Responses to Reviewer #3

Reviewer #3

This paper presents an analysis of the effect of the QBO on stratospheric water vapor, in particular comparing boreal winter and summer. The first part of the analysis is based on ERA5 reanalysis and SWOOSH observations, the second part on CMIP6 climate model simulations. In my opinion, the main new results are: (i) differences in stratospheric water vapor between QBO westerly and easterly phases are significantly smaller in boreal summer than winter, (ii) this seasonal difference in the QBO effect is partly related to stratospheric circulation and partly to convection, (ii) current climate models have issues in simulating these seasonal differences.

Overall, I think this paper addresses an interesting question, presents valid analysis and new results, and should be suitable for publication in ACP. However, I have 2 major comments and a list of specific comments which I'd ask the authors to address before I can recommend publication.

Response: Thanks for your suggestion, which has been very helpful in improving the quality of our paper. We have carefully revised the paper based on the reviewers' comments.

Major comments:

1.) Vertical propagation of QBO effect:

This comment concerns the comparison of the QBO effect on water vapor at different levels. For instance, the paragraph starting at L156 is not clear and even somewhat misleading to me. Why is it meaningful to compare correlations between zonal wind and water vapor calculated at different levels? I see basically two pathways how the QBO can affect stratospheric water vapor: by modulating tropical tropopause temperatures and by modulating stratospheric transport (e.g. via induced secondary circulation). I'd suggest to decribe these two pathways clearly, e.g. already in the introduction.

Response: Thanks for your suggestion. We removed the comparison of water vapor and zonal wind QBO at different levels. In the revised manuscript, we described more clearly the two ways through which QBO affects SWV. That is, how QBO affects the cold point temperature of the tropopause and the transport effect of the BD circulation.

- "The dehydration effect by cold temperature in the lower stratosphere is also more effective in boreal winter than in summer. The intensity of the QBO-related secondary circulation is stronger in the boreal winter than in summer, which not only influences the cold point tropopause temperature in tropical regions but also drives the transport of stratospheric water vapor. The mean vertical transport term via the QBO-related residual circulation is the leading factor controlling the water vapor distribution in the tropical lower stratosphere." (L17-21)
- The effect of QBO on the tropopause temperature is added in Section 4.2. This effect is maximized at a lag of 6 months. The QBO-related secondary circulation distribution and its effect on water vapor transport is also diagnosed using the continuity equation.

- Those two pathways are also summarized in the last section. (L431-444)

The signal from modulating tropical tropopause temperatures propagates upwards and therefore comparison of regressions at different levels needs including lag times. Said that, couldn't it just be that the significant positive correlation at 70 an 10hPa just coincidentally results from the upward propagating tape recorder signal (Fig. 1) and downward propagating wind anomalies (Fig. 2), but has no deeper physical meaning? I see similar difficulties when interpreting Fig. 4, which also compares the QBO effect at different levels. Hence, I'd suggest to include such lag times for a proper comparison of the QBO effect at different levels (e.g. correlating water vapor at different levels with one QBO-index at 30hPa, including lag, see Diallo et al., 2022, https://doi.org/10.5194/acp-22-14303-2022). If this goes beyond the scope of the paper, one could also remove Figs. 3 and 4 and the related discussion from the paper, but then clearly state early in the paper that the QBO here is always defined at 30hPa. Related to that, the respective sentences in the abstract (L15) and summary (L402) need to be clarified or removed.

Response: Thanks for your suggestion. We have modified the original Figure 3 to display the 30 hPa QBO index in relation to water vapor at different levels, and have calculated the lag correlation coefficients between the 30 hPa QBO index and water vapor at each level. See the revised Figure 4.

- "Figure 4 shows the lagged correlation coefficients between the QBO index at 30 hPa and the WV at each level……." (L199-)
- The time lag of QBO's impact is also considered this time. (L279-293).
- "The primary source of SWV is tropical tropospheric WV entering the stratosphere. Figure 4 shows that the modulation effect of 30 hPa zonal wind QBO on 100 hPa WV reaches its maximum after a lag of half a year..." (L220-)
- "As the influence of the QBO signal gradually propagates to lower layers, the temperature anomaly with a lag of 6 months at 100 hPa is shown in Figure 7….." (L279-287)
- Meanwhile, the original Figure 4,5, which depicts water vapor profiles under different QBO phases, remains scientifically meaningful. It illustrates a vertical cross-section of QBO's influence on water vapor, specifically showing the positive-negative-positive structure from bottom to top during QBO westerly phases, with notable differences between northern winter and summer. We have condensed the related content in the main text and moved the figure to the supplementary materials (Figs. S2, S3).
- "During both winter and summer, the influence of QBO on tropical stratospheric WV entry is nearly symmetrical. Under the QBO westerly phase as an example, the distribution of tropical stratospheric WV displays a sandwich structure with positive, negative and positive WV anomalies from the lower to upper layers (Fig. S2). Further, the WV anomalies in the lower stratosphere during winter are stronger than during summer (Fig. S3)." (L216-219)

The abstract and summary have been revised.

- "The 30 hPa QBO index exerts the greatest influence on 100 hPa water vapor at a lag of six months. During northern summer, the peak amplitude of 100 hPa water vapor under different QBO phases in tropical regions reaches ±0.12 ppm at a six-month lag, while in winter it reaches ±0.2 ppm." (L14-17)
- "The 30 hPa QBO index exerts the greatest influence on 100 hPa WV at a lag of six months, and previous studies have also discussed the lag effect of the QBO index on WV in the low stratosphere (Diallo et al., 2022; Ziskin et al., 2022)." (L423-425)

2.) New results versus state-of-the-art:
At some parts the paper is not very clear in what the new results and what just state-of-the-art is. For instance in the summary there are large text parts describing well-known facts regarding the QBO (e.g. L410-418), and also in the rest of the paper (see a few of my specific comments below). Sure, it is absolutely necessary to relate to previous work. But I'd recommend to say more clearly what the new findings of this paper are (my view on these is summarized in my general comment above). Perhaps a clearer structuring of the summary around these could be helpful (first stating the respective new finding, then discussing). Also, formulating related research questions in the introduction could help the reader here.
Response: Thank you for your suggestions. We have revised and refined the abstract (L10-23) and conclusions (L415-461) accordingly.
The research significance has been added to the Introduction.
- "The research on the seasonal differences of WV QBO not only deepens the multi-time scale understanding of the stratospheric and tropospheric coupling, but also provides a scientific basis for cross-seasonal climate prediction." (L76-77)

Specific comments:
L18: I don't understand what is meant by "...dynamic transport...", probably "vertical transport"? And also the connection to the next sentence is not clear to me. Sure, in boreal winter dehydration is stronger. Please reformulate both sentences to clarify what is meant.
Response: This sentence has been relocated.
- "The dehydration effect by cold temperature in the lower stratosphere is also more effective in boreal winter than in summer." (L17-18)

L35: The "tropical path" is the "primary channel" for water vapor into the stratospheric overworld - for the lowermost stratosphere this is not clear. Please clarify.
Response: Changed.
- "The WV in the stratosphere mainly comes from the upward transport of tropospheric water vapor in the tropics……" (L32-)

L134: Overall, I find the agreement between ERA5 and SWOOSH here not too strong and would recommend to discuss the differences in more detail (e.g. the too fast upward propagation of the signal in ERA5, or the too strong dampening of the amplitude).

Response: Thanks for your suggestion. We have revised and only displayed water vapor anomalies below 10 hPa. The similarities and differences between ERA5 and SWOOSH satellite observations have been compared.

- "In terms of data and methods, we compared ERA5 reanalysis with SWOOSH satellite monitoring data and found that ERA5 reanalysis data could reproduce the distribution pattern of SWV (Fig. 1)……" (L164-)

L137: I'm wondering about the years after 2015. Why is there no clear QBO signal in water vapor during these years in ERA5? SWOOSH observations show a water vapor QBO also in these years. Pleae comment.
Response: Thanks for the feedback. We rechecked the code, and the WV QBO signal in the new plot is much clearer. (Figure 2, Figure S1)

Figure 2, caption: State the dataset used (ERA5) in the caption. Also describe the contour values and the meaning of dashed/solid.
Response: Thanks for your suggestion. Changed to "Temporal variations of zonal mean zonal wind anomalies (contours; units: m/s) and temperature anomalies (shadings; units: K) averaged over the equator (5°S–5°N) with removed linear trends in the tropical stratosphere from 1960–2019 for ERA5 reanalysis. The contours are shown at ±15 m/s and ±30 m/s." (L191-193)

L156ff: Refer to Fig. 3 at the beginning of the text where it is discussed.
Response: Figure 3 has been revised (revised Figure 4) to show lag correlations based on the main comments, and the corresponding text has also been modified.

- "Figure 4 shows the lagged correlation coefficients between the QBO index at 30 hPa and the WV at each level....." (L199-)

L162: The weakening of the QBO signal above 5 hPa is well known, and one could refer to e.g. Baldwin et al. (2001). (This comment is related to major comment 2).
Response: This section has been removed from the revised version.

L164: What relationship is to be expected? Please clarify.
Response: This section has been removed from the revised version.

Figure 4, caption: Explain the meaning of the shading in the caption.
Response: The original Figure 4 has been moved to the Supplementary Materials. Added "Dots denote statistical significance at the 95% confidence level based on Student t-test." (Fig. S2)

L258: I don't understand the intention behind this sentence "rising branch in the tropics stronger than the sinking branch in the extratropics". Tropical upwelling should always be balanced by extratropical downwelling. Please clarify.
Response: Changed to "Under the QBO easterly phase in the northern winter, the lower stratosphere vertical residual velocity anomaly shows upwelling in the tropics and

sinking in the Northern Hemisphere subtropics with the ascending branch in the tropics being stronger." (L311-313)

Figure 7: It would be good to have the same y-axis range and labels as in other figures (e.g. Fig. 4, 6) to ease comparison.
Response: The y-axis of Figure 7 is modified to be consistent with the previous figures.

Figure 7, caption: Residual circulation upwelling (!) ... And then give the units directly after "upwelling", not just at the end of the caption.
Response: Thanks for your suggestions. Revised.

- "Figure 8. (a) Residual circulation anomalies during the QBO westerly phase in the northern summer (units: 10^{-5} Pa/s). (b) Residual circulation anomalies during the QBO easterly phase in the northern summer (units: 10-5 Pa/s). (c, d) As in a, b but for residual circulation anomalies for the northern winter (units: 10-5 Pa/s). Dots mark the composite vertical residual velocity anomalies at the 95% confidence level. The shading is the vertical component of the residual velocities." (L323-326)

L295: There is a recent paper by Pena-Ortiz et al. (2024, https://doi.org/10.5194/acp-24-5457-2024) which demonstrates a relation between the QBO and convection in the Asian summer monsoon, of relevance for water vapor variability in the monsoon UTLS. I think it could be enlightening to relate the QBO-convection relation found here to their results.
Response: Added.

- "The QBO modulating the temperature signal on the southern side of the South Asian monsoon (i.e., the Indo-Pacific Warm Pool region) in July and August is related to the changes in equatorial clouds, which in turn affect the WV distribution in the upper troposphere and lower stratosphere of this region (Pena-Ortiz et al., 2024)." (L272-275)

Figure 9, caption: Should be "OLR" not "temperature" anomalies in L310.
Response: Thanks for your suggestions. The original Figure 9 has been moved to the Supplementary Materials. Changed "temperature" to "OLR". (Fig. S5)

L312ff: The take home message from the tracer continuity analysis is not becoming very clear to me from the text here. I think the main result is that it is mainly mean advection by the residual circulation that causes the observed differences between easterly and westerly QBO phases. Please clarify the text that this is getting clearer. (This comment is related to major comment 2).
Response: Thanks for your suggestion. We have incorporated a more detailed description and provided a conclusion at the end.

- "Through the above analysis, it can be found that the SWV changes in the tropics caused by QBO are mainly produced by the mean advection term by the residual circulation, and the cold temperature changes resulting from the residual term at

the bottom of the tropical stratosphere also contributes to SWV variations." (L341-343)

L329ff: ERA5 shows a change in the QBO-related anomaly pattern around 10hPa: below there is a tape-recorder of upward propagating anomalies, whereas above there seems to be a more direct effect of transport modulated by the QBO-induced secondary circulation. This change in anomaly pattern is only visible in a few models (e.g. CESM2-WACCM). I find this an important difference between ERA5 and CMIP6 models and would recommend to discuss it.

Response: Thanks for your suggestion. We added this discussion.

- "ERA5 and SWOOSH show a change in the QBO-related anomaly pattern around 10 hPa. Below 10 hPa there is a tape-recorder of upward propagating anomalies, whereas above 10 hPa there seems to be a more direct effect of transport modulated by the QBO-induced secondary circulation (Fig. S1)." (L360-363)

L351: But even for this model the agreement with ERA5 is not very high.

Response: Changed.

- "The WV correlation coefficient between models (CESM2-WACCM-FV2 and MRI-ESM2-0) and the ERA5 reanalysis exceeds 0.8 (Table 1), but even for those two models the biases relative to ERA5 is not little." (L375-377)

L367: Table 1 says that CESM2-WACCM-FV2 for boreal winter has a correlation coefficient of 0.29. So I'm wondering why it is mentioned here as one of the two models where correlation is higher than 0.5.

Response: Changed to "Only one model (AWI CM-1-1-MR) can simulate the seasonal contrast in WV distribution with the pattern correlation exceeding 0.5…" (L386-388)

L375ff: For the analysis here, a QBO index at 50hPa is used. Before (L102ff) it was argued that in this paper a 30 hPa-index is used as only at such high level all models have a sufficiently significant QBO variability. This seems somewhat contradictory to me. Please clarify.

Response: Thanks for your suggestion. Referring to the updated Figure 4, Figure 11 here revised to show the relationship between the 30 hPa QBO index and the 70 hPa water vapor lagging by six months.

- "Figure 11 shows the scatter plots of QBO westerly phase minus easterly phase for the 30 hPa zonal wind index and 70 hPa WV anomalies with a lag of 6 months in deep tropics among CMIP6 models....." (L393-)

L402: The enhanced correlation for lower and upper stratosphere seems method-related to me (see my major comment above). I'd remove this statement here or clarify.

Response: Thank you for your suggestion.

- "The 30 hPa QBO index exerts the greatest influence on 100 hPa WV at a lag of six months, and previous studies have also discussed the lag effect of the QBO

index on WV in the low stratosphere (Diallo et al., 2022; Ziskin et al., 2022)." (L423-425)

L410ff: In my opinion, most of this paragraph is well-known facts regarding the QBO and induced secondary circulation. Only the last sentence (starting L418) describes the new results of the present paper. I'd recommend to restructure and shorten, so that the focus is on new results. (This comment is related to major comment 2).
Response: Thank you for your suggestion. The revised version focuses on describing the new findings of this paper.

- "The difference in the secondary circulation associated with QBO between winter and summer is compared……" (L439-)

L420: ... controlling factor ... in the tropical lower stratosphere...
Response: Changed to "…in the tropical lower stratosphere." (L444)

Technical corrections:
L13: seasonal differenceS
Response: Changed to "differences". (L12)

L58: The reference is sometimes written "Ziskin Ziv et al. (2022)", sometimes "Ziskin et al. (2022)" (e.g. L60). Please use the same citation label.
Response: Changed to "Ziskin et al. (2022)". (L64)

L192: ... anomalies ... are ...
Response: Changed. (L219)

L212: regulates
Response: Changed. (L236)

L206: ... at 100hPa during winter ... (would be good to add the season here).
Response: It has been removed in the latest revised version.

L247: anomalously strong upwelling ... anomalously strong downwelling ...
Response: Removed.

L256: in the Northern hemisphere suptropics
Response: Changed. (L312)

L427: I'm not entirely sure what is meant here. Do you mean: "The influence of OLR on the tropopause cold point temperature in summer is opposite to the tropical stratospheric temperature anomalies related to the QBO secondary circulation, which ..."
Response: It has been removed in the latest revised version.