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.

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 a 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 R1. 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.

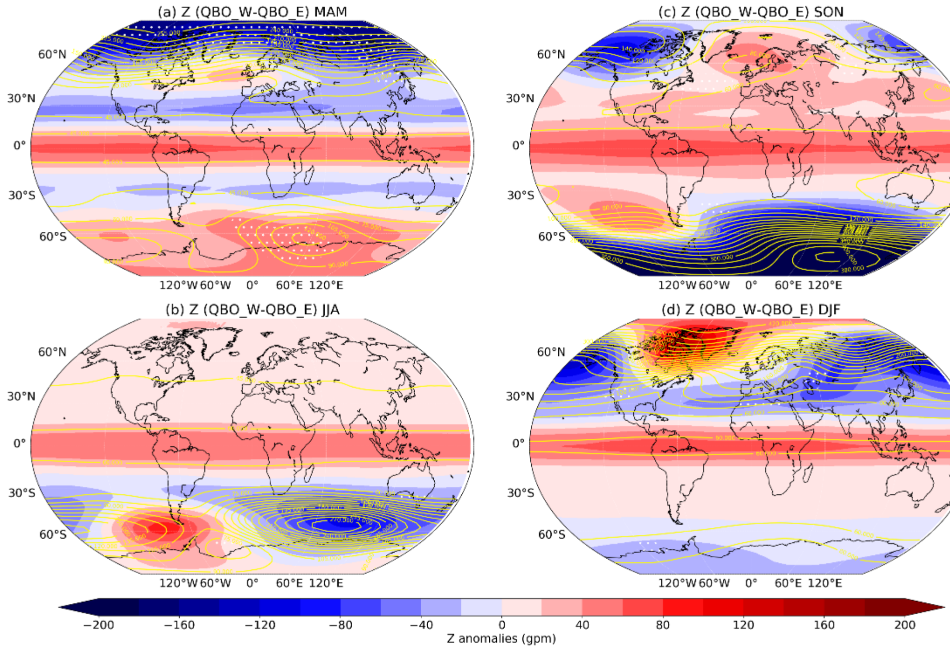


**Figure R1.** Influences of QBO (QBOW-QBOE) on global geopotential height (Z at 10 hPa) based on ERA5 data for the period 1979-2020. The standard deviation of geopotential height in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results that are 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 R2. 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 R3. 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.

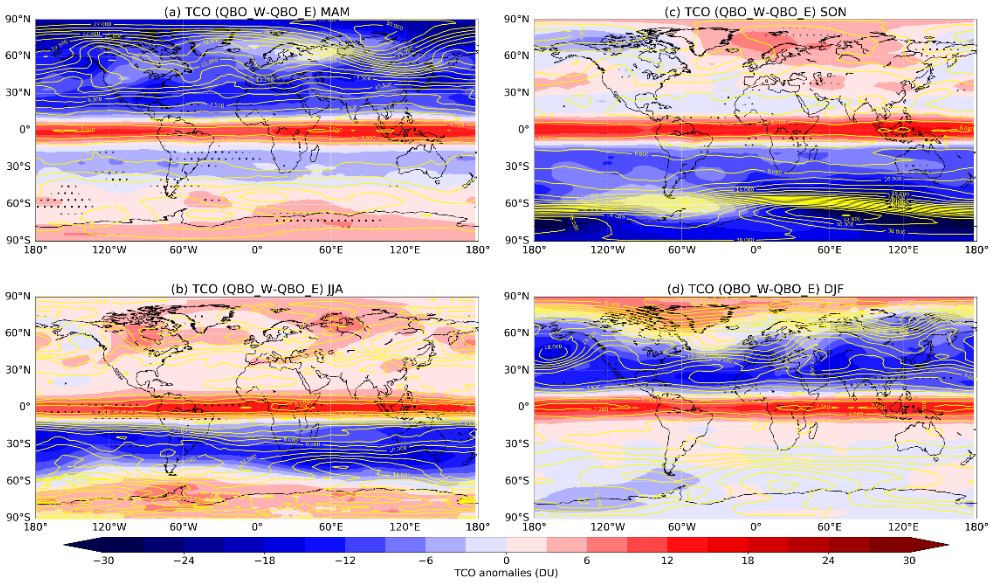


**Figure R2.** Influences of QBO (QBOW-QBOE) on global total column ozone (TCO) in different seasons based on MSR2 data for the period 1979-2020. The standard deviation of TCO in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results that are statistically significant over the 95% level, using the two-tailed Student's t-test.

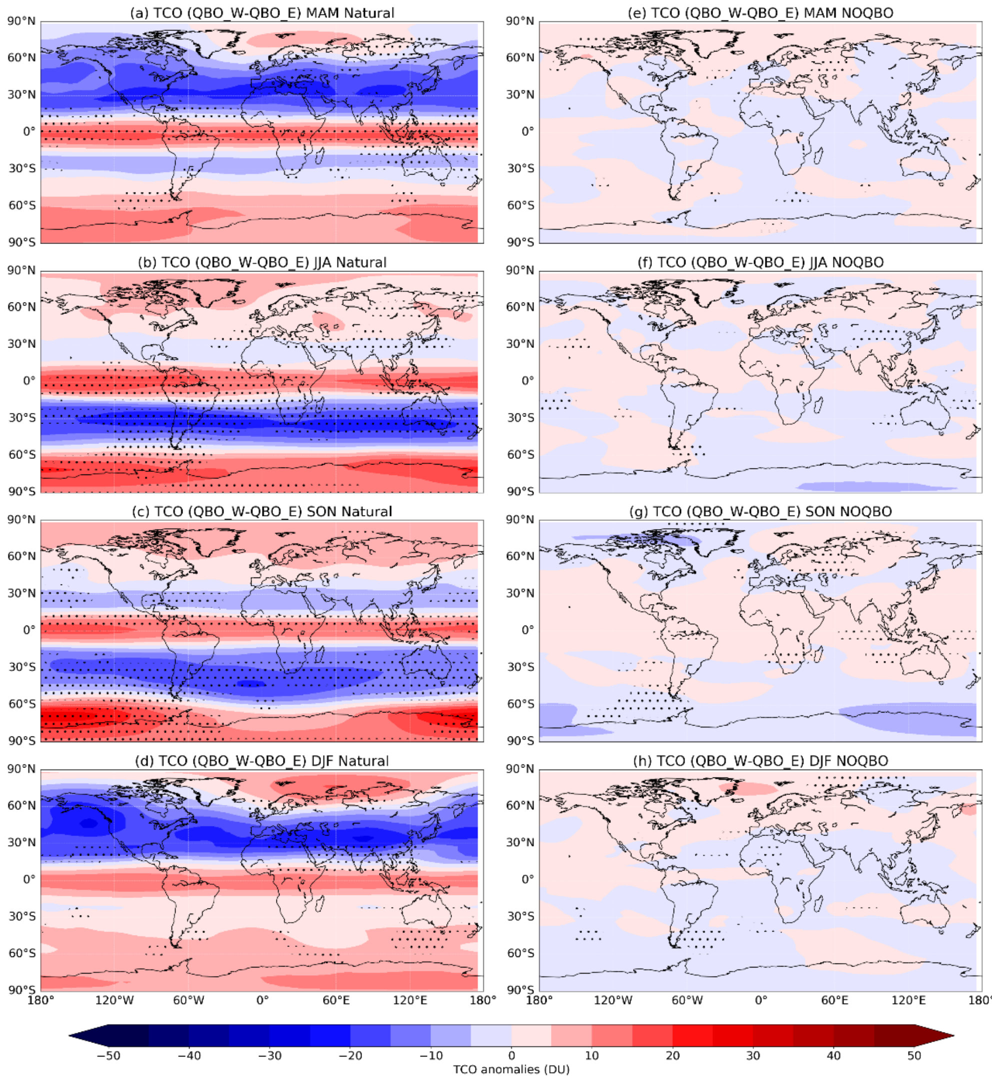


**Figure R3.** Influences of QBO (QBOW-QBOE) on global total column ozone (TCO) in different seasons from the Natural (left) and NOQBO (right) simulations for the period 1955-2099. (a, e) MAM. (b, f) JJA. (c, g) SON. (d, h) DJF. Stippled areas indicate results that are statistically significant over 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. 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 R4, 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.

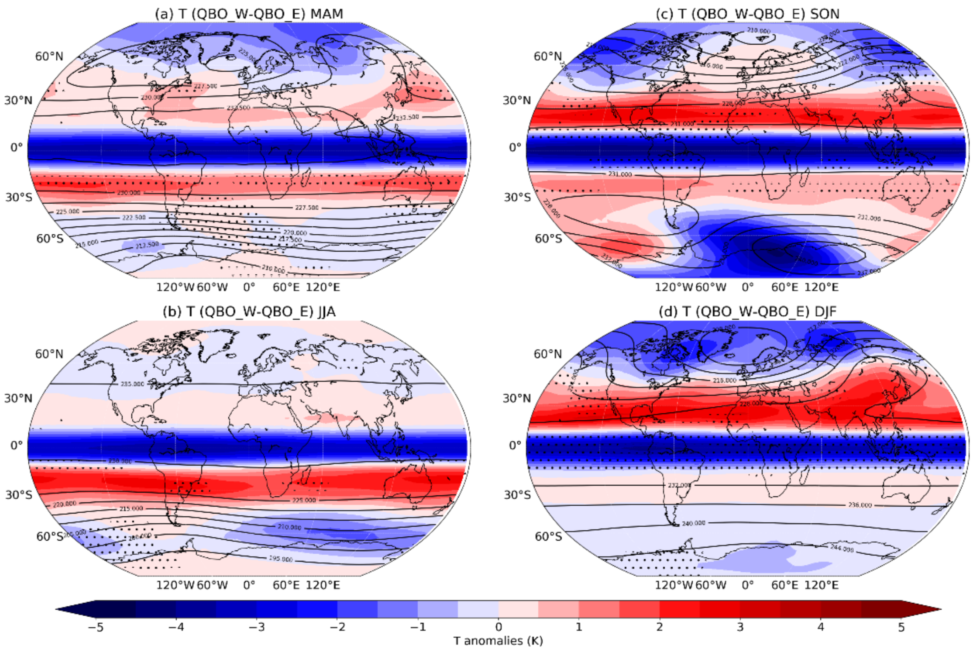


**Figure R4.** Influences of QBO (QBOW-QBOE) on the global temperature at 10 hPa in different seasons based on ERA5 data for the period 1979-2020. The climatology mean of temperature at 50 hPa in each season is also shown (contour lines). (a) MAM. (b) JJA. (c) SON. (d) DJF. Stippled areas indicate results 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.