Responses to Reviewer 1

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.

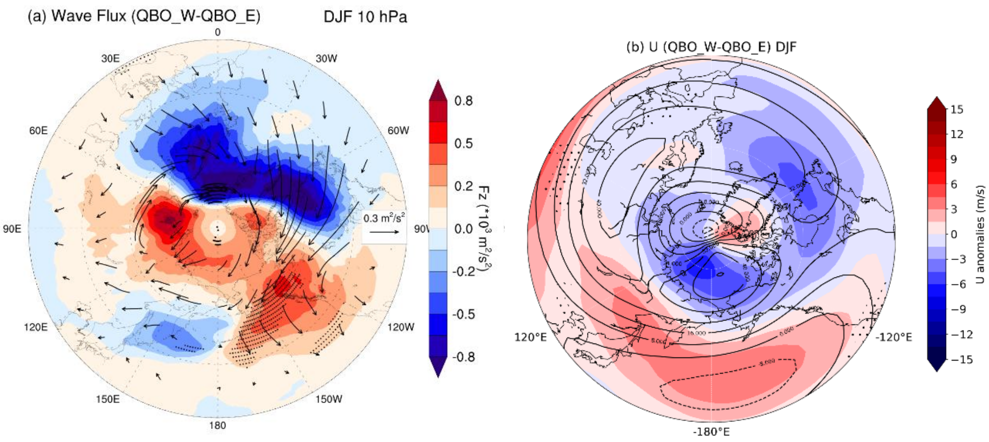
I think the results presented in this manuscript are interesting and scientifically valuable. However, I would like to recommend carefully and thoughtfully describing the correspondence of their results to those in preceding studies that were performed during shorter period and reported as a function 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. The comments are shown in black and our replies are marked as blue.

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).



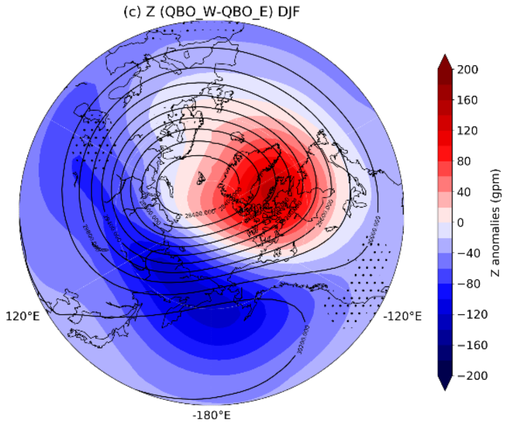


Figure R1. Influences of QBO (QBOW-QBOE) on T-N Flux (a), zonal wind (b) and geopotential height (c) in different seasons at 10 hPa based on ERA5 data for the period 1979-2020. The meridional and zonal components of T-N Flux are shown as vectors and the vertical component is shaded in (a). In (b) and (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.

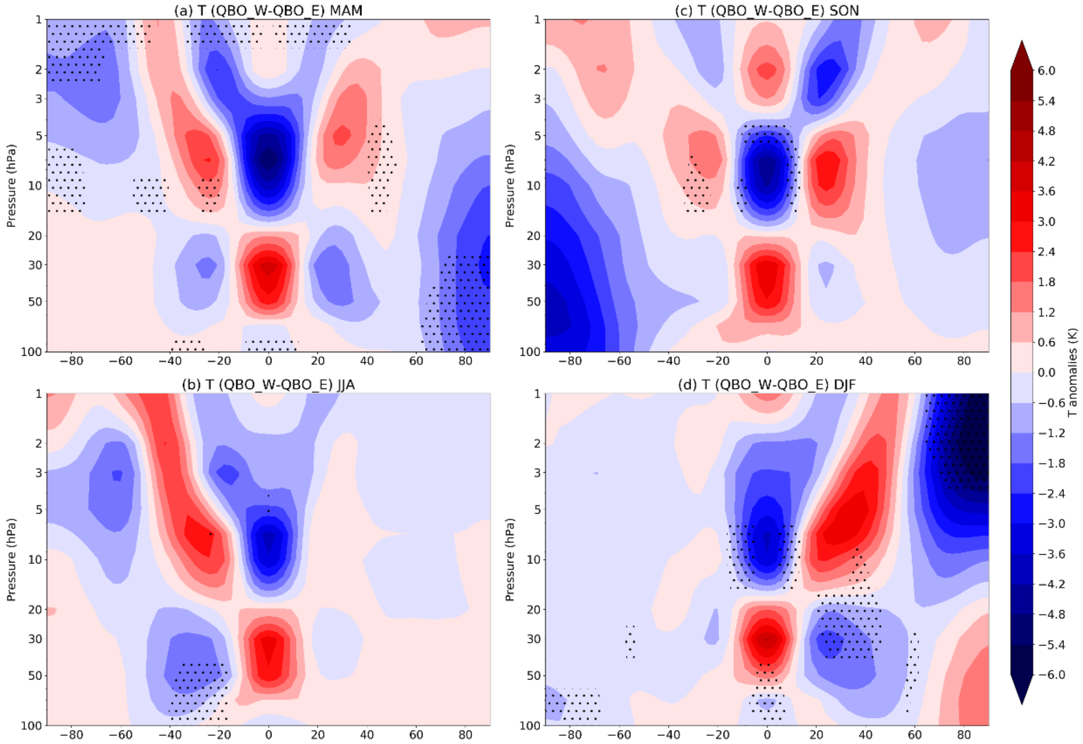


Figure R2. Latitude-height cross-section of temperature anomalies associated with QBO (QBOW-QBOE) based on ERA5 data for the period 1985-2020. **(a)** MAM. **(b)** JJA. **(c)** SON. **(d)** DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed 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.

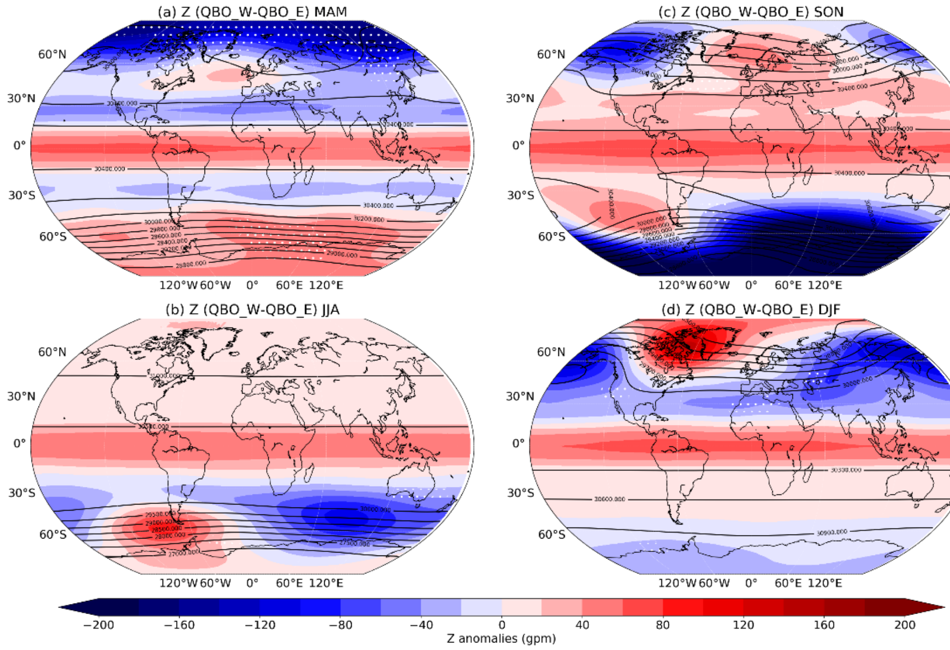


Figure R3. Influences of QBO (QBOW-QBOE) on global geopotential height (Z at 10 hPa) based on ERA5 data for the period 1979-2020. The climatological mean of geopotential height in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results that are statistically 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.

Takaya, K. and Nakamura, H.: A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow, J. Atmos. Sci., 58, 608–627, 2001.

Zhang, J., Xie, F., Ma, Z., Zhang, C., Xu, M., Wang, T., and Zhang, R.: Seasonal Evolution of the Quasi-biennial Oscillation Impact on the Northern Hemisphere Polar Vortex in Winter, J. Geophys. Res., 124, 12 568–12 586, https://doi.org/10.1029/2019JD030966, 2019.

Responses to Reviewer 2

Wang et al investigate the influence of the QBO on total column ozone and stratospheric ozone. The authors confirm previous work on the role of the QBO for tropical and subtropical ozone. The main novelty of this paper is that it finds that the QBO at 20hPa has a zonally asymmetric imprint on subpolar ozone that is especially pronounced in DJF. This zonal structure occurs despite the QBO at 20hPa having a relatively weak impact on zonal mean stratospheric conditions. This result is not particularly surprising, but appears to not have been noticed before. A similar effect is also evident in a chemistry-climate model.

There are several major issues with the paper in its current form as described below. After these are addressed this paper should be publishable.

We thank the reviewer for the valuable comments and suggestions which helps to improve the manuscript substantially. 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 can be found in the revised manuscript as well as the point-to-point response as follows. The comments are shown in black and our replies are marked as blue.

Major comments:

1. I found the stippling on the plots that are intended to indicate statistical significance confusing. On most figures, regions with no discernable anomaly are still stippled, while the strongest anomalies are often not stippled at all. The simplest explanation is that there is a bug somewhere, however I apologize if I misunderstood something.

We have checked the code carefully, and there is not any bug in the code. In the region with strong anomalies, the variability is also large, which makes it hard to pass the statistical significance. For example, the standard deviation and the QBO signals of geopotential height (Z) are shown in the figure R4. The standard deviation of geopotential height is very large during DJF in the Arctic and during JJA and SON in the Antarctic, which makes the strong geopotential height anomalies not statistically significant.

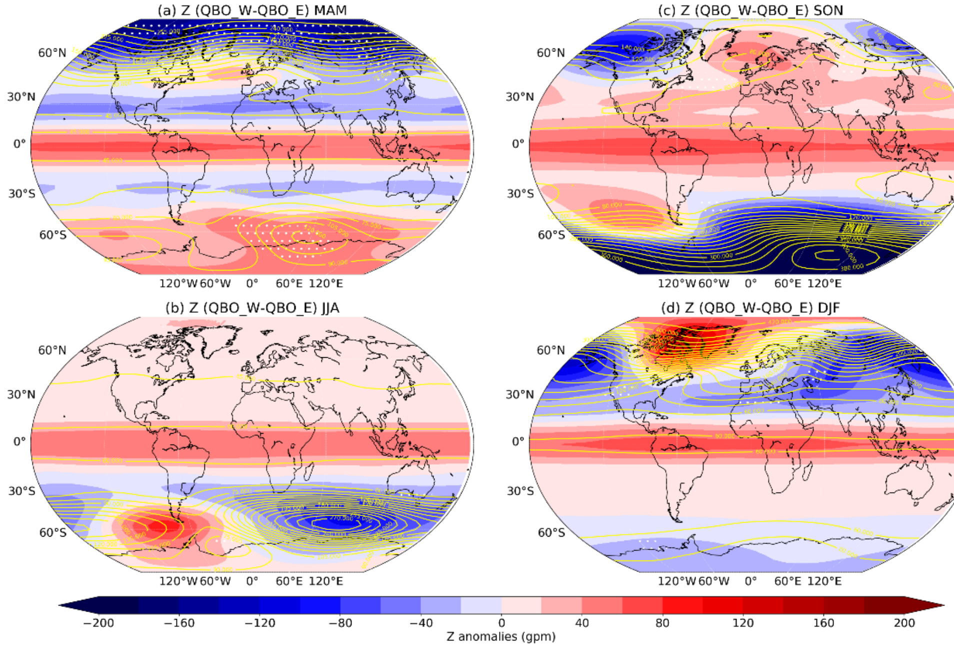


Figure R4. Influences of QBO (QBOW-QBOE) on global geopotential height (Z at 10 hPa) based on ERA5 data for the period 1979-2020. The standard deviation of geopotential height in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

2. The key results of this paper appear to be only significant at the 90% level, if I understand the paper correctly. This is a fairly low bar. Would all significance in polar regions go away if the threshold was raised to 95%? Relatedly, it is surprising that the zonal structure in Figure 3d (in DJF when zonal structure is strongest) is not significant while it is in the annual average in Figure 2. Presumably this is because there is more variability in DJF, but this just begs the question as to how robust this zonal asymmetry truly is. In particular there is no clear explanation as to why this particular phase of the QBO should have the effect on Z* that it appears to have had over these ~40 years, and so I'm skeptical that additional data will necessarily support the authors conclusions. That being said, the model runs help demonstrate robustness.

We thank the reviewer for the valuable comments. We have updated all the figures to raise the significance to the 95% threshold, and the results do not change that much. We apologize for choosing the 90% level in the last version of the manuscript. As the reviewer indicated, the variability of TCO in DJF is strong, especially over the regions where the QBO related anomalies are strong. This can be seen from the standard deviation of TCO in different seasons as shown in Figure R5. The other possible reason is that Figure 2 used monthly anomalies with data samples of 492, while Figure 3 used seasonal mean with only 41 data samples, which will reduce the freedom of the significance test.

To further show the robustness of the results, we show the corresponding QBO signals of TCO in our Natural and NOQBO simulations in Figure R6. With a longer period of 145 years, the TCO anomalies associated with QBO in the Natural simulation are more significant. The robust impact of QBO on TCO can be further confirmed by the large difference between the Natural and NOQBO simulations. While the QBO is not nudged in the NOQBO simulation, the signals shown in the Natural run disappear.

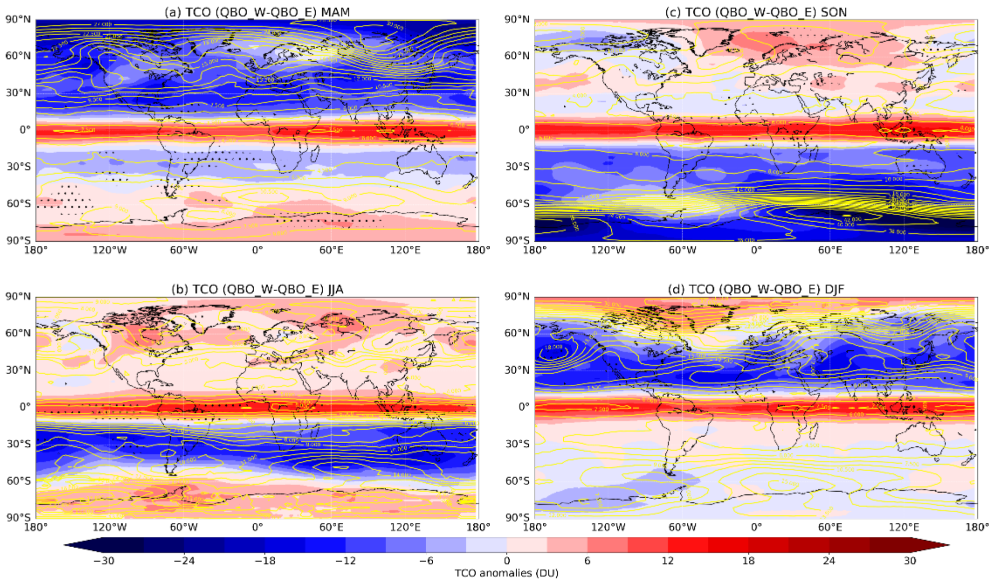


Figure R5. Influences of QBO (QBOW-QBOE) on global total column ozone (TCO) in different seasons based on MSR2 data for the period 1979-2020. The standard deviation of TCO in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

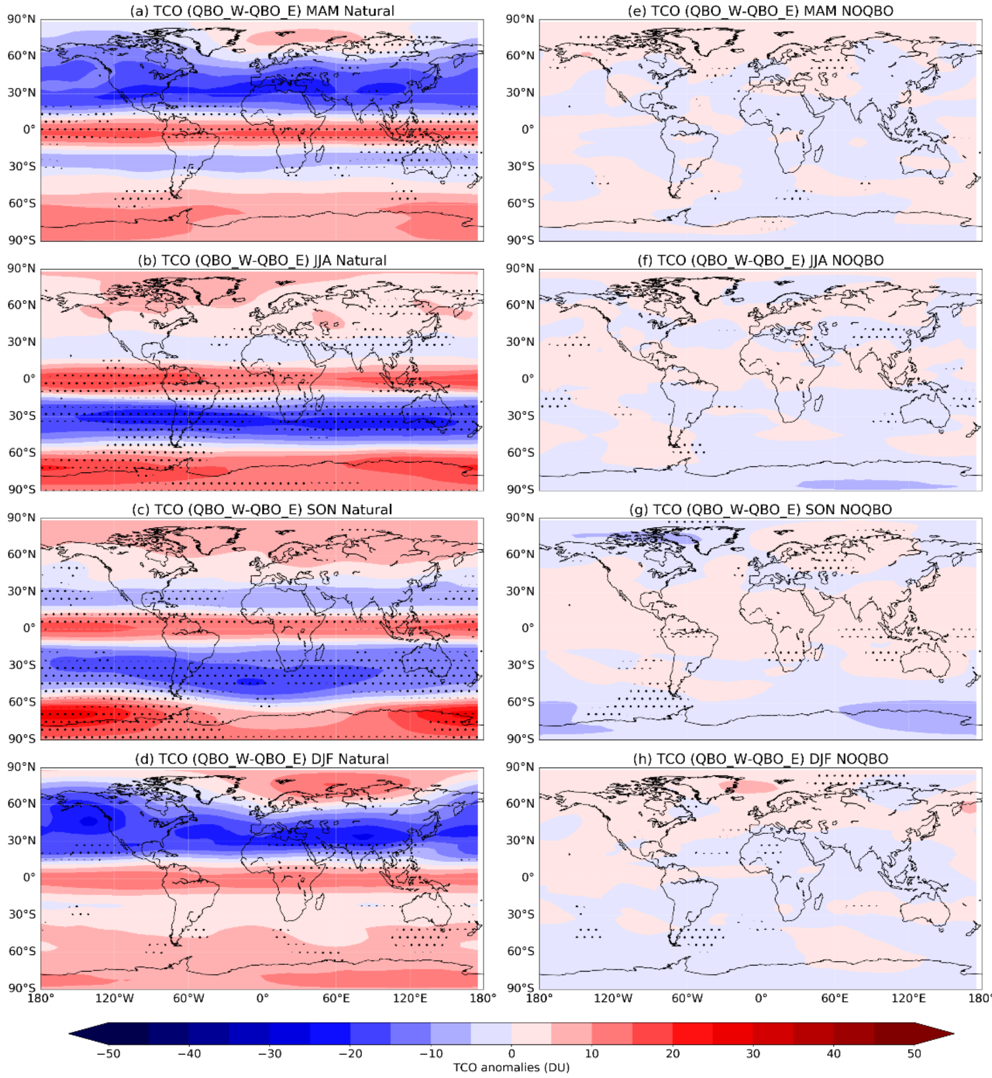


Figure R6. Influences of QBO (QBOW-QBOE) on global total column ozone (TCO) in different seasons from the Natural (left) and NOQBO (right) simulations for the period 1955-2099. (a, e) MAM. (b, f) JJA. (c, g) SON. (d, h) DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

3. The dynamical explanation in Section 3.4 (lines 244-247) needs further refinement. Specifically, why exactly is a local ridge associated with more ozone, and a local trough with less ozone, in Figure 11? If it was just meridional advection, then the ozone anomalies should be collocated with the nodes of the height pattern, not the extrema.

We thank the reviewer for the good comments. The positive geopotential height anomalies in eastern North America and western Eurasia, and the negative anomalies over other regions of the Arctic, indicates a shift of the polar vortex. While the polar vortex acts as a barrier that damps the meridional transport and mixing between the polar region and the midlatitudes, it is very cold and the ozone concentrations are very low in the polar vortex. This shift of the polar vortex therefore leads to positive ozone anomalies in eastern North America and western Eurasia and negative ozone anomalies in eastern Eurasia and the North Pacific. As the other reviewer indicated, temperature changes should be also considered for the ozone changes since the chemical reactions are temperature dependent. We then added some discussion about the influences of the temperature-dependent chemical effects. As shown in Figure R7, there are negative temperature anomalies collocated with the local trough. In the polar region, cold temperature anomalies may lead to more ozone destruction and subsequent negative ozone anomalies. Therefore, ozone anomalies may be caused by a combined effect of dynamical transport and temperature-dependent chemical reactions. We have added some discussions in the revised manuscript.

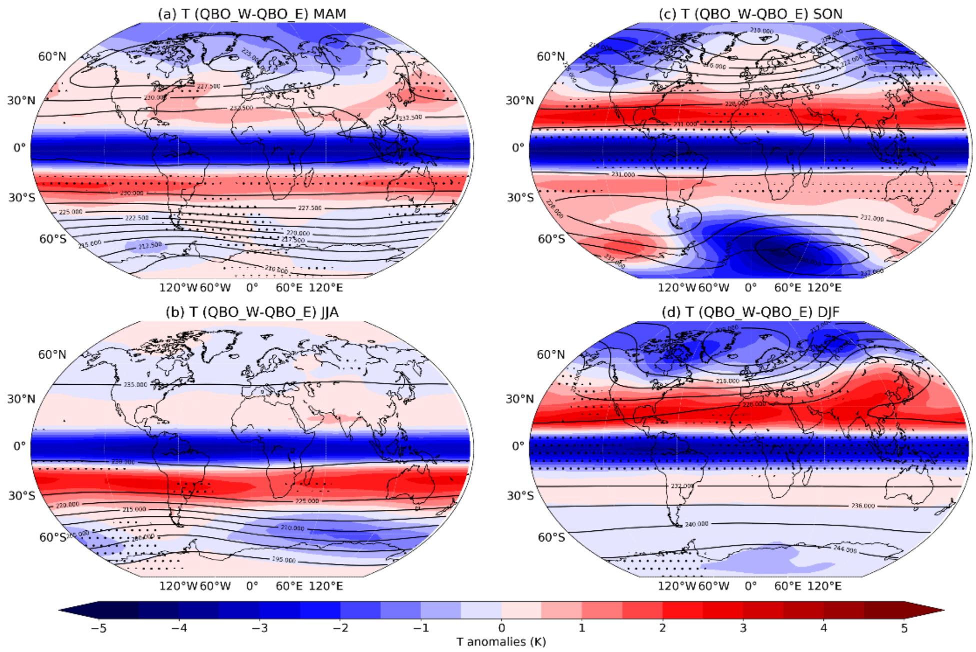


Figure R7. Influences of QBO (QBOW-QBOE) on the global temperature at 10 hPa in different seasons based on ERA5 data for the period 1979-2020. The climatology mean of temperature at 50 hPa in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

4.Much of the discussion and many of the figures more or less confirm earlier published work. (I'm specifically referring to the tropical and subtropical impacts of the QBO.) In this reviewer's opinion these figures can be moved to supplemental material, in order to focus more on the novel results.

We agree with the reviewer that there are some figures and discussions about the tropical and subtropical impacts of the QBO similar to earlier published work. We have reduced some of the discussions. However, including these figures would be helpful for the readers to understand the impacts of QBO from the tropics to extra-tropics and from zonal mean to zonal structures. In addition, the other reviewer shows interests in and has some comments about the zonal mean features of the QBO impacts. We are sorry but hope to keep the figures in the main text.

Minor comments:

1. There are two papers the authors appear to have not cited that are relevant to zonal asymmetries in the polar response to the QBO: Silverman et al 2018 and Elsbury et al 2021. While the focus in the current work differs from these paper, these papers should be discussed

   Thank you very much for the important information. The papers help us a lot to further understand the underlying mechanism. We have cited the two papers and added some discussion in the revised manuscript.

2. Line 39-40: It is unclear what is the precise mechanism whereby the QBO affects the polar vortex. Garfinkel et al 2012 find evidence for a different mechanism though it is still unclear which mechanism is most important. This is discussed in the Elsbury et al paper

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

   "Such changes in zonal winds modify the vertical propagation of planetary waves and influence the strength of the polar vortex as well as the Brewer-Dobson circulation (BDC) according to the Holton-Tan mechanism (Holton and Tan, 1980, 1982; Watson and Gray, 2014; Zhang et al., 2019; Baldwin et al., 2019) or the QBO implicit meridional circulation mechanism (Garfinkel et al., 2012; Elsbury et al., 2020), and therefore play an important role in determining the dynamical circulation in the whole stratosphere (Naoe and Shibata, 2010; Garfinkel and Hartmann, 2011a, b; Anstey and Shepherd, 2014; Andrews et al., 2019; Zhang et al., 2020)."

3. There are numerous technical edits that need to be made. Please send the paper to an English editor.

   We are sorry for that. However, it is not easy for us to find a native speaker to help us with the manuscript. We have checked the whole manuscript carefully from sentence to sentence and hope the text has been improved significantly.

4. Line 43 compositions -> trace gases.

   Corrected.

5. Line 53: the details of where the peaks lay depends on the level used to define the QBO

   Thanks. We have modified the sentence as suggested.

6. Line 59 how are global patterns of ozone important for regional health? Please revise.

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

   "While the global pattern of ozone changes is important to the regional UV radiation as well as weather and climate, it is therefore interesting to look through the zonal differences of QBO in ozone."

7. Line 189-190 This discussion implies that the upper stratospheric ozone anomaly is dynamically driven and not photochemically driven. Please provide additional evidence/discussion as to whether photochemical processes are indeed not important

   Sorry for the misunderstanding here. Photochemical processes may also contribute to the ozone anomalies here. We have revised this sentence and added some discussions here.

8. Line 233-234 implies a specific direction of causality between T and vertical wind anomalies. While the statement is clearly true, the direction of causality is not necessarily clear, as both the T and w responses are fundamentally linked to the wind shear via thermal wind balance and mass continuity.

   Thanks for the good comments. We have revised this sentence as follows:

   "This is possibly related to the anomalously strong upwelling of the BDC in the tropics as seen in Fig. 6 and subsequent dynamical cooling."

Elsbury, D, Peings, Y, Magnusdottir, G. Variation in the Holton–Tan effect by longitude. Q J R Meteorol Soc. 2021; 1767– 1787. https://doi.org/10.1002/qj.3993

Silverman, Vered, Nili Harnik, Katja Matthes, Sandro W. Lubis, and Sebastian Wahl. "Radiative effects of ozone waves on the Northern Hemisphere polar vortex and its modulation by the QBO." Atmospheric Chemistry and Physics 18, no. 9 (2018): 6637-6659.

Garfinkel, C.I., Shaw, T.A., Hartmann, D.L. and Waugh, D.W., 2012. Does the Holton–Tan mechanism explain how the quasi-biennial oscillation modulates the Arctic polar vortex?. Journal of the Atmospheric Sciences, 69(5), pp.1713-1733.

We thank the reviewer for the important information. We have read through the papers carefully and cited these references in the revised manuscript.