Reply to anonymous Referee #2

Received and published: 29 January 2020

This paper presents the equatorial QBO influences on the Northern Hemisphere winter circulation. Many previous studies focused on the stratospheric pathways of this influences, while this manuscript proposes a possible mechanism for tropospheric pathways of this influences through the modulation of Rossby wave activities induced by the QBO-related convection over the tropical western Pacific and the Indian Ocean.
This topic is interesting and valuable for this scientific area. However, there are some issues as mentioned below. For these reasons, I recommend minor revisions.

We appreciate Reviewer #2 very much for the constructive comments and suggestions, in particular for detailed comments. We have carefully incorporated comments and suggestions, which, we believe, improved the manuscript in its content and presentation. Our responses to the specific comments can be found below in black (Reviewer #2's comments and suggestions) and blue (our responses).

Minor comments:

(1) p.2, l.75: The definition of QBO is based on the absolute values of equatorial zonal wind >3m/s. Please check another threshold and mention it.

>Thank you for your comment.
We tried the case with the critical zonal wind speed set to 0 m/s, which gave 14 E-QBO and 23 W-QBO winters. The OLR difference is similar to the original Fig. 3a, especially one over the tropical western Pacific is robust (Fig. RC2.1 shown below).

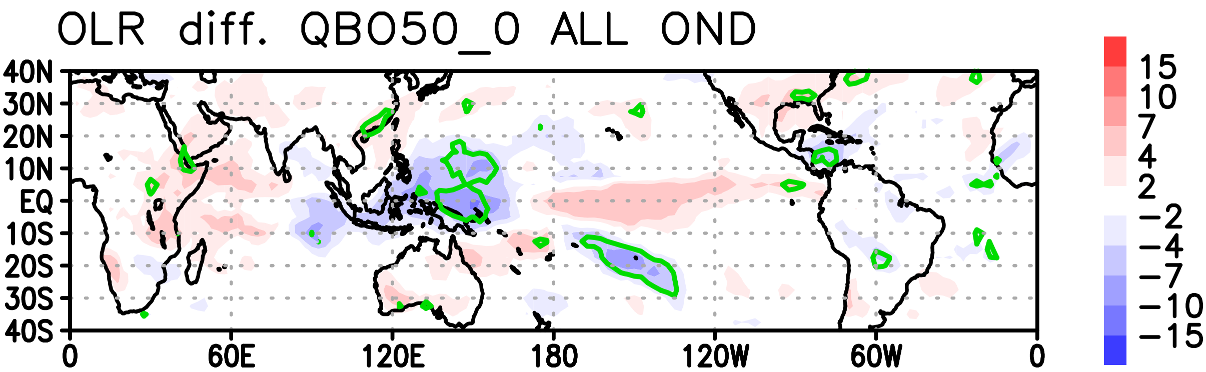

Fig. RC2.1. OND mean OLR difference between EQBO and WQBO winters. The criterion wind speed for QBO is 0 m/s.

We also examined the case in which the QBO was defined at 40 hPa with the 3m/s criterion, giving 18 EQBO and 14 WQBO winters. The number of EQBO winters is larger than that of WQBO winters. The OLR composite is also shown below (Fig. RC2.2). In both cases the results are not sensitive even when we change the QBO criterion slightly.

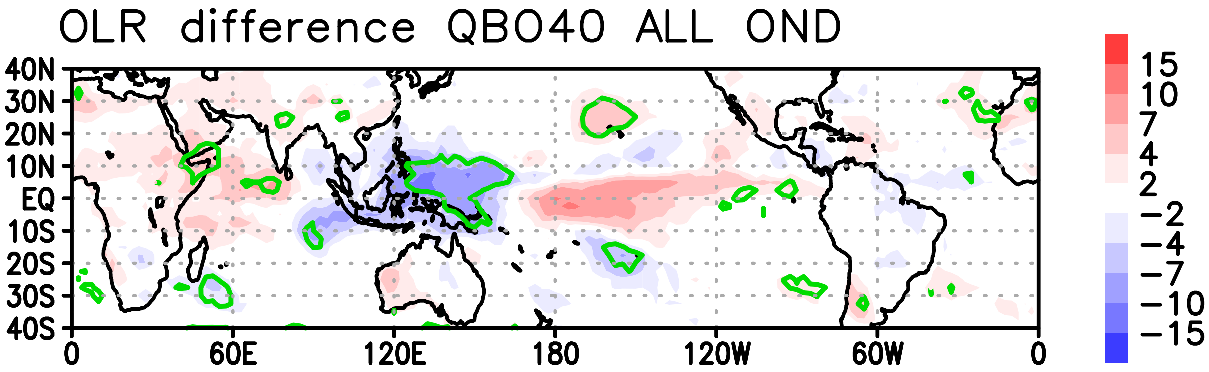

Fig. RC2.2. OND mean OLR difference between EQBO and WQBO winters. The reference height for the QBO definition is chosen at 40 hPa.

We added the following sentences at p.2, line 83.

"We also examined two cases in which we changed the threshold wind speed set to 0 m/s (14 EQBO and 23 WQBO winters) and the reference height to 40 hPa (18 EQBO and 14 WQBO winters). In both cases, the results show a high degree of robustness."

(2) p.4, l.150: The difference between Fig. 5a and 5b indicates the influence of ENSO on the equatorial east Pacific as the downward around 150W with positive OLR in Fig. 3a. Is this interference from ENSO really ruled out in later analysis?

>We think that in the present context of the QBO impacts the resemblance between composite differences (EQBO minus WQBO) with and without ENSO (both El Nino and La Nina) events mostly ruled out possible compound influences in mid- to high-latitudes from ENSO (please see Figure 7). As you pointed out there are, however, some differences in the Walker circulation between two composite differences with and without ENSO events, especially in sinking branches (Figure 5a and b). Noting this we have made a series of AGCM experiments. In addition to CONV1 (heating in the western tropical Pacific) and CONV2 (heating in the western tropical Pacific and cooling in the tropical Indian Ocean), results from the experiments with adding negative convective heating placed in the central tropical Pacific around 150°W, 0°N (CONV3P) and in the tropical Atlantic around 30°W, 10°N (CONV3A) are analyzed.

In fact, the setting for CONV3A with two sinking branches, one in the Indian Ocean and the other in the Atlantic Ocean mimics the QBO signal without ENSO most (Fig. 5b). The mid- to high-latitudes horizontal pattern in geopotential height anomalies at 250 hPa and zonal-mean zonal wind anomalies (Fig. RC2.3) are similar to the observed QBO signal (Fig. 7b). But most significantly, those horizontal and meridional patterns are captured in all experiments including CONV1 with heating only in the western tropical Pacific. We interpret this that the western tropical Pacific is the most influential to extra-tropics and polar vortex.

Above sentences are added in the revised version.

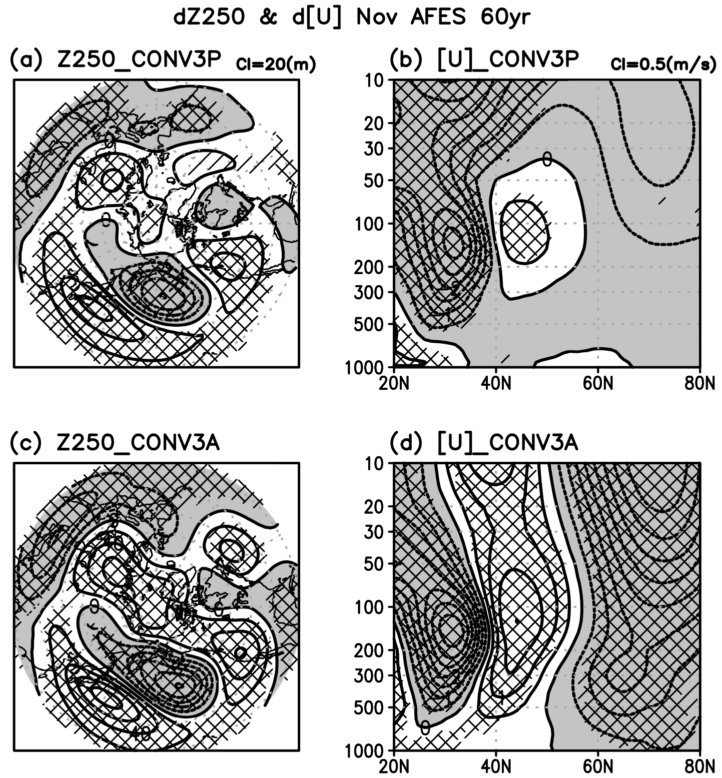

Fig. RC2.3. AGCM simulated responses of Z250 and [U]. Same as Fig. 12 but for CONV3P and CONV3A experiments.

(3) p.5, l.l.165-170: Some references are needed for the constructive interference between the anomalous Rossby wave response and the background climatological stationary wave. Smith et al. (2010) showed the linear interference between these waves in their model. Using reanalysis data, Garfinkel et al. (2010) showed the constructive interference between the ENSO-related anomaly and climatology, and Yamashita et al. (2015) showed this interference between the QBO/solar-related anomaly and the climatology.
The constructive interference in Smith et al. (2010) is linear process, thus, it is reasonable that the constructive interference is reproduced with the LBM.

Garfinkel, C. I., D. L. Hartmann, and F. Sassi (2010), Tropospheric precursors of anomalous Northern Hemisphere stratospheric polar vortices, J. Climate, 23, 3282-3299.
Smith, K. L., C. G. Fletcher, and P. J. Kushner (2010), The role of linear interference in the annular mode response to . extratropical surface forcing, J. Climate, 23, 6036-6050.
Yamashita, Y., H. Akiyoshi, T. G. Shepherd, and M. Takahashi (2015), The combined influences of westerly phase of the quasibiennial oscillation and 11-year solar maximum conditions on the Northern Hemisphere extratropical winter circulation, J. Meteor. Soc. Japan, 93, 629-644.

>Thank you for introducing appropriate references.
We added the following sentence and references.
"The linear interference between the Rossby wave response and background climatological stationary wave has been studied in previous studies, e.g. the interference between extratropical surface forcing and the annular mode (Smith et al., 2010), the tropospheric precursor and the stratospheric polar vortex (Garfinkel et al., 2010), and the solar maximum and westerly QBO (Yamashita et al., 2015)."

(4) Some modifications of introduction are needed as mentioned below.
p.1, l.35: Holton and Tan, 1980, 1982 only show a plausible mechanism, as the latitudinal position of the zero-wind critical surface of stationary Rossby wave is primally controlled by the equatorial QBO. Recently, Watson and Gray (2014) posted this line of discussion with their model.

Watson, P.A.G., and L.J. Gray (2014) How does the quasi-biennial oscillation affect the stratospheric polar vortex?, J. Atmos. Sci., 71, 391-409

> Thank you. We modified the sentence following your suggestion.

"Holton and Tan (1980, 1982) only showed a plausible mechanism, as the latitudinal position of the zero-wind critical surface of stationary Rossby wave is primarily controlled by the equatorial QBO. Recently, Watson and Gray (2014) posted this line of discussion with their model."

p.1, l.35: "this critical latitude mechanism is not effective": The wave propagation change between the EQBO and WQBO is similar to the previous studies in highlatitudes and around equator in Naoe and Shibata (2010)'s results, in agreement with Holton-Tan relationship. In contrast, another propagation change, which is opposite to the critical line control, is analyzed in mid-latitudes by Naoe and Shibata (2010). White et al. (2015) suggested the enhanced upward wave propagation at midlatitudes due to the enhanced wave growth rather critical latitude mechanism, explaining the QBOrelated change in mid-latitudes as well as the polar vortex change in high-latitudes.

White, I.P., H. Lu, N.J. Mitchell, and T. Phillips (2015), Dynamical response to the QBO in the northern winter stratosphere: Signatures in wave forcing and eddy fluxes of potential vorticity. J.Atmos. Sci., 72, 4487-4507.

> Thank you. We modified the sentence following your suggestion.

"Naoe and Shibata (2010) analyzed Holton-Tan relationship by a QBO-producing chemistry-climate model (CCM) and reanalysis data. They showed the conventional critical latitude mechanism that the equatorial winds in the lower stratosphere acted as a waveguide for planetary wave propagation did not hold. White et al. (2015) suggested the enhanced upward wave propagation at mid-latitudes due to the enhanced wave growth rather than the critical latitude mechanism, explaining the QBO-related change in mid-latitudes as well as the polar vortex change in high-latitudes."

p.1, l.35: "The secondary circulation associated with the QBO in the subtropics": Naoe and Shibata (2010) and Yamashita et al. (2011) suggested the significance of the secondary circulation induced by the equatorial QBO in middle stratosphere rather lower stratosphere. In contrast, Garfinkel et al. (2012) and Lu et al. (2014) suggested the significance of the QBO-induced meridional circulation anomalies extend from the subtropics to the midlatitudes in relation to the midlatitudes change of Rossby waves due to the changes in index of refraction.

> Thank you. We modified the sentence following your suggestion.

“Naoe and Shibata (2010) and Yamashita et al. (2011) suggested the importance of the secondary circulation induced by the equatorial QBO in the middle stratosphere rather than the lower stratosphere. Garfinkel et al. (2012) and Lu et al. (2014) pointed the significance of the QBO-induced meridional circulation anomalies extending from the subtropics to mid-latitudes through changes in the refraction index and modulation of Rossby wave propagation.”

Other comments:

p.4, l.155: The middle tropospheric values of red lines (WQBO) are positive and the blue lines (EQBO) are negative in Fig. 6. Does it indicate the relatively large diabatic heating in the WQBO?

> Thank you very much. The figure caption had an error. Blue lines show WQBO and Red lines show EQBO. We corrected it.

p.6, l.210: Fig. 9a shows the dipole pattern between mid-latitudes and Polar region, while Fig. 12a shows the tri-pole pattern.

> Yes, indeed. The linear response to a tropical heating is warming of the tropical troposphere. This results in positive geopotential height anomalies in the tropics and increased subtropical westerlies. We do not know how the tri-pole pattern arises, but suspect non-linear effects.

p.5, l.200: I suppose that “no interaction between the anomalous response and climatological fields” in terms of nonlinear processes, since the LBM model has the constructive interference for linear processes only.

> Thank you. We added “anomalous” and “since the LBM has the interference for linear processes only” in that sentence.

p.6, l.215: I suppose that the constructive interference is valid, when the anomalous waves and climatological waves are in phase, as the description of wavenumber 1 field at p.5, l.170. But, their wavenumber 2 fields in Fig.8 are out of phase.

>For wavenumber 2 in Figs. 8b and d, anomalies (E-W, shade) lie east of climatological trough and ridge. We made amplitude plots as a function of latitude, following Reviewer 2’s suggestion.

Latitudinal profiles of wave-1 and wave-2 amplitudes for EQBO and WQBO are shown below (Figure RC1.2). “Peak values of the wave amplitude increase in EQBO Novembers both for wave-1 and wave-2 and regardless of all or non-ENSO composites.“ The figure and above sentence are added in the revised version. Also description for wave-2 was modified.

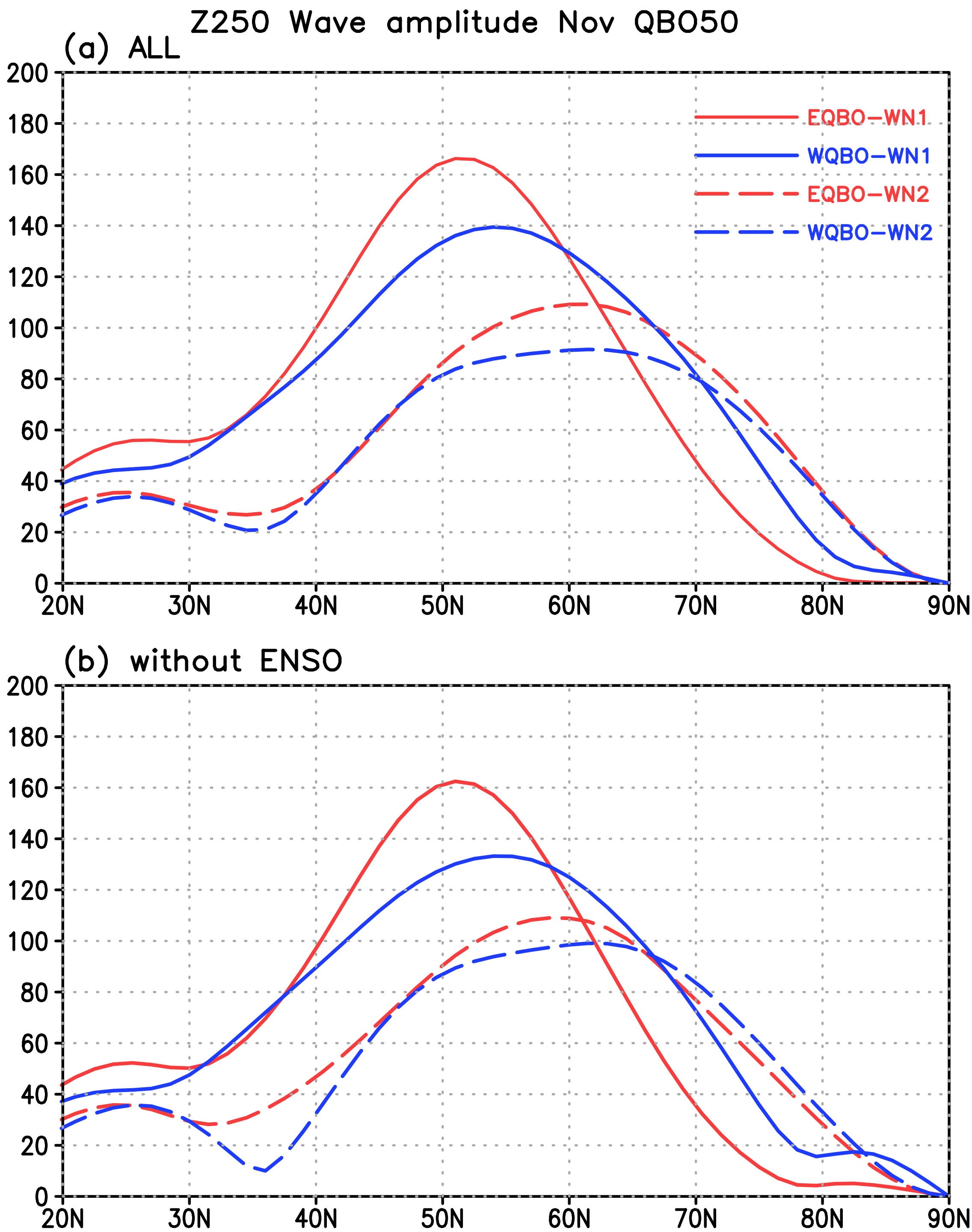

Figure RC2.4. (new Fig. 9) Wave amplitudes at 250 hPa as a function of latitude in the different QBO phases for November. Red (blue) solid line denotes wave-1 in the EQBO (WQBO) composite. Red (blue) dashed line denotes wave-2 in the EQBO (WQBO) composite. Y-axis denotes amplitude in m. (a) All composite. (b) Composite without ENSO winters.

Typos: p.1, l.35: atmospheric general circulation models (AGCMs)

> Thank you very much. We corrected it.

p.4, l.145: Fig. 4c, 5c -> Fig. 3c, 4c

> Thank you very much. We corrected it.