing amplitude and period, any scale forcing at the equatorial tropopause can cause QBO–like oscillation of the zonal flow in the lower stratosphere. It is very important because there are a lot of local sources of internal gravity waves in the equatorial tropopause but their scales are different.(Tsuda et al., 1993).

3. *On the forcing amplitude*

In order to detect the sensitivity of the zonal mean flow oscillation to the forcing amplitude, we apply 10, 12.5, 15 and 20 K as $T_f$ and keep the forcing period and scale as 15 days and 5000 km, respectively, to make four experiments. The periods and amplitudes of the zonal mean flow oscillations of the four experiments are illustrated in Fig.6.

Corresponding to the four forcing amplitudes, the periods of the zonal mean flow oscillations are about 76, 45, 30 and 17 months with their amplitudes equal to 20, 29, 35 and 43 $ms^{-1}$, respectively. The oscillation becomes faster and more intensive as the forcing amplitude increases. It is reasonable. One–dimensional model has proved that the oscillation becomes faster and intensive if the vertical momentum flux becomes larger (Dunkerton, 1981a). In this model, the vertical momentum flux is dominated by the amplitude of theforcing. The zonal and time averaged vertical momentum fluxes in some periods are calculated and shown in Fig. 7. It is clear that the vertical momentum flux is larger if the forcing amplitude is larger.

## VI. CONCLUDING REMARKS

In this paper, a zonal–vertical two–dimensional model is used to study the possibility

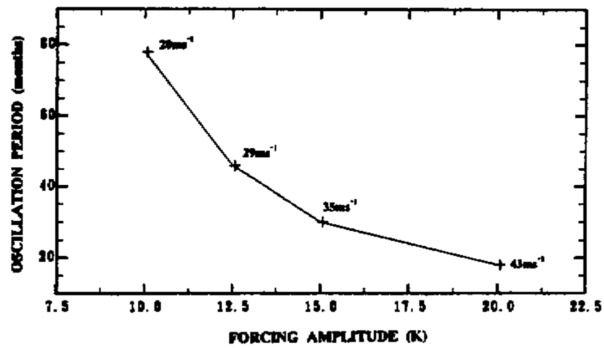


Fig. 6. Oscillation periods and amplitudes of the zonal mean flow for different forcing amplitudes when the forcing period and scale are 15 days and 5000 km, respectively.

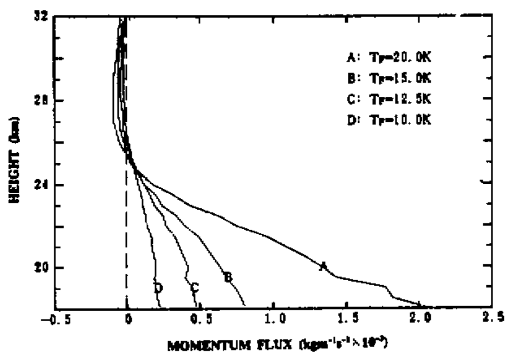


Fig. 7. Vertical profiles of zonal– and time–averaged vertical momentum fluxes during the one–fourth of one period of the zonal mean flow oscillation when the zonal mean flow changes from easterly to westerly. Air density takes the values of standard atmosphere from Roy (1965).

that QBO is caused by local thermal activities at the equatorial tropopause. Although the waves source, which is a narrow longitudinal temperature oscillation, only generates internal gravity waves, the model successfully reproduces QBO–like oscillations of the zonal mean flow if the forcing period, scale and amplitude take appropriate values. This result also proves that the Rossby waves are not important in the QBO's generation, which is consistent with the results of Takahashi and Holton (1991).

The dependence of the oscillation on the forcing period shows that the periods of the forced waves must be less than 17.5 days. Otherwise the forced waves can not excite QBO–like oscillations of the zonal mean flow. The analysis of the sensibility of the oscillation to the forcing scale proves that, with appropriate forcing amplitude and period, the model always reproduces QBO–like oscillations with any forcing scale. This result suggests that the local thermal activities at the tropical tropopause can induce the long period zonal flow oscillations occurring in the lower equatorial stratosphere.

This paper attempts to explore the possibility that QBO is induced by local thermal activities at the tropical tropopause. The whole work has been centered on the premise that both the zonal flow and wave properties must be coherently elucidated. Although the results are very encouraging, we can not give the conclusion that QBO is generated directly by local thermal activities. One reason is that the model is a zonal–vertical model and does not include wave energy dispersion in latitudinal directions. Another reason is that there is not only one thermal local wave source, but also many other local thermal sources, which depends on the weather, and terrain wave sources in the tropical troposphere. Although Takahashi (1993) used a zonal–vertical two–dimensional primitive model including tropical stratosphere and troposphere, made some simulations, the zonal flow features in the stratosphere are far from the observational results. Three–dimensional models including both tropical troposphere and stratosphere, and especially the detail works on wave propagation and wave–flow interactions are needed.

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