Comments on "Zonally asymmetric influences of the Quasi-Biennial Oscillation on stratospheric ozone" by Wang et al.

General comments

This paper reports a global ozone anomaly and associated meteorological field anomalies due to the QBO. Merged satellite data of the ozone and its column amount, ERA5 reanalysis data, and CESM-WACCM model simulation output are used for analysis. The authors analyzed the difference in ozone and meteorological fields between the westerly and easterly phase composites and showed the QBO signals globally. In particular, the signals at high latitudes showed a clear zonal asymmetry. The authors also discuss seasonal differences in the QBO signals and their zonal asymmetry.

I think the results presented in this manuscript are interesting and scientifically valuable. However, I would like to recommend carefully and thoughtfully describing the correspondence of their results to those in preceding studies that were performed during shorter period and reported as a function of latitude. This would help this research be more valuable in the research field. Moreover, there are some misleading descriptions of chemical effects on ozone anomalies in the tropical middle and upper stratosphere. Therefore, I recommend that some revisions be made before acceptance.

We thank the reviewer for the very helpful comments. We have revised the manuscript carefully based on the comments and suggestions of the reviewer and hope that the manuscript has been improved significantly. More details of the revision can be found in the revised manuscript as well as the point-to-point response as follows.

Major comments

As I stated in the general comments, I think that more carefully describing the correspondence of this study's results to results from preceding studies reported as a function of latitude (wave amplitude, zonal-mean zonal winds, temperature, etc.) may greatly improve this paper scientifically. The analysis of the zonal asymmetry of QBO signals is new and interesting. However, preceding studies also imply zonal asymmetry through the wave amplitude or wave flux (E-P flux). For example, Holton and Tan (1980) suggested that the wave amplitude in the high-latitude stratosphere may change depending on the QBO phase. This already indicates a change in the zonal asymmetry of the dynamical field and in the strength of the zonal-mean zonal wind. Figure 12 is an interesting figure that demonstrates the longitudinal phase of the QBO signals and less zonal asymmetry of the geopotential height field in the westerly phase of QBO as compared to the easterly phase using climatology (contours) and anomaly (colors) fields, with a slight phase shift from the climatology of wave number one, which is the dominant mode of the wave activity. I would suggest that the authors explain the connection of the 3D anomalies due to the QBO to the zonal-mean anomalies as a function of latitude.

We thank the reviewer very much for the constructive suggestion. We have read through more literatures and added further analysis using the wave flux (T-N Flux, Takaya and Nakamura, 2001). Now we have some discussion about the connection between the zonal-mean anomalies and the zonal asymmetric features. As reported by previous literatures, during QBOW at 20 hPa (QBOE at 50 hPa), there are enhanced upward wave fluxes from the troposphere to the stratosphere in high-latitudes of the northern hemisphere in DJF (e.g., Naoe and Shibata 2010; Elsbury et al., 2020). However, the planetary waves propagate upward preferred over the regions of eastern Eurasia and north America (Figure R1a and also in Figures S5f and S5h of Elsbury et al., 2020, note that what they show are anomalies during QBOE while we show in QBOW), maybe due to the large climatological planetary wave flux in this sector (White et al., 2019). At the same time, seen from its meridional and zonal components, the T-N Flux converges over the north Atlantic sector but diverges over the north Pacific sector in the high-latitudes, which leads to acceleration and deceleration of zonal winds, respectively (Figure R1b). Such asymmetric wave propagation leads to perturbations of the polar vortex, i.e. a trough over the eastern Eurasia and North Pacific sector and a ridge over the North Atlantic sector (Figure R1c). The shift of the polar vortex from the North Atlantic to the Eurasia and North Pacific sector results in downward propagation of planetary waves over the North Atlantic (Figure R1a, and also in Zhang et al., 2019; Elsbury et al., 2020).

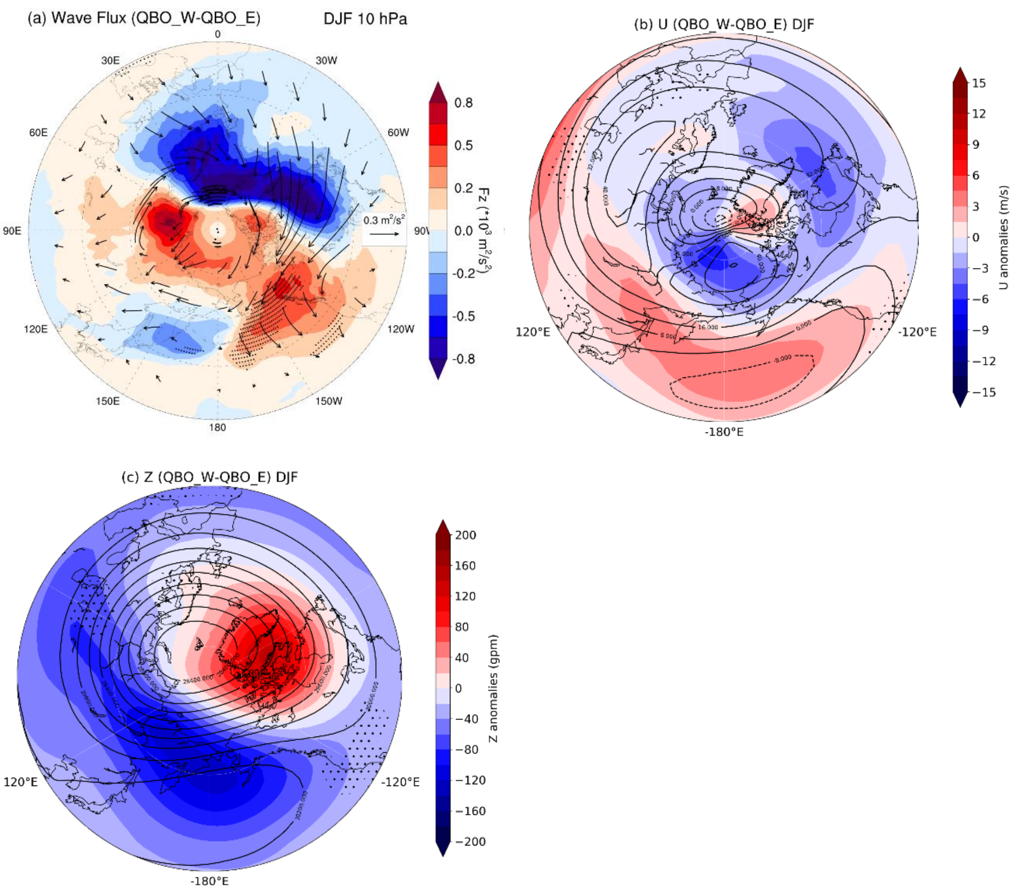

Figure R1. Influences of QBO (QBOW-QBOE) on T-N Flux (a), zonal wind (b) and geopotential height (c) in different seasons at 10 hPa based on ERA5 data for the period 1979-2020. The meridional and zonal components of T-N Flux are shown as vectors and the vertical component is shaded in (a). In (b) and (c), the climatological mean is also shown as contour lines and the QBO related anomalies are shaded. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

Another point is that the author should state the chemical effect on the ozone anomaly in the middle and upper stratosphere. To clarify the chemical effect in the QBO, I recommend that the authors show a latitude–height cross section of the temperature anomaly, such as in Figs. 5 and 6, and discuss the possibility of a chemical effect. As shown in Fig.6, positive anomalies of w* are evident above the ozone mixing ratio maximum (around 10 hPa), and accordingly, positive ozone anomalies are also evident, as shown in Fig. 5. The authors said that this positive ozone anomaly was caused by transport above the ozone mixing ratio peak. However, I think that the ozone at these altitudes in the tropics is also influenced by chemistry (e.g., Fig.1 of Solomon et al., 1985). If temperature at these altitudes has negative anomalies associated with the positive anomalies of w*, then the chemical effect should lead to a positive ozone anomaly, because a lower temperature leads to more ozone due to the temperature dependence of reaction coefficients in the gas phase chemistry. Then the positive ozone anomaly is consistent with the chemically induced anomaly as well as the dynamically induced (transport) anomaly.

We thank the reviewer for the very helpful comments. We have added a figure in the supplemental material to show the latitude–height cross section of the temperature anomaly associated with QBO as the reviewer suggested. We agree with the reviewer that the temperature dependent chemical effects should also be considered. As the reviewer expected, negative temperature anomalies can be found in the middle stratosphere in the tropics, which contributes to the positive ozone anomalies correspondingly. We have added some discussion about this effect in the revised manuscript.

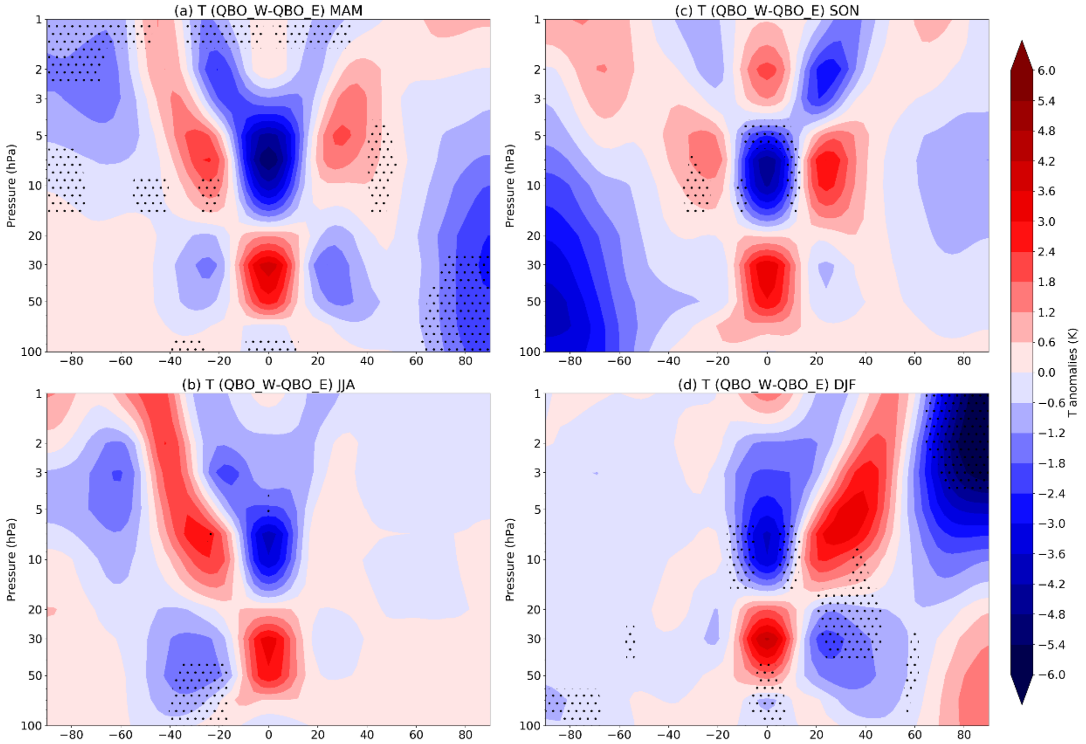

Figure R2. Latitude-height cross-section of temperature anomalies associated with QBO (QBOW-QBOE) based on ERA5 data for the period 1985-2020. **(a)** MAM. **(b)** JJA. **(c)** SON. **(d)** DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

Finally, the color range around the zero value is indicated by white in the most of the figures. This makes the positive and negative anomalies around zero hard to distinguish. It would be better to change the color scale so that the blue shades can indicate negative anomalies and the red shades can indicate positive ones, with the boundary at the zero value.

Thanks for the good comments. We have adapted all the figures as suggested.

Minor comments

Lines 24 and 25: “Fahey et al., 2018” should be “WMO, 2018”
Corrected.
Lines 145–147: The explanation of positive and negative anomalies around the South Pole is not evident from Figure 2(a) and (b) because the negative and positive anomalies are represented by the same color (white) in the range [-2, 2].
We have adapted Figure 2 and now it is more evident. Some of the descriptions are also modified due to the new figure.
Lines 175–176: The positive anomaly over the equator from ERA5 is not separated vertically, which is different from C3S.

Sorry for the inaccuracy description. We have updated the description as follows: "QBO signals in ERA5 ozone (Fig. 4b) are in good agreement with the merged satellite data, except that the positive anomalies over the equator from ERA5 are not separated vertically."

Lines 177–178: The positive anomaly in the upper stratosphere from the CESM-WACCM Natural run is located at a little higher altitude and extended higher than the observations.

Sorry for the inaccuracy description. We have updated the description as follows: "The CESM-WACCM model also shows good consistency with the satellite and ERA5 data in the Natural run with a QBO nudging (Fig. 4c), although the positive anomaly in the tropical upper stratosphere from the Natural run is located at a little higher altitude and extended higher than the observations, and the negative signals are extended higher up to the upper stratosphere in the extra-tropics.".

Lines 188–192: The transport effect is important in the lower stratosphere, but I think in the middle and upper stratosphere in the tropics, the chemical effect through temperature change is also important (e.g., Fig.1 of Solomon et al., 1985). For example, the positive ozone anomalies above 10 hPa in the tropics may partly or almost totally be caused by negative temperature anomalies that can be caused by the positive w* anomalies. It would be helpful if the authors could show the latitude–height cross section of temperature anomalies.

Thanks for the very helpful suggestion. We have added a figure to show the latitude–height cross section of the temperature anomaly associated with QBO as the reviewer suggested and discussed this in the revised manuscript.

Lines 207–208: If you discuss correspondence to TCO, checking the ozone anomaly around 50 hPa as well as 10 hPa would be necessary, because ozone concentration (molecules per volume) is at its maximum around 50 hPa. Although the anomaly at 50 hPa is described at the end of the paragraph, I would recommend mentioning ozone anomalies at these two pressure levels accordingly.

Thanks for the good comment. We have added two figures to show the corresponding changes of ozone at 50 hPa associated with QBO and also more discussion about the 50 hPa ozone anomalies in the revised manuscript.

Lines 209–211: What is the meteorological field behind this ozone anomaly distribution at 10 hPa? Are Figures S5 and S6 helpful to explain it?

Yes, the ozone anomalies can be explained by the geopotential height anomalies as shown in Fig. R3c and Figs. S5-S6. Comparing Figure R3 and Figure 8 in the main text, positive ozone anomalies are well located in the regions with positive geopotential height anomalies, which indicate a weaker polar vortex. We have added some discussion about this in Section 3.4.

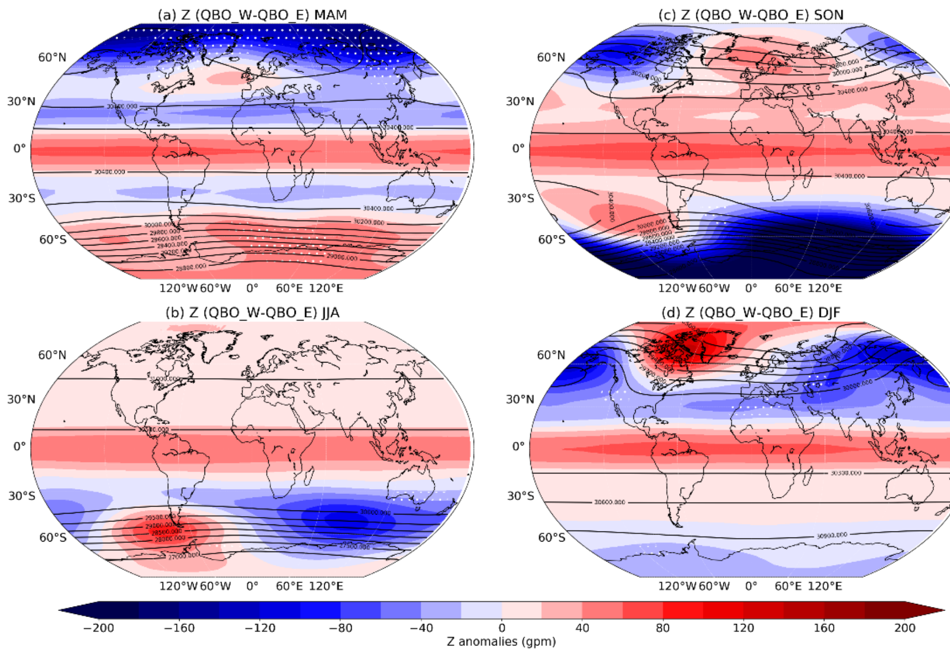

Figure R3. Influences of QBO (QBOW-QBOE) on global geopotential height (Z at 10 hPa) based on ERA5 data for the period 1979-2020. The climatological mean of geopotential height in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

Lines 239–240: I do not agree. In the framework of gas phase chemistry, a low-temperature anomaly leads to a high ozone-concentration anomaly due to the temperature dependence of reaction coefficients. The region where the low-temperature anomaly leads chemically to a low-ozone anomaly is limited in the polar lower stratosphere where heterogeneous reactions on the PSCs work.

We apologize for the mistake here. Yes, low temperatures should lead to high ozone concentrations in the tropics of the stratosphere. We have corrected the description correspondingly.

Line 250: I think that over the Antarctic, the ERA5 data show negative anomalies in the western hemisphere as well as the eastern hemisphere. A zonally asymmetric anomaly is evident only around 60ºS.

Sorry for the inaccuracy description. We have updated the description as follows:

"On the other hand, there are some negative ozone anomalies in the eastern hemisphere (0-140 º W) around 60º S from the ERA5 data (Fig. S3), although the signals are not statistically significant."

Lines 293–294: I do not agree in terms of ozone in the middle and upper stratosphere in the topics but agree in terms of TCO.

Sorry for the inaccuracy description. We have updated the description as follows:

"According to the analysis of meteorological parameters, we found that the QBO influences on ozone are related to both dynamical transport and temperature-dependent chemical production.".

References:

Elsbury, D., Peings, Y., and Magnusdottir, G.: Variation in the Holton-Tan effect by longitude, Quart. J. Roy. Meteor. Soc., 147, 1767–1787, https://doi.org/10.1002/qj.3993, 2021.

Garfinkel, C. I., Shaw, T. A., Hartmann, D. L., and Waugh, D. W.: Does the Holton-Tan Mechanism Explain How the Quasi-Biennial Oscillation Modulates the Arctic Polar Vortex?, J. Atmos. Sci., 69, 1713–1733, https://doi.org/10.1175/JAS-D-11-0209.1, 2012.

Naoe, H. and Shibata, K.: Equatorial quasi-biennial oscillation influence on northern winter extratropical circulation, J. Geophys. Res., 115, https://doi.org/10.1029/2009JD012952, 2010.

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