A Minimal Model of QBO-Like Oscillation in a Stratosphere-Troposphere Coupled System under a Radiative-Moist Convective Quasi-Equilibrium State

Shigeo Yoden¹, Hoang-Hai Bui¹,², and Eriko Nishimoto¹
¹Department of Geophysics, Kyoto University, Kyoto, Japan
²Hanoi University of Science, Vietnam National University, Hanoi, Vietnam

Abstract

We re-examine the internal oscillation dynamically analogous to the equatorial quasi-biennial oscillation (QBO) that was firstly obtained by Held et al. (1993; hereafter HHR93) as a radiative-convective quasi-equilibrium state in a highly-idealized two-dimensional regional model with explicit moist convections under a periodic lateral boundary condition without Coriolis effects. A QBO-like oscillation with a period of 120.6 days is obtained for the control experiment with a similar configuration as HHR93. The QBO-like oscillation is a robust feature, not sensitive to the choice of model configuration such as domain size and horizontal resolution, or boundary conditions such as prescribed zonal wind at the top and sea surface temperature.

The obtained QBO-like oscillations show downward propagation of the zonal mean signals in the stratosphere as revealed by observations and wave-mean flow interaction theories, while unlike the observed equatorial QBO, they have a clear signal in the zonal mean zonal wind and temperature in the troposphere. The zonal mean precipitation also varies in accordance with the oscillation, though its day-to-day fluctuation is very large compared to the long-period oscillation.


1. Introduction

The quasi-biennial oscillation (QBO) of the equatorial stratosphere is considered as an internal oscillation due to wave-mean flow interactions under a zonally periodic boundary condition (see e.g., Baldwin et al. 2001). Classical QBO theories (Lindzen and Holton 1968; Holton and Lindzen 1972) assumed the separation of the troposphere where waves are generated, from the stratosphere where interactions take place, by specifying time-constant wave forcing at the bottom boundary near the tropopause. In a laboratory analogue of the QBO, a standing internal gravity wave was forced mechanically at the bottom boundary (Plumb and McEwan 1978) or at the top (Otobe et al. 1998) of an annulus of salt-stratified water. The separation is a theoretical idealization under an assumption of “independent stratospheric variations” in stratosphere-only models (Yoden et al. 2002).

In the real atmosphere, however, there is no such a clear boundary separating the stratosphere and the troposphere. Dynamical coupling between them in the extra-tropics has drawn much attention over recent years (see, e.g., Yoden et al. 2002), whereas relatively little attention has been paid to the coupling in the tropics, in particular, to the downward influence of the stratosphere to the troposphere. Only a few observational studies have shown some evidence of the downward influence of the stratospheric QBO. Gray (1984) pointed out an apparent influence of the QBO on Atlantic tropical cyclone activity for the period of 1950–1982, although such a statistically significant relationship was not obtained for a longer dataset including the period of 1983–2008 (Camargo and Sobel 2010). By analyzing the records of outgoing long-wave radiation and highly reflective cloud index over decades, Collimore, et al. (1998, 2003) showed a relationship between the QBO and tropical deep convection through the modulations of tropopause height and cross-tropopause zonal wind shear.

The use of general circulation models (GCMs) of the atmosphere provides a complementary means to explore possible stratosphere-troposphere coupling mechanisms related to the QBO. Takahashi (1996) first succeeded in GCM simulation of a QBO-like oscillation for realistic sea surface temperature (SST) and surface topography, whereas Horinouchi and Yoden (1998) performed an idealized “aqua-planet” experiment for analyzing wave-mean flow interactions associated with the QBO. Recently, four models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulated the QBO realistically and projected its future change (Kawatani and Hamilton 2013). Even though these high-end numerical models might include the coupling process associated with the QBO, no attempt has been made to analyze possible downward influence deep in the troposphere, as far as we know, perhaps due to too weak signals or limitation in spatial resolutions of these global models. Any parameterization schemes on cumulus convections and/or small-scale gravity waves, which are considered as major sources of model uncertainty, are necessary to simulate the QBO.

Regional cloud-resolving models (CRMs) have been used to investigate convectively generated stratospheric gravity waves (Fovell et al. 1992; Alexander et al. 1995) and their possible role in forcing the QBO in the equatorial stratosphere (Alexander and Holton 1997). However, downward influence of the QBO to the troposphere has been beyond the scope of these studies. Held et al. (1993, hereafter HHR93) introduced another type of two-dimensional CRM with a periodic lateral boundary condition and obtained a QBO-like oscillation with a period of about 60 days in a radiative-moist convective quasi-equilibrium state, though they did not report much about the oscillation without any description about the dynamical coupling between the stratosphere and the troposphere.

In this study, we reexamine the HHR93 results by performing much longer time integrations up to 2 years of a state-of-the-art regional CRM to describe the oscillation characteristics more precisely. We also study robustness of the QBO-like oscillation in a series of experiments by changing some model parameters. We focus on the phenomenological description in this letter, and detailed dynamical analyses of the oscillation, including a momentum budget analysis, will be reported in a separated paper.

2. Model and experimental design

The Advanced Research WRF (ARW) version 3 (Skamarock et al. 2008) is used to conduct a series of two-dimensional regional simulations of the tropical troposphere and stratosphere.
A periodic boundary condition is assumed in the zonal direction so that the zonally averaged winds are free to evolve. The Coriolis parameter is set to zero.

The control experiment has a similar configuration as HHR93; 640 km domain width with 5 km horizontal resolution and 130 vertical levels up to 26 km from the surface at the initial state. At the bottom boundary, SST is uniform and constant at 27°C. At the top boundary, a traditional Rayleigh damping layer is introduced for 5 km depth to absorb vertically-propagating gravity waves by relaxing dependent variables to the reference state given as the initial condition.

An idealized zonally uniform initial condition is given by the climatological profiles of temperature and moisture on the equator (gray solid line in Fig. 1 for temperature) that were created from the ERA-Interim reanalysis dataset (Dee et al. 2011) and a constant zonal wind of 5 m s⁻¹ in the entire domain. Time integrations are made for two years with a time increment of Δt = 10 s.

Convective parameterization is turned off in all experiments. WRF Single-Moment 6-class (WSM6) scheme is used for cloud microphysics to represent explicit moist convection. As for the references for this scheme, see Skamarock et al. (2008, Section 8.1.5). For radiation schemes, the Rapid Radiative Transfer Model (RRTM) (ibid., Section 8.6.1) is used for longwave radiation, and MMS5 (Dudhia) (ibid., Section 8.6.5) for shortwave radiation. We set the solar declination to the equinox condition and fix the solar insolation to the daily averaged value (436 W m⁻²). Planetary boundary layer scheme is Yonsei University (YSU) PBL (ibid., Section 8.5.2) with surface fluxes based on Monin-Obukhov similarity theory, and the 1.5 order prognostic TKE closure option (ibid., Section 4.2.4) is used for the eddy viscosities.

Nine experiments (2)–(10) as summarized in Table 1 are carried out to investigate sensitivity of the QBO-like oscillation obtained in Control case (1) to model configurations, boundary conditions, or cloud microphysics.

### 3. Results

Figure 1 shows vertical profiles of the zonal mean temperature in quasi-equilibrium state for Control case (black line behind green line) and the nine other cases of the experiments, together with the initial state (gray solid line). In all the experiments except for Warm rain case with Kessler scheme (Skamarock et al. 2008, Section 8.1.1), QBO-like oscillations are obtained as described below (Figs. 2 and 3). The zonal mean temperature for the nine cases (1)–(9) shows similar lapse rate (7.7 K km⁻¹) as the observed climatology (i.e., the initial state), and has lower values about 5–10 K than the climatology through the troposphere; SST_30 case (orange line) is about 5 K lower, SST_25 (dark blue line) and Fine (gray dashed line) cases are the lowest over 10 K, and the others are in between. The tropopause for the nine cases is located at 11–13 km, several km below the climatology. In Hitop cases (red line and black dashed line), temperature in the stratosphere is much lower than the climatology because of the lack of shortwave heating due to ozone.

Note that the Warm rain experiment has a very different vertical profile of the zonal mean temperature (red dashed line). In this quasi-equilibrium state without QBO-like oscillation, moist convections are not very active and much smaller lapse rate of 3.2 K km⁻¹ is maintained up to the elevated tropopause at the height of 24 km just below the Rayleigh damping layer. The changed lapse rate would be a consequence of the very different spatial distributions of clouds and moisture that give different diabatic heating by the atmospheric radiation and cloud microphysics.

### Table 1. List of the ten experiments performed in this study.

<table>
<thead>
<tr>
<th>Case number</th>
<th>Case name</th>
<th>Description</th>
<th>Mean period [days]</th>
<th>Standard Deviation [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Control</td>
<td>See the caption</td>
<td>120.6</td>
<td>3.0</td>
</tr>
<tr>
<td>(2)</td>
<td>Control_0</td>
<td>$U_{\text{ref}} = 0$ m s⁻¹</td>
<td>135.0</td>
<td>1.7</td>
</tr>
<tr>
<td>(3)</td>
<td>Fine</td>
<td>$\Delta x = 5$ km, $\Delta x = 2$ km, $N_y = 320$</td>
<td>124.6*</td>
<td>3.1*</td>
</tr>
<tr>
<td>(4)</td>
<td>Coarse</td>
<td>$\Delta x = 10$ km, $N_y = 64$</td>
<td>121.3</td>
<td>0.5</td>
</tr>
<tr>
<td>(5)</td>
<td>Wide</td>
<td>$N_y = 256$ (double domain)</td>
<td>112.3</td>
<td>1.4</td>
</tr>
<tr>
<td>(6)</td>
<td>Hitop</td>
<td>$Z_{\text{ref}} = 40$ km, $N_y = 200$</td>
<td>134.8</td>
<td>0.9</td>
</tr>
<tr>
<td>(7)</td>
<td>SST_25</td>
<td>SST = 25°C</td>
<td>132.8</td>
<td>0.4</td>
</tr>
<tr>
<td>(8)</td>
<td>SST_30</td>
<td>SST = 30°C</td>
<td>111.9</td>
<td>0.6</td>
</tr>
<tr>
<td>(9)</td>
<td>Warm rain</td>
<td>Kessler microphysics</td>
<td>133.2</td>
<td>0.7</td>
</tr>
<tr>
<td>(10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2 shows QBO-like oscillations of the zonal mean zonal wind for (a) Control, (b) Control_0, (c) Hitop, and (d) Hitop_0 cases. All of the cases show clear oscillations both in the stratosphere and the troposphere with a kink around the tropopause. If we look at zero-wind lines in the plot of Hitop_0 case as an example, we can easily identify the downward propagation of the oscillation from the bottom of the Rayleigh damping layer (~30 km) to the tropopause (~13 km) at a mean speed of roughly 170 m day\(^{-1}\) (the descending time is about 100 days). The downward propagation is slower in Control_0 case with 120 m day\(^{-1}\) (about 65 days for the height range from 20 km to 12 km). Downward propagation of the oscillation continues to the surface at a mean speed of about 260 m day\(^{-1}\) (about 50 days from 13 km to 0 km) in Hitop_0 case.

The QBO-like oscillation of the zonal mean zonal wind is symmetric with respect to the zero wind in the cases with \(U_{\text{top}} = 0\) m s\(^{-1}\) (Figs. 2b, d), whereas positive wind phase is longer and its maximum wind speed is larger in the cases with \(U_{\text{top}} = 5\) m s\(^{-1}\) (Figs. 2a, c). Dependence of the asymmetric nature of the oscillation on the top boundary condition \(U_{\text{top}}\) is clear throughout the stratosphere and the troposphere.

The oscillation period is not very different for all the cases as listed in Table 1 (the fourth column); from 111.9 days for SST_25 to 135.0 days for Control_0. The estimation of the mean period of the oscillation is robust with small standard deviation, 3.1 days at most, throughout the stratosphere and troposphere (the last column). Note that the oscillation period becomes longer as SST increases from 25 to 30°C, as opposed to the expectation of shorter period due to more convections.

Figure 3 shows the time mean and variations of the zonal mean zonal wind for eight cases. The time mean (thick line) is almost 0 m s\(^{-1}\) in Control_0 (b) and Hitop_0 (f) cases with \(U_{\text{top}} = 0\) m s\(^{-1}\) due to the symmetric nature of the oscillation as described above. In the cases with \(U_{\text{top}} = 5\) m s\(^{-1}\) except for Hitop case (e), on the other hand, the time mean is greater than \(U_{\text{top}}\) in the stratosphere and the upper troposphere. The variable range also shows
an almost symmetric profile with respect to the zero wind in the two cases with $U_{\text{top}} = 0 \text{ m s}^{-1}$ (Figs. 3b, f), whereas it is asymmetric in the cases with $U_{\text{top}} = 5 \text{ m s}^{-1}$, largely due to the non-zero values of the mean zonal wind and skewness of the variations. These asymmetric features of the oscillation are attributable to the artificial top boundary condition for the zonal wind and the asymmetry becomes smaller if the top boundary is moved upward (c).

The amplitude of the oscillation has two peaks as shown in Fig. 3; in Hitop cases it has the maximum in the stratosphere at ~24 km and the second maximum at ~11 km, a few km below the tropopause with a local minimum at ~13 km. In the other cases with $Z_{\text{top}} = 26 \text{ km}$, the stratospheric maximum is comparable to or smaller than the tropospheric maximum due to the influence of the top boundary damping.

Some other aspects of the QBO-like oscillation in the stratosphere-troposphere coupled system are shown in Fig. 4 for Hitop_0 case. Time variation of the zonal mean zonal wind in the mid-stratosphere is characterized by rapid transition to the opposite sign and very gradual approach to one of the extreme values alternatively, in similar way as the observed QBO. On the other hand, the time variation in the troposphere shows more gradual increase and decrease.

Figure 4b shows a time-height section of the zonal mean temperature anomaly from the time mean. In the stratosphere, the descent of warm anomalies is clear around the timing of the rapid transition of the mean zonal wind, suggesting the importance of vertical turbulent mixing associated with the large vertical shear in the transition phase. Tropospheric temperature also shows periodic variations associated with the QBO-like oscillation, though there is little phase lag through the troposphere in contrast to the mean zonal wind oscillation. The zonal mean daily precipitation (Fig. 4c) also shows the time variation associated with the QBO-like oscillation in the low-pass filtered component (thick blue line), though high frequency components are dominant and produce quite irregular variations.

4. Discussion

We demonstrated the QBO-like oscillations of the zonal mean zonal wind have a clear signal even in the troposphere, in which organized convective momentum transport (Lane and Moncrieff 2010) might be important because of tilted convective structures by vertical shear of the mean zonal wind (not shown). We also showed the zonal mean temperature and precipitation vary periodically in accordance with the mean zonal wind oscillations. Further investigation on the interrelation between the mean zonal wind oscillations and moist convections in the troposphere is under way.

The present experimental framework is highly idealized and simplified if compared to the real atmosphere. This is a two-dimensional model on a non-rotating plane without Coriolis effects, instead of the three-dimensional atmosphere on the rotating spherical earth. Clear features of the QBO-like oscillations in the troposphere obtained in this model may be weakened or smeared by the influences of such complicated processes in the real atmosphere. However, we think the use of a hierarchy of numerical models, including this type of idealized simple one, is useful to deepen our dynamical understanding of the equatorial QBO and to reduce the gap between an idealized theory and the complex real atmosphere (Hoskins 1983; Held 2005). We can regard the present model as a minimal model, or a maximally simplified model to study the dynamics of the stratosphere-troposphere coupling process associated with the equatorial QBO. Takahashi (1993) made a unique experiment with a two-dimensional model along the equator derived from a GCM without the rotation of the earth, and obtained a QBO-like oscillation with a period less than 100 days, with clear signal even in the troposphere and associated change in the direction of precipitation movement (his Figs. 1b and 3). The model resolution was very coarse with the truncation zonal wavenumber of 10, and the convective parameterization of Kuo scheme was retained. Some aqua-planet experiments with three-dimensional GCMs show QBO-like oscillations with a hint of associated variations in the troposphere (Horinouchi and Yoden 1998). However, most of the analyses in these studies were focused on the stratospheric part of the oscillation. It would be timely to reinvestigate the dynamics of the QBO-like oscillations obtained in these hierarchies of idealized two- and three-dimensional global models from a viewpoint of stratosphere-troposphere dynamical coupling in the tropics.

The experimental framework introduced by HHR93 was quite unique in the sense that a self-sustained radiative-moist convective quasi-equilibrium state was obtained in a CRM. In this minimal model, Rayleigh damping layer placed at the top boundary plays an important role to sustain a quasi-equilibrium state by absorbing vertically-propagating gravity waves and preventing their artificial reflection (Klemp et al. 2008). Only a very weak cooling trend is discernible in the stratosphere for the two year integrations as shown in Fig. 4b. The altitude of the top boundary and the prescribed reference value in the Rayleigh damping layer are also important to determine the oscillation amplitude and the downward propagation speed of the oscillation signals as shown in Figs. 2 and 3. High frequency gravity waves with a large vertical group velocity are artificially attenuated in this damping layer to influence the zonal-mean momentum budget in the layer and below. As shown in Fig. 1, the thermal structure near the top boundary is also influenced by the relaxation process of artificial cooling in Warm rain case and heating in the other cases.

Yoden and Holton (1988) studied symmetric or asymmetric features of a QBO-like oscillation in a simple stratosphere-only model, and showed that time variation of the zonal mean zonal wind is symmetric if the wave forcing is symmetric (or, a standing wave) at the bottom boundary, whereas it is not if the wave forcing is not symmetric. In this study with the minimal model of QBO-like oscillation, we demonstrated some examples of asymmetric time variations due to asymmetric (i.e., nonzero) zonal wind forcing given by the top boundary condition in Control and Hitop cases (Figs. 2a, c). On the other hand, in Control_0 and Hitop_0
cases with the symmetric forcing, the time variation of the zonal mean zonal wind is almost symmetric (Figs. 2b, d), which is implicitly indicative of symmetric nature of wave momentum fluxes generated by moist convections in a statistical sense.

5. Conclusions

We reexamined the QBO-like oscillation reported by Held et al. (1993), and robustly reproduced such oscillations in the nine cases (Table 1) except for Warm rain case with Kessler cloud microphysics. The oscillation period is from 111.9 to 135.0 days, which is not that sensitive to the choice of experimental parameters. The QBO-like oscillations show downward propagation of zonal mean signals in the stratosphere, similar as the observations (Fig. 2). Even in the troposphere, the zonal mean temperature and precipitation are also modulated in association with the QBO-like oscillation of the zonal mean zonal wind (Fig. 4).

The present model can be regarded as the minimal model that can produce a QBO-like oscillation in the stratosphere-troposphere coupled system under a radiative-moist convective quasi-equilibrium state, and the model would be useful for better understanding the QBO dynamics. Detailed dynamical analyses including momentum budget in the oscillation will be reported in a separated paper.

Acknowledgements

We thank Dale Durran for his helpful discussion and comments on our numerical experiments. This work was supported by JSPS KAKENHI (S) Grant Number 24224011. The stay of HHB as a research fellow was supported by Kyoto University’s Global COE Program “Sustainability/Survivability Science for a Resilient Society Adaptable to Extreme Weather Conditions” for FY2009-13.

References


Manuscript received 25 March 2014, accepted 19 June 2014 SOLA: https://www.jstage.jst.go.jp/browse/sola/