NOTES AND CORRESPONDENCE

Sensitivity of the QBO to Mean Tropical Upwelling under a Changing Climate Simulated with an Earth System Model

Shingo WATANABE and Yoshio KAWATANI

Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

(Manuscript received 25 February 2011, in final form 1 September 2011)

Abstract

The sensitivity of the equatorial quasi-biennial oscillation (QBO) to increasing greenhouse gas (GHG) concentrations over time is evaluated using a high-top (85 km) earth system model, which generates the QBO using a non-orographic gravity wave drag parameterization. Based on a pre-industrial control run (1850), a $1/2$ CO₂ run and a $4 \times$ CO₂ run are performed as sensitivity experiments. In addition, long-term transient behaviors of the QBO in a historical climate run (1850–2005) and a future projection run (2006–2100) are investigated. The period of the simulated QBO lengthens in a GHG-rich warmer climate, changing from a quasi-regular 24 months in 1850–1980 to a variable 24–31 months in 1980–2050, although never exceeding 31 months even in the extremely warm $4 \times$ CO₂ run. Such elongation of the QBO period is mostly caused by strengthening of the mean tropical upwelling of the Brewer-Dobson circulation, which counteracts the wave forcing that drives the QBO. Simultaneous reductions in the easterly wind maximum of the QBO are also caused by this mechanism.

1. Introduction

The equatorial quasi-biennial oscillation (QBO) is an atmospheric phenomenon characterized by descending shear zones of the zonal mean zonal winds in the equatorial lower stratosphere. The QBO is driven by wave-mean flow interactions of zonal winds and upward-propagating atmospheric waves, such as equatorially-trapped Kelvin waves and nonstationary gravity waves (GWs) (e.g., Baldwin et al. 2001). There is increasing evidence that the QBO has significant remote dynamical effects on the circulation in the extratropical stratosphere (e.g., Holton and Tan 1980) and in the extratropical lower atmosphere even down to the surface

(e.g., Thompson et al. 2002; Boer and Hamilton 2008; Marshall and Scaife 2009). Although none of the climate models employed in the IPCC-AR4 (Fourth Assessment Report of the Intergovernmental Panel on Climate Change) reproduced the QBO, several climate models that may be used in the next assessment report (AR5) will have a self-consistently generated QBO within the model. The model used in the present study is one such QBO-generating climate model.

As the zonal wind shear zones of QBO descend against the tropical upwelling of the Brewer-Dobson circulation (BDC), the descent speed and period of the QBO depend on the balance between the strength of wave forcing and strength of the tropical upwelling. The period of the QBO has considerable variability in past observations from 1950 to present, ranging from 19 months to 34 months with an average of about 28 months. Although it is not possible to determine a significant trend in the QBO period since 1950, several studies have provided at least some indirect evidence for long-term

Corresponding author: Shingo Watanabe, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan.
E-mail: wnabe@jamstec.go.jp
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changes in QBO behavior prior to 1950 (e.g., Hamilton and Garcia 1994; Teitelbaum et al. 1995). Furthermore, increasing concentrations of well-mixed GHGs and warming in the tropical troposphere and sea surface temperature likely affect the generation of atmospheric waves as well as upwelling of BDC, which may change the future behavior of the QBO.

The sensitivity of the QBO to the strength of wave forcing has been studied in numerical simulations of various complexity. Several two- and three-dimensional mechanistic model studies have demonstrated the dependence of QBO behavior on externally modified wave forcing (wave fluxes given at the lower boundary of the models) (e.g., Dunkerton 1985; Takahashi and Boville 1992). Stronger wave forcing generally results in a faster descent of the QBO zonal winds, a shorter QBO period, and a larger QBO amplitude.

Estimating how the QBO may change in response to prescribed climate changing forcing, in particular increasing GHGs over time, requires comprehensive global climate models with the ability to consistently simulate the QBO, changes in wave forcing (wave fluxes generated in the troposphere) and mean tropical upwelling of BDC. Simulating the QBO using an atmospheric general circulation model (GCM) has been challenging because it requires fine vertical resolution (typically less than 700 m in the lower stratosphere) as well as wave forcing due to small-scale nonstationary GWs, which cannot be explicitly resolved by typical GCMs employed by IPCC-AR4 class climate models. To date, a few GCMs have reproduced QBO-like oscillations (called QBO for simplicity hereafter) with only explicitly resolved waves (Takahashi 1996, 1999; Hamilton et al. 1999, 2001; Watanabe and Takahashi 2005; Watanabe et al. 2008a; Kawatani et al. 2005, 2010a, 2010b, 2011). Other GCMs including the model used in this study simulate QBO using non-orographic GW drag parameterizations (GWDP) that represent the effects of unresolved sub-grid GWs (Scaife et al. 2000; Giorgetta et al. 2002; Shibata and Deushi 2005; Giorgetta et al. 2006; Watanabe et al. 2008b). In these models, the wave fluxes of GWDP must be arbitrarily tuned to obtain realistic QBO behavior in the recent-past climate. Therefore, the fairly uncertain assumption that generation of sub-grid GWs is unchanged through time must be embedded in the long-term transient simulations of such models.

By using the MAECHAM5 GCM with a non-orographic GWDP, Giorgetta and Doege (2005) investigated the sensitivity of the QBO to a possible increase of sub-grid GW generation in the future $2 \times \text{CO}_2$ climate, and found a reduction of the QBO period in the future strong-GW simulations. Recently, Kawatani et al. (2011) investigated the response of the QBO to CO_2 doubling (from 345 to 690 ppmv) using a T106L72 atmospheric GCM in which nonstationary GWs are explicitly resolved. The period of the simulated QBO lengthened from 24 months in the present-day run to 25–29 months in the $2 \times \text{CO}_2$ run, mostly due to strengthened mean tropical upwelling. The absolute amount of GW momentum flux in the tropics did not change significantly between the present and $2 \times \text{CO}_2$ runs. Although such results might be model dependent, they encourage the assumption that steady sub-grid GW generation in the non-orographic GWDP holds at least for the future QBO projection.

Previous studies have focused on the QBO in present vs. $2 \times \text{CO}_2$ runs in atmosphere-only GCMs adapting prescribed climatological sea surface temperatures (Giorgetta and Doege 2005; Kawatani et al. 2011). The present study investigates the sensitivity of the QBO to a wider range of GHG concentrations via analyses of a series of CMIP5, Coupled Model Intercomparison Project phase-5) runs conducted using an integrated Earth System Model (MIROC-ESM). This model includes a coupled atmosphere-ocean climate model, so that responses of mean tropical upwelling to GHG concentrations would be obtained more self-consistently than in previous studies. Since the present version of MIROC-ESM employs a common steady GW source in the tropics in all runs, sensitivity of the QBO to mean tropical upwelling in a changing climate is expected to be elucidated in this study.

2. Model and experimental designs

MIROC-ESM has been developed to be used in long-term global simulations of CMIP5, which may contribute to the IPCC-AR5. In addition to the ordinary coupled global climate model, i.e., an atmosphere with online aerosols, oceans, sea-ice, rivers, and land surface, this model includes the terrestrial and ocean biogeochemistry as well as a well-resolved stratosphere (Watanabe et al. 2008b; Watanabe 2008; Watanabe et al. 2011). The atmospheric GCM has T42 horizontal resolution and contains 80 layers from the surface to 85 km

height. In MIROC-ESM, the QBO is generated by a combination of explicitly resolved wave forcing and sub-grid GW forcing due to a non-orographic GWDP proposed by Hines (1997) (Watanabe et al. 2008b). In the series of CMIP5 runs, a common steady GW source was specified in the tropical lower troposphere. We empirically tuned the steady GW source so that the realistic QBO period was reproduced under present-day (2000 A.D.) conditions.

A summary of the experimental settings of the CMIP5 runs presented in this study is as follows: CONTROL is a pre-industrial control run in which every external forcing such as the CO₂ concentration is fixed at its 1850 A.D. value (~ 285 ppmv). HIST is a transient historical simulation through 1850–2005 A.D. in which historical forcing such as GHG concentrations, emission of aerosol precursors, solar spectral irradiance, volcanic aerosols, and land use changes are specified (Watanabe et al. 2011). A future projection run is performed through 2006–2300 A.D. with transient external forcing based on a socio-economic scenario from the Representative Concentration Pathways (RCP4.5) (Moss et al. 2010). $4 \times \text{CO}_2$ is a run used to estimate the transient response of the climate system in the model to an abrupt quadruplication of the CO₂ concentration. At the beginning of that run, the CO₂ concentration is quadrupled (~ 1140 ppmv) from the initial state of CONTROL, and all other forcing are fixed as in CONTROL. In addition, a $1/2 \times \text{CO}_2$ run is performed in this study in which the CO₂ concentration is abruptly halved (~ 142 ppmv) at the beginning. The same seasonally-varying ozone concentration was prescribed in CONTROL, $1/2 \times \text{CO}_2$ and $4 \times \text{CO}_2$, while transient variations in ozone were imposed in HIST and RCP4.5 associated with anthropogenic changes in ozone depleting substances and the strength of BDC impacting the stratospheric ozone. Anthropogenic changes in ozone precursors in the troposphere are also considered. These ozone datasets are different from those recommended by CMIP5 and prepared by ourselves (see Kawase et al. 2011 for details).

3. Results

Figure 1 compares the time evolution of the global mean surface air temperature anomalies (dTs), annual mean upward mass flux at the 70 hPa level ($Fu70$), and profiles of the equatorial mean zonal wind (Ueq) for representative periods

of the CMIP5 transient simulations, i.e., HIST and RCP4.5, along with Ueq in the ERA40 reanalysis (Uppala et al. 2005). Figure 2 shows the results of the sensitivity experiments for different CO₂ concentrations, i.e., CONTROL, $1/2 \times \text{CO}_2$ and $4 \times \text{CO}_2$. The following results will focus on those particular periods displayed in each panel of Figs. 1 and 2. During the 1960–2000 period of HIST, dTs , defined as the difference from the 1850–2100 average in CONTROL, shows decadal-scale variability embedded in a secular warming trend. Transient cooling episodes in the surface temperatures are mainly associated with major volcanic eruptions, though not discussed in this paper. $Fu70$, a proxy of the strength of BDC (e.g., Butchart et al. 2006, 2010), increases from about 5.8 Mt s^{-1} in 1960 to 6.3 Mt s^{-1} in 2000. This increasing trend in $Fu70$ agrees with previous GCM and CCM (coupled chemistry-climate model) multi-model studies (e.g., Butchart et al. 2006, 2010). Ueq shows descending shear zones of the zonal mean zonal winds resembling the QBO in the ERA40 reanalysis shown in Fig. 1a. The period of the QBO is about 2 years before 1980, but lengthens to 26–29 months thereafter. This transition of periodicity is obviously unrealistic compared to the more variable QBO period in the ERA40 reanalysis. A significant underestimation of the QBO easterlies is also evident in the model, suggesting that the model somehow failed to reproduce the balance between the strength of wave forcing and the strength of tropical upwelling during this period. dTs and $Fu70$ continue to increase between 2010–2050 of RCP4.5, during which time the shear zones descend more irregularly compared to HIST. The QBO period ranges from 24 to 31 months over 2010–2050.

In CONTROL, dTs and $Fu70$ show no significant trend. $Fu70$ has an average of 5.4 Mt s^{-1} , with a significant interannual variability of approximately 10% and is probably associated with the model's internal variability such as sudden stratospheric warming and ENSO. The QBO period is exactly 2 years in most cycles such that every QBO easterly (westerly) wind onset occurs in February (April) at 20 hPa. This seasonality could be in accordance with that observed at 50 hPa (e.g., Baldwin et al. 2001), considering the difference in altitude. In $1/2 \times \text{CO}_2$, dTs decreases with time to be about -2 K after 20 years. $Fu70$ rapidly decreases from about 5 to 4.5 Mt s^{-1} in the first 5 years. The period of the QBO in $1/2 \times \text{CO}_2$ is slightly less than 2 years (see Fig. 4a for the power

Fig. 1. Time evolution of the global mean surface air temperature anomalies in degrees (red curve, see left axis), annual mean upward mass flux at 70 hPa in 10^9 kg s^{-1} (blue curve, see right axis), and profiles of the equatorial zonal mean zonal wind. The horizontal line at 20 hPa corresponds to the level of composite analysis in Fig. 4. The surface temperature anomaly and upward mass flux are omitted for ERA-40.

Fig. 2. As in Fig. 1, but for the sensitivity experiments.

Fig. 3. (a) and (b) Vertical profiles of the residual mean vertical winds averaged over 20N–20S. The solid curve shows the average of each run, and dotted curves show the plus/minus one standard deviation from the average (see text). (c) Ratio of the residual mean vertical winds in each run to those in CONTROL.

spectra of U_{eq} at 20 hPa). The time-height structures of the QBO in the rapidly warming $4 \times \text{CO}_2$ run are strikingly different from those in CONTROL. The strength of the easterlies is significantly weakened, and the shear zones descend irregularly in contrast to the quasi-regular descents in CONTROL. $Fu70$ accelerates from about 6 to 8 Mt s^{-1} in the first 20 years. These results for both the transient experiments and sensitivity experiments imply that the behavior of the QBO has strong sensitivity to the strength of the mean tropical upwelling of BDC that increases with GHG concentrations.

Figure 3 compares profiles of the residual mean vertical winds ($\overline{w^*}$) (e.g., Andrews et al. 1987) averaged over 20N–20S of each run. The solid curve shows the average of each run during the whole period displayed in Figs. 1 and 2. Dotted curves indicate plus/minus one standard deviation from the average, which corresponds to seasonal and intra-seasonal variations, i.e., calculated using high-pass filtered (>15 months) $\overline{w^*}$ in order to eliminate effects of QBO secondary circulation. The shape of the vertical profiles are basically similar in all runs, that is, $\overline{w^*}$ decreases with increasing altitude from 100 to 50 hPa, and increases upward above 50 hPa. The standard deviations of $\overline{w^*}$ have a common tendency in all runs for significant increases with altitude above 50 hPa. The mean $\overline{w^*}$ distribution in HIST quantitatively agrees with that derived from stratospheric tape recorder signals of

water vapor in the real atmosphere, considering the uncertainty in the observations (e.g., Schoeberl et al. 2008).

Mean $\overline{w^*}$ has an obvious positive correlation to GHG concentration. Comparing $4 \times \text{CO}_2$, $(1/2 \times \text{CO}_2)$ to CONTROL, the upwelling increases (decreases) by about +70% (–22%), +45% (–16%), and +40% (–12%) at 70, 50, and 20 hPa, respectively. Mean increases in $\overline{w^*}$ in HIST (RCP4.5) are approximately +10% (+20%), with larger increases from 50–100 hPa, compared to CONTROL. As has been documented in previous GCM and CCM studies (e.g., Butchart et al. 2006; Garcia and Randel 2008; McLandress and Shepherd 2009; Kawatani et al. 2011; Butchart et al. 2010; Okamoto et al. 2011), the changes in tropical $\overline{w^*}$ are mostly explained by changes in the subtropical wave driving of BDC, that is, strengthening in (resolved and parameterized) wave dissipation in the upper part and equatorward flank of the subtropical jets (not shown).

Figure 4a shows the power spectra of U_{eq} at 20 hPa, which are calculated over the period of each run displayed in Fig. 1. The 20 hPa level is chosen because the strengthening of upward motions likely starts to affect the downward propagation of QBO zonal wind shears slightly above this level (Fig. 3). The period of the QBO lengthens in warmer runs, but never exceeds 31 months. Figure 4b compares the composite average time series of

Fig. 4. (a) Power spectra of the equatorial zonal mean zonal wind at 20 hPa, which are calculated for the period of each run displayed in Fig. 1. (b) Composite average time series of the equatorial mean zonal wind at 20 hPa with westerly onset, averaged between 10N–10S. The dashed line shows ERA40. (c) as in (b) but for the net eastward acceleration (tendency) of the equatorial mean zonal wind. (d) as in (b) but for eastward total, i.e., resolved and parameterized, wave forcing (long dashed curves) and total, i.e., meridional and vertical, advection (dotted curves) terms. Only those for CONTROL and $4 \times \text{CO}_2$ are presented.

U_{eq} for each run at 20 hPa for the westerly onset at the same level. Interestingly, the duration of the QBO westerlies (10–11 months) does not change, whereas the duration of the QBO easterlies increases. This asymmetry in the zonal wind changes is associated with changes in the net easterly/westerly accelerations shown in Fig. 4c. The net easterly acceleration becomes weaker and prolonged in warmer runs, which is caused by changes in the momentum budget.

Results of the momentum budget analysis based on the Transformed Eulerian Mean equations (e.g., Andrews et al. 1987) are presented for CONTROL and $4 \times \text{CO}_2$. Figure 4d compares eastward accelerations of the QBO zonal winds due to the total (resolved and parameterized) wave forcing and the net (meridional and vertical) advection of the zonal mean zonal wind associated with the residual mean circulation. In the QBO easterly acceleration period of each run the effect of the tropical upwelling compensates for the wave forcing. The compensation effect in $4 \times \text{CO}_2$ is generally stronger than in CONTROL and cancels out up to 75% of the wave forcing in a certain period of easterly acceleration. This effect due to strengthening of the mean tropical upwelling weakens the net easterly acceleration of the QBO, which leads to a decrease in the easterly wind maximum and elongation of the period of the QBO in the higher-GHG concentration runs.

4. Discussion and conclusion

The sensitivity of the QBO to increasing GHG concentrations was evaluated by comparing a series of CMIP5 runs conducted using MIROC-ESM, in which a common steady GW source for the non-orographic GWDP was specified in the tropics. The strength of mean tropical upwelling systematically increases with increasing GHG concentrations, which leads to an increase in the upward advection of the QBO zonal wind shears that compensate for the wave forcing driving the QBO. The period of the QBO lengthens with increasing mean tropical upwelling, and the maximal easterlies of the QBO decrease at the same time. The dominant period of the simulated QBO changes from 23 months in the coldest $1/2 \times \text{CO}_2$ run to 27–30 months in the extremely warm $4 \times \text{CO}_2$ run.

The present results qualitatively agree with those of Kawatani et al. (2011), and confirm that similar responses are obtained over a wide range of GHG concentrations including the transient GHG scenar-

ios. These results are likely model dependent, but the general tendency of increasing mean tropical upwelling is a common feature in previous GCM and CCM multi-model studies (e.g., Butchart et al. 2006; Butchart et al. 2010). Therefore, qualitatively similar responses would be obtained in other GCMs if steady GW generation was assumed.

As for the reality of the present simulations, the QBO behavior in the time-height cross-section in HIST was less variable than has been measured and the easterly winds were significantly underestimated. Furthermore, there is no observational evidence that the QBO period lengthened between 1960–2000. In this respect, more efforts to reduce uncertainties in the model associated with parameterized GW forcing are required to reproduce transient behaviors of the QBO more realistically, and further observations and comprehensive modeling studies are necessary to estimate GW characteristics through time (e.g., Alexander et al. 2010).

Acknowledgments

The authors would like to thank two anonymous referees for their constructive comments on the original manuscript. They are grateful to Akira Noda for his helpful suggestions for experimental designs. This study was supported by the Innovative Program of Climate Change Projection for the 21st Century, MEXT, Japan. The numerical simulations in this study were performed using the Earth Simulator, and figures were drawn using GTOOL and the GFD-DENNOU Library.

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