Unprecedented Quasi-Biennial Oscillation (QBO) disruption in 2015-2016: Implications for tropical waves and ozone

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Abstract During the Northern Hemisphere (NH) winter of 2015/16, quasi-biennial oscillation (QBO) exhibited a significant disruption that was unprecedented in the observational record. It was characterized by an upward displacement of the westerly wind anomalies. Since traveling wave activity induces the QBO and in turn affects the ozone distribution, it is worth understanding how this anomalous change affects tropical waves activity (including Kelvin and MRG waves) and ozone. This study used assimilated ozone product from the Modern-Era Retrospective Analysis version 2 (MERRA2). The results showed that Kelvin and MRG wave activities are appreciably strong during this period. The strengthening of Kelvin wave activity is consistent with a persistent westerly background flow, favoring upward propagation of Kelvin waves into the stratosphere. On the other hand, the significant strengthening of MRG wave activity may be associated with enhanced equatorward propagation of extratropical Rossby waves due to strong El-Nino event. Furthermore, the results also indicated that the anomalous change in the QBO leads to increasing temperature and ozone concentration in the tropical lower stratosphere. Based on ozone budget analysis, we showed that the increase in total ozone tendency is largely attributable to the increase in dynamical ozone transport, being consistent with the QBO-induced residual circulation between the mid and low latitude, in the lower stratosphere.

1. Introduction
Quasi-Biennial Oscillation (QBO) is the dominant mode of interannual variability in the tropical stratosphere, characterized by a downward propagation of zonal wind in the equatorial lower-stratosphere, with a period averaging approximately 28 months [11-12]. QBO is generated by the interaction between zonal mean flow and equatorial planetary waves [1]. QBO is known to influence the ozone transport and chemical processes at lower-stratosphere. Consistent with Alsepan et al. [2], the westerly phase of QBO increases the ozone concentration in the lower stratosphere, while easterly phase of QBO decreases the ozone levels. This relationship is directly explained by the interaction between QBO and residual circulation in the tropical lower stratosphere, which is known as a primary mechanism of ozone transport between middle and low latitudes.
From December 2015 to May 2016, QBO exhibited a significant disruption, in which the westerly phase of QBO persisted in time [3]. This was unprecedented in 1953-present according to the observational record [4] and [5]. Such unprecedented QBO behavior can affect the Kelvin and MRG wave activities as well as ozone distribution in the tropical lower stratosphere. This study will investigate in detail how the unprecedented QBO in 2015-16 influences the equatorial waves activities and the subsequent ozone distribution during this period.

2. Methods

We used both multilevel daily and monthly averaged zonal wind, meridional wind, temperature, ozone, and ozone tendencies datasets from the Modern Era Retrospective-Analysis for Research and Application (MERRA-2) obtained from NOAA Satellite during 7 years of period (January 2010 – June 2017). This study focused on the equatorial latitudinal bands, between 6°N – 6°S with spatial resolution of 1.5° x 1.5° and altitudes between 100 hPa – 10 hPa.

2.1. Space-Time Spectral Analysis (STSA)

STSA is used to analyze equatorial wave properties and its spectrum energy as a function of zonal wavenumber (k) and frequency (ω). The modified STSA procedure from Lubis and Jacobi [6] was performed with NCAR Command Language (NCL).

Based on the results of STSA, a filter was carried out to isolate each tropical wave activity spatially.

2.2. Total Ozone Budget Analysis

This method is used to calculate the contribution of different processes (dynamics or chemistry) to the total ozone change associated during QBO. The mathematical formula can be formulated as follows (equation 1):

\[
\frac{\partial O_3}{\partial t}_{TOT} = \frac{\partial O_3}{\partial t}_{CHM} + \frac{\partial O_3}{\partial t}_{DYN} + \frac{\partial O_3}{\partial t}_{MST} + \frac{\partial O_3}{\partial t}_{TRB} + \frac{\partial O_3}{\partial t}_{ANA}
\]  

(1)

The variables used in this study are CHM (photochemistry processes), DYN (dynamical processes), ANA (correction factor) and TOT (total ozone tendency), while the TRB (turbulence) and MST (moist processes) variables have only small contribution to the total ozone change.

3. Results

3.1. QBO Propagation Anomaly in 2015-16.

Upward propagation of QBO westerly wind occured at approximately 30 – 15 hPa (~23-28 km). This condition is began to evolve in December 2015 until mid-April 2016. This observed upward displacement speed is known small (3-9 m/s), made the propagation of normal easterly phase began to develop at 40 hPa [3].

![Figure 1. Time-height plot of monthly mean - zonal mean wind between 100 and 10 hPa from Jan 2010 to Jun 2017 in MERRA2.](image-url)
### 3.2. Propagation of Equatorial Tropical Waves

As discussed earlier, the modified STSA procedure from Lubis and Jacobi [6] is used to analyze equatorial waves dispersion and its spectrum energy as a function of zonal wavenumber \( k \) and frequency \( \omega \). We used zonal and meridional wind fields to detect equatorial waves activities, which is, Kelvin and MRG waves. As a preparation of this procedure, the data is detrended first, in order to eliminate trend in the data.

Figure 2(a)-(c) show the wavenumber-frequency diagram of zonal variable at three different altitude (70, 50, and 10 hPa). This diagram shows clear activities of Kelvin and MRG waves, with an increasing of phase speed in conjunction with height. This condition applies to Kelvin and MRG waves. The high phase speed of Kelvin and MRG waves are in contrast with their characteristics in the troposphere, which are much slower due to the effect of convection.

Figure 3(a)-(c) show the wavenumber-frequency diagram of meridional wind component at three different altitude (70, 50, and 10 hPa). This diagram shows decreasing of MRG phase speed and stronger signal in conjunction with increasing height. Kelvin waves do not show a significant activities in the wind component, consistent with equatorial waves theory by Holton [7].
Figure 4 shows the kinetics energy as the result of Kelvin waves propagation which presented on height and time cross section during the unprecedented QBO, while Figure 5 shows kinetics energy of MRG waves at the same period. Based on Figure 4, stronger Kelvin kinetic energy occurs during the unprecedented QBO. This condition follows the mechanism of equatorial waves propagation. Explained by Newman [3], although this upward westerly directly cut off through the path of downward easterly, but the observed wind speed is relatively weak (~3-9 m/s). This weak westerly wind speed causes Kelvin waves to propagate upward freely, followed by the strengthening of its kinetic energy. In the other hand (Figure 5), the dissipation of easterly phase of QBO (red box) is associated with stronger MRG waves than normal years, which also freely propagate upward during the phenomena; based on equatorial waves propagation mechanism. There is still possibility from previous research [13] if these stronger MRG waves may caused by the contribution of equatorward extratropical Rossby associated with Strong El-Nino 2015-16.

3.3. Association of QBO and Temperature
Relationship between zonal wind anomaly (QBO) and temperature anomaly satisfies the thermal wind equation. This equation show the association between the vertical variation of zonal wind and temperature. Explained by Alsepan [2], westerly (easterly) wind shear anomaly is associated with warm (cold) temperature anomaly in the equator.
We will explain the association with thermal wind equation. By ignoring the contribution of vertical and meridional wind to the QBO oscillation, thermal wind equation mathematically is written as follow (equation 2):

$$\beta y \frac{\partial \bar{u}}{\partial z} = -\frac{RH}{u} \frac{\partial \bar{T}}{\partial y}$$

(2)

In the equator, $y=0$, then $\frac{\partial \bar{T}}{\partial y} = 0$ using L’Hopital rule, the thermal wind equation can be formulated as follows (equation 3):

$$\frac{\partial \bar{u}}{\partial z} = -\frac{R}{H} \frac{\partial^2 \bar{T}}{\partial y^2}$$

(3)

Where $u$ is zonal wind, $\bar{z}$ is log-pressure height, $R$ is gas constant for dry air, $H \approx 7$ km, $\beta$ is variation of coriolis parameter in latitude, $T$ is temperature, and $y$ is latitude [8].

The equation explain the temperature change by the variation of zonal wind shear. Second derivative of temperature variable has negative sign (eq. 3), means a maximum turning point. This condition means easterly (westerly) wind shear will associate with positive (negative) temperature anomaly. Related to the upward propagation of westerly-QBO in 2015-16, Figure 6 shows that unprecedented QBO associated with a positive temperature anomaly is consistent with the thermal wind theory.

### 3.4. Association of QBO and Ozone

Figure 7 shows the association between zonal wind and ozone anomaly. The results show positive ozone anomalies during the unprecedented QBO, means that there is an increase of ozone concentration, consistent with theory explained by Alsepan [2], the increasing of ozone concentration is known associated with positive wind shear anomaly (eastward wind).

![Figure 6](image1.png)

**Figure 6.** Relationship between zonal-mean zonal wind (contour) and temperature anomaly (shading).

![Figure 7](image2.png)

**Figure 7.** Relationship between zonal-mean zonal wind (contour) and ozone anomaly (shading).
The basic theory of these ozone concentration change processes is clearly shown by the ozone transport schemes during all QBO phase in Figure 8. This scheme show the reason why ozone concentration increase when there is an observed upward propagation of westerly wind. The relationship is explained by the Brewer-Dobson Circulation. During westerly phase of QBO, which the circulation is getting weaker thus, causes longer period of ozone production. In the lower-stratosphere, ozone concentration change will have positive correlation with temperature anomaly. This suggests that ozone change in lower-stratosphere is mostly driven by dynamical process. In the upper-stratosphere, the ozone change is negatively correlated with temperature anomaly, following Stolarski [9], ozone change in this layer is mostly driven by photochemical processes. Figure 8 represent ozone change for all phase of QBO. In this study, to explain the unprecedented event, we can use easterly QBO scheme as the unprecedented QBO occurs in easterly phase.

![Figure 8. Schematic presentation of the relationship between ozone transport and temperature change during easterly (left) and westerly (right) phases of QBO.](image)

3.5. Ozone Tendencies

Figure 9 show the association between ozone concentration anomaly with ozone tendency at equator. This graphic display what processes have most control of the change in ozone concentration anomaly at different level, especially during the unprecedented QBO. Every line in the graphic has each definition, DOXDTTOT (solid red and orange line) is the time derivative of total ozone tendencies, DOXDTDYN (dashed green line) is the time derivative of ozone transport associated with dynamical process, DOXDTCHM (dashed black line) is the time derivative of ozone transport associated with photochemistry processes, and DOXDTANA (dashed brown line) is the residual value of the time derivative of total ozone tendencies that act as a bias corrector. The level of 10 hPa (~31 km) is taken as a representation of upper-stratospheric layer, while the level of 30 hPa (~25 km) is taken as a representation of lower-stratospheric layer. At 10 hPa during westerly upward propagation, ozone concentration increases by around 2-4 ppm, followed by the residual variable of ozone tendencies (DOXDTANA), which indirectly represent the value of photochemistry processes (DOXDTCHM). In 2015-16, the increase of ozone concentration is significantly higher than in normal condition (~1-2 ppm). Furthermore, the upward propagation of QBO also implicates longer duration of the increase of ozone concentration, as demonstrated by positive ozone anomaly that persists in longer period (~24 months) than in normal mode of QBO (~12 months).

Different condition occurs at 30 hPa where the anomaly change of ozone is driven by ozone transport processes (dynamics) [10]. At this level, ozone concentration increases by 0.3-0.7 ppm, followed by the increase of transport processes around 0.2-0.6 ppm. During the unprecedented QBO, the increase of ozone concentration at this level is not significant as well as previous years of QBO, but occurs in longer period (~20 months).

The illustration about the relationship of ozone tendencies variable during westerly upward propagation is presented in Figure 10. The result show dynamic processes as a driver of ozone concentration change at lower-stratosphere, which mostly tend to has positive anomaly during the
upward propagation. As we can see from Figure 10, DOXDTdyn has bias near the intersection of upward propagation. This bias is not consistent with previous result (Figure 9). To correct this bias, we apply the correction on DOXDTdyn with DOXDTana so that it the result is consistent with Figure 9. Furthermore, DOXDTCHM also can not represents the relationship between photochemical process and upward propagation, which an increase of photochemical process will occurs as the wind goes upward. Thus, we apply bias correction on DOXDTCHM with DOXDTana so that the result is consistent with Figure 9.

![Figure 9](image.png)

**Figure 9.** The time-series of ozone tendency budget terms: total tendency (solid red and yellow), tendency due to chemistry (dashed red), due to dynamics (dashed green), at residual (dashed black), at three different stratospheric levels.
4. Conclusion
The anomalous change in the QBO in 2015-2016 had a direct impact on tropical wave activities and ozone distribution in the lower stratosphere. Our results indicated that the Kelvin and MRG waves are appreciably strong during this period. This is consistent with recent study by Lin et al. [14] showing that tropical mixed Rossby gravity waves made an appreciable contribution to the deceleration of the equatorial westerly jet by its horizontal eddy momentum fluxes. We found that the strengthening of Kelvin wave activity is associated with a persistent westerly background flow, favoring upward propagation of Kelvin waves into the stratosphere. On the other hand, the significant strengthening of MRG wave activity can be caused by the contribution of the equatorward extratropical Rossby waves associated with strong El Nino in 2015-16. Furthermore, the results also indicated that the anomalous change in the QBO leads to increase in ozone concentration in the tropical lower stratosphere, which persists for several months. The increase of ozone concentration in the lower stratosphere is found to be consistent with increasing dynamical ozone transport due to a strengthening of the Brewer-Dobson Circulation, while in the upper-stratosphere is mostly driven by the photochemical processes. Understanding the role of midlatitude Rossby wave dynamical forcing in the anomalous 2015-2016 QBO is intriguing and will be left to future research.

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