Diagnosis of Annual Synchronization of the Quasi-Biennial Oscillation: Results from JRA-25/JCDAS Reanalysis and MRI Chemistry-Climate Model Data

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Abstract

Data from the Japanese 25-yr reanalysis/Japan Meteorological Agency Climate Data Assimilation System (JRA-25/JCDAS) and the chemistry climate model (CCM) of the Meteorological Research Institute (MRI) were used in this study to investigate the annual synchronization tendency of the quasi-biennial oscillation (QBO) in the equatorial stratosphere. The annual synchronization refers to phase transitions of the QBO that tend to occur for specific seasons.

The JRA-25/JCDAS reanalysis data exhibit similar features of the annual synchronization. The present diagnosis based on the transformed-Eulerian mean zonal momentum equation shows that zonal wind accelerations for the annual synchronization are largely unexplained by explicitly calculated terms, with a small contribution from resolved wave driving and a strong canceling effect from vertical advection.

The CCM does not simulate the annual synchronization as observed, although it does simulate general features of the QBO, as well as annual variation in equatorial upwelling with some differences. The absence of the annual synchronization is related to an almost seasonally uniform distribution of parameterized gravity wave forcing.

It is speculated from these results collectively that seasonal variation of convection and gravity waves plays a key role in inducing the annual synchronization tendency of the QBO under actual conditions.

Keywords quasi-biennial oscillation; annual synchronization; reanalysis data; chemistry climate model data

1. Introduction

The quasi-biennial oscillation (QBO) is a vital feature of low-frequency variability in the tropical stratosphere (e.g., Andrews et al. 1987; Baldwin et al. 2001; Labitzke and van Loon 1999) and is well characterized by the downward propagation of easterly and westerly wind regimes with a variable period averaging approximately 28 months.

The mechanism of the QBO is essentially understood from the perspective of fluid dynamics or from the interaction of the mean zonal flow with various equatorial waves and gravity waves that originate from active convection in the tropical troposphere. Moreover, it is believed that a combination of equatorial waves results in most of the momentum flux needed to drive the QBO. It is difficult to quantitatively estimate the relative contributions from these waves through observations (Baldwin et al. 2001). This is mainly
because of the relatively small temporal and spatial scales of gravity waves. Recently, Kawatani et al. (2010) presented such a quantitative estimation including important contributions from gravity waves for driving a simulated QBO. The QBO was obtained by a three-year simulation with a high-resolution general circulation model (GCM) without gravity wave forcing (GWF) parameterization.

The QBO under actual conditions has been observed to be modulated by several factors, such as the annual/seasonal cycle (Dunkerton and Delsi 1985; Dunkerton 1990; Wallace et al. 1993), El Niño/Southern Oscillation (Taguchi 2010), volcanic eruptions (Dunkerton 1983), and the solar cycle (Salby and Callaghan 2000). Note that the modulation by the solar cycle is nonstationary in time and induces some uncertainty (Hamilton 2002; Fischer and Tung 2008). It is also shown in GCM and chemistry climate model (CCM) studies that simulated QBO-like oscillations change with global warming (Kawatani et al. 2011; Shibata and Deushi 2012). Annual/seasonal modulation could occur without the interannually varying factors in principle, whereas the modulation may be affected by the factors. These modulations still appear to be inadequately understood, although better understanding is important for certain practical purposes such as for prediction.

This practical importance of understanding the variability and dynamics of the QBO is supported by Boer and Hamilton (2008). They showed that in the context of the second Historical Forecasting Project (HFP2), knowledge of the QBO adds extratropical, albeit modest, skill, particularly around the North Atlantic. It is hypothesized that this additional skill is based on the fact that the QBO affects the extratropical stratosphere (Holton and Tan 1980) and the troposphere below it (Baldwin and Dunkerton 2001).

This study focuses on the modulation of the QBO associated with the annual/seasonal cycle, excluding the interannually varying factors. A notable feature of the seasonal modulation is that phase transitions of the QBO tend to occur in specific seasons. In particular, reversals of zonal wind at 50 hPa occur much more frequently in June-July-August (JJA) than in DJF (December-January-February). This tendency, known as annual/seasonal synchronization, seasonal locking, or phase alignment with the annual/seasonal cycle, is the main focus of this study. This annual synchronization feature may be related to the significant seasonal change in the descent rates of the QBO (faster for Northern Hemisphere (NH) spring and slower for NH winter) reported by Wallace et al. (1993) by considering the stalling tendency of the easterly phase of the QBO.

Several previous studies have examined possible mechanisms of the annual synchronization tendency. On the basis of two-dimensional model calculations, Dunkerton (1990) determined that a seasonal variation in equatorial wave activity, tropopause zonal wind, or Brewer-Dobson circulation (BDC) leads to seasonal modulation of a simulated QBO as observed. The numerical studies of Kinnersley and Pawson (1996) and Hampson and Haynes (2004) both support the importance of the annual cycle of the BDC upwelling in the seasonal modulation of the QBO, including annual synchronization. These studies reproduced the observed seasonal changes in the descent rates and phase alignment of the QBO in the models when annual variation in tropical upwelling was given.

This study attempts to conduct a diagnostic analysis for the mechanism of the annual synchronization tendency of the QBO. We use two datasets, including the Japanese 25-yr reanalysis (JRA-25)/Japan Meteorological Agency Climate Data Assimilation System (JCDAS) reanalysis and Meteorological Research Institute (MRI) CCM data, to diagnose the zonal momentum budget in the framework of the transformed Eulerian mean (TEM) equation relevant to the QBO and its annual synchronization. The approach of this study differs from that in the above numerical studies in the sense that we seek to diagnostically clarify the contributor to the QBO and its annual synchronization in data that expresses the QBO reasonably well. An additional note is that both datasets have restrictions for the diagnosis, mainly in representing small-scale waves (GWs), as documented in Section 2.

The rest of the paper is organized as follows. Section 2 explains the reanalysis and CCM data as well as the diagnosis method. Section 3 describes the results from both reanalysis (Section 3.1) and CCM data (Section 3.2), and Section 4 provides a summary and discussion.

2. Data and analysis method

2.1 Data

a. JRA-25/JCDAS data

This study employs the daily means of the JRA-25/JCDAS data (Onogi et al. 2007). The horizontal resolution of the analyzed data is $2.5^\circ \times 2.5^\circ$, with 23 pressure levels up to 0.4 hPa. We use the daily data to calculate several quantities of interest and then obtain their monthly means. We choose data with this horizontal resolution to facilitate a comparison with CCM data with a similar horizontal resolution (Section
2.1b). The data period is 30 years from 1979 to 2008; the JRA-25 data extend until 2004, after which the JCDAS data are available. For simplicity, these data are hereafter referred to as the JRA-25 reanalysis data.

The forecast model used for the JRA-25 data is a primitive equation model with a horizontal resolution of $1.125^\circ \times 1.125^\circ$, including 320 longitudinal grids × 160 latitudinal grids and 40 levels up to 0.4 hPa. The model includes orographic rather than nonorographic GWF parameterization. The JRA-25 data assimilation system employs a three-dimensional variational analysis method. The data assimilated in the system include upper air (radiosonde) wind observations as conventional data. The upper air observations generally extend to the stratosphere, up to 10 hPa, although the number of assimilated data decreases with increasing height at that level (Fig. 2 of Onogi et al. 2007).

The use of daily means of the resolution is unlikely to detract from the results presented in this study, although some information on the temporal and spatial pretreatment does not apply. We confirm for a shorter five-year period from 2000 to 2004 that our results from the daily means of the resolution are generally similar in terms of the zonal momentum budget to those from six-hourly data of the original horizontal and vertical resolutions (Section 3.1).

After comparison of the data with equatorial radiosonde observations in terms of zonal wind (Section 2.1c), we regard the JRA-25 data as an effective representation of the QBO under actual conditions. We expect and confirm a close agreement between the JRA-25 and radiosonde data.

However, it should be noted that the JRA-25 data also have limitations, the most significant of which is that the model or data does not explicitly express small-scale GWs owing to the resolution. Nonorographic GWF, which likely plays an important role in the QBO, is not included even with parameterization. Therefore, the effects are estimated only indirectly (Section 2.2b). Parameterized orographic GWF is essentially irrelevant to the QBO. The effects of data assimilation as well as temporal/spatial smoothing may also affect budget calculations.

b. MRI CCM data

We also utilize the MRI CCM simulation data. The model is based on the standard middle atmosphere version of the MRI GCM (Shibata et al. 1999). The version is a primitive equation model with major physical processes such as radiation, convection, the behavior of the planetary boundary layer, and ground hydrology with the biosphere. The convection scheme is based on Arakawa and Schubert (1974). The CCM utilized here includes three major modifications to the standard version (Shibata and Deushi 2005, 2008). The resolution is T42L68, with enhanced vertical grid spacing of 500 m between 100 hPa and 10 hPa. The horizontal diffusion of the $\nabla^2$ form is weakened to approximately one-tenth of the standard value above 100 hPa in order to simulate a QBO-like oscillation. Rayleigh friction in the standard version is replaced by a nonorographic GWF scheme with a time-constant source as reported by Hines (1997). The source strength is enhanced with respect to the latitude between 30°N and 30°S by adding a Gaussian-function source (0.7 m s$^{-1}$) to the isotropic source (2.3 m s$^{-1}$). The model also includes orographic GWF parameterization for GWs with a short vertical wavelength (Iwasaki et al. 1989); however, the effect is essentially irrelevant to the QBO-like oscillation.

The simulations span 25 years forced with observed sea-surface temperatures (SSTs) from 1980 to 2004. Five ensemble runs were performed and are analyzed here. The CCM simulates general features of the stratosphere as shown by Eyre et al. (2006) and Butchart et al. (2010) as a part of the SPARC CCMVal project for a scenario REF-1. In particular, the CCM spontaneously simulates the QBO-like oscillation in the tropical stratosphere that resembles the QBO under actual conditions, as shown by Shibata and Deushi (2005, 2008) and later in this study. We refer to the simulated QBO-like oscillation as QBO for simplicity.

The CCM also reasonably simulates the annual cycle of the BDC upwelling, with a stronger upwelling for NH winter, in the tropical stratosphere (Fig. 1; Butchart et al. 2010). Notable height-dependent differences appear in the annual mean and annual-cycle amplitude in the CCM upwelling from the JRA-25 counterpart. For the lower part near 100 hPa, the CCM effectively reproduces the annual mean but underestimates the amplitude. As the height increases to approximately 50 hPa, the modeled amplitude approaches the reanalysis result, whereas the modeled annual mean becomes much smaller. For the upper part above approximately 20 hPa, the CCM effectively simulates both features well. The phase of the annual cycle, or timings of the maximum or minimum upwelling, is essentially similar between the JRA-25 and CCM data.

This study employs monthly mean fields located at 64 latitudinal grids and interpolated onto 24 levels. The Eliassen-Palm (EP) flux terms are first calculated on a daily basis and then averaged to obtain monthly means. We assume that the results from the preliminary
comparison for the JRA-25 data are applicable to the CCM in the sense that the use of the vertically interpolated daily data will not adversely affect our study.

c. Radiosonde data

For a comparison with zonal wind variability in the JRA-25 data, we consider monthly mean zonal wind based on radiosonde observations at three equatorial stations and compiled at Free University of Berlin (FUB). The data is defined at 7 levels from 70 to 10 hPa. The data period used here is matched to the 1979–2008 period of the JRA-25 data, unless stated otherwise. Further details of the data can be found in Taguchi (2010).

2.2 Analysis Method

a. Extraction of low-frequency variability

To focus on low-frequency QBO signals, we filter out monthly fluctuations in the quantities of interest, including zonal wind, and each term in the TEM equation in Section 2.2b by two steps: deseasonalization and application of a five-month running mean to monthly mean data. The term “deseasonalization” refers to removal of the climatological mean seasonal cycle from each quantity. The data at and near the beginning and end of the period are also simply smoothed, as reported by Taguchi (2010). We refer to the resultant monthly data as anomalies and mostly focus on these values below.

b. TEM diagnosis

Our main diagnosis for the reanalysis and CCM data is based on the zonal momentum equation in the TEM equations (Eq. (3.5.2a) in Andrews et al. 1987):

\[
\frac{\partial [u]}{\partial t} = -[v] \ast \left\{ \frac{1}{a \cos \phi} \frac{\partial ([u] \cos \phi)}{\partial \phi} - f \right\} - [w] \ast \frac{\partial [u]}{\partial z} + \frac{1}{\rho_o a \cos \phi} \nabla \cdot F + X.
\]  

(1)

The notations follow those in Andrews et al. (1987), except that the zonal mean is denoted by square brackets, and the residual circulation is denoted by $[v]^*$ and $[w]^*$. Each term of the equation is simply expressed as follows:

\[ T \equiv \frac{\partial [u]}{\partial t} : \text{tendency} \]

\[ M \equiv -[v] \ast \left\{ \frac{1}{a \cos \phi} \frac{\partial ([u] \cos \phi)}{\partial \phi} - f \right\} \]

: meridional advection

\[ V \equiv -[w] \ast \frac{\partial [u]}{\partial z} : \text{vertical advection} \]

\[ D \equiv \frac{1}{\rho_o a \cos \phi} \nabla \cdot F \]

: driving (divergence of EP flux) by resolved waves

The term X represents all other effects. By using these symbols, Eq. (1) can be expressed as $T = M + V + D + X$.

We directly apply Eq. (1) for the reanalysis data as follows:

* to obtain daily means of $[u]$, $[v]^*$, $[w]^*$, and $\nabla \cdot F$ and their monthly mean fields,
* to calculate all terms (T, M, V, and D, except for X) in Eq. (1) from the unfiltered monthly mean data,
* to obtain the term X as a residual of all other terms.

The procedure to calculate T, M, V, and D on a monthly basis is valid because the result is generally
similar when we calculate these terms on a daily basis and then obtain the monthly means (not shown). Note that the term $X$ includes driving by unresolved small-scale waves in addition to the effects of temporal and spatial smoothing/interpolation. The methodology used here is similar to that reported by Monier and Weare (2011).

We apply the filtering procedures (Section 2.2a) to the advection terms to diagnose QBO variations after calculating these terms from the unfiltered monthly mean data. This procedure is valid for the present purpose because it can capture the role of the annual cycle of the BDC upwelling, if any, in the tendency of zonal wind anomalies relevant to the annual synchronization.

We repeat the diagnostic calculation for the CCM data. To emphasize a different treatment of GWF in the CCM data, however, we break down the $X$ term into nonorographic GWF $G$ and $X'$ as $X = G + X'$. In the CCM data, the nonorographic GWF term is provided; orographic GWF plays a negligible role in the equatorial stratosphere of interest. The $X'$ term is calculated as a residual of all other terms including $G$.

3. Results

3.1 JRA-25/ICDAS reanalysis data

Figures 2a and 2b compare the time–height sections of monthly zonal wind in the equatorial stratosphere between the radiosonde (Fig. 2a) and JRA-25 reanalysis data (Fig. 2b) for the period from 1979 to 2008. Panel d plots zonal wind at 50 hPa in the two datasets. The figure uses reanalysis data over the equator for comparison of the observations at the equatorial stations. This comparison shows that the reanalysis data strongly correlate with the radiosonde observations in the time series, as was expected.

The spectral amplitude of the 50 hPa zonal wind in the JRA-25 data exhibits a peak at a period somewhat shorter than 30 months, which is consistent with the radiosonde data (Fig. 3, solid lines). This result agrees with the similar QBO period of approximately 28 months (e.g., Baldwin et al. 2001). Therefore, we can regard the JRA-25 data as an accurate representation of the QBO of zonal wind under actual conditions.

A closer comparison of the radiosonde and reanalysis data also suggests some differences. The reanalysis
wind is smoother (Figs. 2a and 2b), probably reflecting the reanalysis procedure and zonal mean. The easterly wind in the reanalysis data tends to be somewhat weaker at lower levels such as 50 hPa (Fig. 2d).

To examine the annual synchronization tendency, Fig. 4a plots the reanalysis zonal wind at 50 hPa as a function of calendar months, and we show reanalysis results averaged between 5°N and 5°S to examine the representative features in the tropical stratosphere. The panel also includes frequency distribution of the wind for each month, represented by a shade of gray. The QBO has often been examined at the 50 hPa level in terms of time series, including the annual synchronization tendency (e.g., Baldwin et al. 2001).

We can thus confirm the annual synchronization tendency in the frequency distributions. The 50-hPa wind frequently changes direction for specific months in NH spring and early summer, particularly for April–June (AMJ; Fig. 4e). It should be noted that the frequencies of zonal wind reversals are low for the other months, particularly for July–September (JAS) and November. These features are common between both westerly and easterly reversals (Fig. 4e). The westerly reversals indicate that wind changes from easterly to westerly, and vice versa. These results are also supported in the radiosonde observations of the longer period from 1958 to 2008, indicated by gray lines in Fig. 4e; the frequency values are converted to those for 30 years. Figure 4a also reveals high
frequencies of the zonal wind at approximately 10 m s\(^{-1}\) and \(-15\) m s\(^{-1}\) throughout the year, with values of approximately \(-15\) m s\(^{-1}\) absent in NH spring.

The timings by month of phase reversals in the JRA-25 data closely correlate with those in the FUB data (Fig. 2d). The timings of westerly reversals in the JRA-25 data are identical to those in the FUB data for 8 of the 13 cases in the 1979–2008 period. The ratio is also similar for easterly reversals, for 7 of the 13 cases. The time difference is 1 (±1 or ±1) for most cases, even when the timings are not identical between the two data.

The annual synchronization tendency, or the frequency bias of the zonal wind reversals in the JRA-25 data depending on season, is emphasized in Fig. 5. The figure compares the frequencies of reversals at 50 hPa between AMJ (crosses) and JAS (circles)–months. The two groups, each consisting of three months, are chosen because the frequency difference between them is the greatest. We consider westerly (top) and easterly (bottom) reversals separately. The westerly reversals occur eight times for AMJ in the 30 years and do not occur for JAS. The frequency bias for easterly reversals is 7:1 (times for 30 years) between the AMJ and JAS periods.

The annual synchronization tendency of the zonal wind can be related to the high frequencies of zonal wind extremes (Fig. 4a) and a seasonal variation of the zonal wind tendency (Fig. 4b). The tendency also exhibits strong seasonality, as shown by Kinnersley and Pawson (1996) and Wallace et al. (1993), and is characterized by high-magnitude accelerations for NH spring to mid-summer (Fig. 4b). Strong positive accelerations also occur for NH winter. Several exceptions are noted, in which strong positive accelerations occur for NH late summer to autumn.

The seasonal variation of zonal wind acceleration combined with the high frequencies of zonal wind extremes essentially corresponds to the annual synchronization feature. The acceleration tends to be greater in magnitude around the time when the zonal wind changes its sign than when it resides around either positive or negative extremes. Therefore, the strong accelerations occurring for specific months are key features for the annual synchronization tendency and are thus examined below.

We next diagnose the zonal momentum budget to examine the contributions from all terms on the right-hand side (RHS) to the tendency on the left-hand side (LHS) of Eq. (1). Figure 6 displays scatter plots between each term on the RHS (x-axis) and the tendency T (y-axis) in the JRA-25 data for all 360 months (12 months \(\times\) 30 years). Vertical advection V and residual X made largest contributions in magnitude. The V term tends to act in the opposite sense to T, as the data points distribute near the \(y = -x\) line (Fig. 6b); that is, V acts to almost cancel T. The residual term X tends to be in the same sense to T and is larger in magnitude (Fig. 6d). The two terms V and X show high correlations in magnitude with T, as shown in the panels in Fig. 6. The important contribution from X in the context of the QBO is consistent with that reported by Monier and Weare (2011). The wave driving D makes a small contribution, although it is positively correlated with T (Fig. 6c). The contribution from the meridional advection M is negligible (Fig. 6a). To
summarize the budget, $T$ is largely balanced with $X$ against the strong canceling effect of $V$. Such roles of $D$ and $X$ are also seen in the time series (Fig. 4c, 4d).

The overall zonal momentum budget holds when six-hourly data of the original spatial resolution are used instead of the daily means of the 2.5° × 2.5° L23 resolution (not shown). Although the use of the original-resolution data results in an increase in the contribution from the resolved wave driving to the tendency, the overall budget is similar. The EP flux divergence becomes larger in magnitude for the original-resolution data, implying an underestimate of wave driving in the low-resolution data. The increasing contribution from the resolved wave driving with the resolution agrees with the result for short-period waves with large fluxes in the equatorial stratosphere (Sato and Dunkerton 1997; Baldwin et al. 2001). However, the reproducibility of such waves in reanalysis data may still leave some uncertainty.

Figure 7a further examines the relative contributions from the two dominant forcing terms $V$ and $X$ in driving $T$ for the JRA-25 data. The panel shows a scatter plot between $X$ and $V$. A strong, linear relationship is evident between $X$ and $V$; $V = -0.52X$.

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**Fig. 6.** Scatter plots showing contribution from each forcing term (x-axis) to the zonal wind tendency $T$ (y-axis) as diagnosed in the TEM zonal momentum equation at 50 hPa: (a) meridional advection $M$, (b) vertical advection $V$, (c) driving of resolves waves $D$, and (d) residual $X$. All of these quantities have a unit of m/s/month in this figure. Crosses denote data for AMJ, and circles represent those for the other months. Correlation coefficients for all months are indicated in the panels. Each panel also includes frequency distributions of the forcing term (bottom) and tendency (right).
$4.2 \times 10^{-7}$ (in m s$^{-1}$/month) corresponds to a correlation coefficient of $-0.92$. It then follows that the relative contributions from $V$ and $X$ to $T$ are approximately constant with $T$ (or phase of the QBO) and season and that the contribution from $X$ is larger in magnitude than that from $V$. Note that the contribution from $V$ has a sign opposite to that of $T$ (Fig. 6b). Therefore, it is valid to claim that the $X$ term plays a critical role over $V$ in driving the seasonality of $T$. These determinations also hold for the stalling feature of the QBO, although this feature is not of primary interest in this study.

It is also noted that this result does not agree with the theory that the annual cycle in the vertical advection $V$, or tropical upwelling, is the main driver of the annual synchronization of the QBO. The concept is that the annual cycle of the upwelling yields the annual synchronization tendency of the propagation, or the phase, of the QBO. The downward propagation tendency of the QBO is interrupted by the strongest upwelling for NH winter before it is allowed by the weakening of the upwelling for NH spring. This concept does not agree with the present result that $V$ is proportional to $T$ in magnitude, with an opposite sign.

Figure 7a also highlights data of 50-hPa wind reversals (colored dots) and those of no reversals (gray dots), and it plots black contours of $X + V$ as an approximate tendency. It is evident that the zonal wind reversals roughly occur when the tendency (acceleration) is large in magnitude and that the

$$\text{TOP/BOTTOM 30\% OF AMJ}$$

![Graph showing zonal momentum budget](image)

Fig. 8. Bar chart showing the zonal momentum budget when the zonal wind tendency averaged for AMJ of each year appeared in top (dark shades, positive tendency) or bottom (thin shades, negative tendency) 30% of the 30 years. The values for the negative tendency cases are inverted in sign.
occurrence has some seasonal preference. These features ensure that the annual synchronization occurs under the strong influence of X.

We emphasize such a zonal momentum budget for the AMJ period in Fig. 8, in which average contributions from the four terms for the top or bottom 30% of the 30 years are plotted. The AMJ period is a three-month period in which the frequency of zonal wind reversals is the greatest (Figs. 4e and 5). Strong accelerations also occur in (and around) this period (Fig. 4b). The following result is generally insensitive to the exact choice of the AMJ period and is similar for MAM and MJJ periods. The bar chart ensures that the aforementioned balance also holds for the key period of interest. The tendency is effectively explained by the balance between the two terms such that X has an excessive contribution and V has a canceling effect.

These results show that a large part of the tendency is not explained by the explicitly calculated terms but is left for the residual term X. That is, the tendency term T is largely contributed by X for the two cases. In the first case, the complete data of all months whereas in the second case, data of strong accelerations for the specific seasons of interest are considered. The latter case is a key feature for the annual synchronization of the QBO. In addition to the effects of data assimilation, the X term includes driving by small-scale waves that are unresolved in the reanalysis data. Therefore, we interpret the results to speculate that such seasonal variation in waves, considered to be GWs, plays an important role in the annual synchronization tendency of the QBO. The speculation that X is contributed from GWs is consistent with the result of Monier and Weare (2011).

3.2 MRI CCM simulation data

The zonal wind variability simulated in the CCM generally exhibits realistic features that resemble the observed QBO in downward propagation and time series (Fig. 2), as shown by Shibata and Deushi (2005). The spectral amplitude of the simulated QBO also peaks at periods around 28 months, as shown in the reanalysis and radiosonde data (Fig. 3).

A closer inspection also shows some differences between the simulated and observed QBO. A notable difference is that the wind variability of the simulated QBO is weaker in magnitude for both westerly and easterly peaks, particularly for the latter at 50 hPa (Fig. 2). This is consistent with the finding of a weaker spectral peak for the CCM (Fig. 3). In addition, the stalling feature of the easterly phase observed in the actual QBO is weak in the simulated QBO (Fig. 2), although this feature is not of primary interest here.

Despite the reasonable simulation of the QBO, the CCM did not show the same annual synchronization tendency as that observed (Fig. 9). The line plots in the panels (a–d) in Fig. 9 are based on an ensemble run, whereas the frequencies in (a, e) are for all five ensemble runs. On the other hand, the zonal wind reversals at 50 hPa preferentially occur for AMJ under
actual conditions (Fig. 4e). Such a frequency bias is essentially absent from the simulations: zonal wind reversals occur rather uniformly with respect to month or season. The possibility exists that reversals are rare for January to March, although even this feature, if true, is different from the observed frequency bias.

Figure 5 ensures that in the simulations, the frequencies of either westerly or easterly wind reversals at 50 hPa are indistinguishable between AMJ and JAS. The 95% confidence intervals calculated from all five ensemble runs with Student’s t distribution heavily overlap between the two seasons. These two seasons were chosen because the annual synchronization tendency is best captured under the actual conditions during these times; in particular, the actual QBO has the strongest frequency contrast in terms of 50 hPa wind reversals.

It is important to emphasize that the absence of the annual synchronization from the simulations does not agree with the argument by Kinnersley and Pawson (1996) and Hampson and Haynes (2004), which was mentioned in Section 1. Although the CCM does reasonably simulate the QBO together with annual variation in the tropical BDC upwelling (Fig. 1), it does not simulate any observed annual synchronization tendency of the QBO. The differences in the CCM upwelling from the JRA-25 data (Fig. 1) may play some role in the absence of the annual synchronization tendency, as discussed in the last paragraph of this subsection.

The absence of the annual synchronization tendency from the simulations reflects that the seasonality of zonal wind tendency T differs from the reanalysis results. On the other hand, the T term in the JRA-25
data tends to be large in magnitude for specific seasons (Fig. 4b); the CCM counterpart is rather uniform in season, with some exceptions (Fig. 9b). The tendency term in the CCM exhibits significant positive accelerations for March to August of several years. The negative accelerations are smaller in magnitude and show more uniform seasonality than the positive ones.

To examine the reason for the CCM simulating such different seasonal distributions of the tendency term without the annual synchronization as observed, TEM diagnosis is applied to the simulation data in all five ensemble runs (Fig. 10). Figure 10 represents a CCM counterpart of Fig. 6, except that Fig. 10d plots the GWF term G. It is noted that the diagnostic calculations of Eq. (1) for the simulation data leaves a considerable residual as X′ (not shown). One major factor for this result could be that the output data analyzed here are interpolated from the original 68 levels of the model to only 24 levels. The residual also includes the effect of temporal smoothing or the use of the monthly means calculated from daily means.

A comparison of Figs. 6 and 10 reveals both common and different features of the zonal momentum budget between the JRA-25 and CCM results. Two common features are that M makes a negligible contribution and V roughly exerts an offsetting effect for a large part of the distributions. The contribution from V is negligible when T is positive and large, which differs from the JRA-25 data. Such differences indicate that the upwelling is generally weaker in the CCM than in the JRA-25 data, as indicated in Fig. 1. The distributions for D and G are notably similar in the simulations; the two wave driving terms generally make similar contributions to T. This result is consistent with that reported by Shibata and Deushi (2005), who determined that the forcings of D and G are generally of similar magnitude. Shibata and Deushi further showed that the two forcings have different phase relationships with zonal wind variability.

The scatter plot between G and V for the CCM (Fig. 7b) also confirms the differences from the reanalysis results. No seasonal preference is apparent for the occurrence of zonal wind reversals (colored dots) or the G term, which is consistent with Fig. 9d. In addition, the distribution for the CCM is more widely scattered than that for the JRA-25 data, with a correlation coefficient of −0.42. These results hold when D is also considered (not shown).

Thus, we can relate the absence of the annual synchronization from the CCM to two different factors from the reanalysis data: the driving terms D and G and the vertical advection term V. The seasonality of D and G is weak in the simulations; in particular, they are relatively uniform with respect to season (Figs. 9c and 9d). Moreover, no clear seasonality is apparent in the residual term X′ (not shown). This result is in contrast to the strong seasonality of T in the JRA-25 data, which is roughly proportional to X including the effect of small-scale unresolved waves. Therefore, our speculation is that the absence of the annual synchronization from the CCM is owing to that of seasonality of the GWF term G. This theory can be traced to the formulation of the GWF scheme (Hines 1997), where parameterized GWs are radiated irrespective of season. That is, if G in the CCM had as clear seasonality as X in the JRA-25 data, the CCM would exhibit the annual synchronization tendency of the QBO. Observations have shown that GW activity, in fact, differs among seasons reflecting convective activity (e.g., Tsuda et al. 2009).

The differences in CCM upwelling from the reanalysis result (Fig. 1) may also affect the absence of the QBO annual synchronization. In the JRA-25 data, the seasonality of V is contributed by both the mean and annual cycle in the upwelling (not shown). Therefore, the underestimation of the time mean upwelling in the CCM is likely to affect the seasonality of V, and hence that of T. Nonetheless, a combination of the reanalysis and CCM results leads to the speculation that the seasonality in G is likely a key for annual synchronization (Section 4).

4. Summary and discussion

This study has investigated the so-called annual synchronization tendency of the QBO in the JRA-25 reanalysis and MRI CCM simulation data in terms of its features, or reproducibility for the CCM, and momentum balance. The annual synchronization tendency is such that zonal wind reversals of the QBO mostly occur for specific seasons such as NH spring to early summer at 50 hPa.

The reanalysis data exhibit the same annual synchronization features as the radiosonde data because the JRA-25 data incorporates radiosonde observations. We relate the annual synchronization tendency to the seasonality of zonal wind accelerations in the sense that strong accelerations occur for specific seasons of zonal wind reversals. Our diagnosis of the zonal momentum balance based on the TEM equation shows that a large part of the zonal wind tendency is unexplained by explicitly calculated terms, with a small contribution from the resolved wave driving D and a strong canceling effect from the vertical
advection V.

The CCM does not reproduce the annual synchronization as observed, although it reasonably simulates general features of the QBO as well as of those of annual variation in the equatorial upwelling, with some differences. We can again relate the absence of the annual synchronization to the seasonality of accelerations, which is weak in the simulation case. On the other hand, both D and GWF G make similar contributions to driving T. The seasonality of GWF and D is relatively uniform in seasons leading to the absence of the annual synchronization. It is possible that the absence of the QBO annual synchronization is also affected by the differences in the upwelling in the CCM.

These reanalysis and simulation results are interpreted as an abduction to determine that seasonal variation in the activity of small-scale GWs plays a critical role in the annual synchronization of the QBO under actual conditions. In the reanalysis results, the role of GWs is unresolved in the data and included in the large residual X. For the simulation results, the GWF parameterization assumes a seasonally constant GW source, releasing the simulated QBO from annual synchronization. Observations show strong seasonal changes in convection and GWs (e.g., Tsuda et al. 2009).

Although the absence of the QBO annual synchronization from the CCM may also be affected by the modeled upwelling, the role of the upwelling through V is secondary because in the reanalysis data, V acts to just cancel T, whereas X is the main driver of T; the importance of the seasonality of GWs can explain both reanalysis and CCM results. More realistic simulation of the tropical upwelling in the CCM is desirable for a more convincing diagnosis. More direct evidence can be obtained from simulations that include seasonally varying sources for parameterized GWs; however, such simulations are beyond the scope of this study and are left for future research.

Our results and suggestions are thus different from those of Kinnersley and Pawson (1996) and Hampton and Haynes (2004). These numerical studies presented observed annual synchronization of simulated QBO when imposing annually varying BDC upwelling in the equatorial stratosphere.

This study, along with Taguchi (2010), therefore suggests the requirement of a GCM for realistic QBO simulations including seasonal and ENSO modulations. For such realistic simulations, the GCM must simulate or include appropriate changes in convection and GWs with seasonal and ENSO conditions. On the other hand, this study suggests the importance of the seasonality of convection and GWs in the annual synchronization of the QBO. Taguchi (2010) speculated that their changes with ENSO are also a key for ENSO-related modulation of the QBO, with weaker amplitude and faster phase propagation during El Niño conditions. Thus, realistic QBO simulation in a GCM is important both dynamically and practically (Boer and Hamilton 2008).

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