Responses to Reviewer #1

Reviewer #1

The authors present an analysis of the seasonality of QBO effects on stratospheric water vapor in ERA5 reanalysis data, the observation-based SWOOSH data set, and CMIP models. In general, I find that this analysis provides sufficient new knowledge about the QBO impact on stratospheric water vapor to merit publication. I also think that mostly the analysis is well presented. I have some specific concerns about details of the analysis, its interpretation, and references to earlier work that I will list in the following, and which I think should be addressed before I can recommend a publication.

Response: Thank you for your comments concerning our manuscript. Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our research. We have studied the comments carefully and made corrections which we hope meet with approval.

Introduction: I think the motivation for this study should be sharpened. From the introduction I have the impression that the main research gap is given in the following sentences: "However, it still remains unclear whether the effects of the QBO on stratospheric water vapor differ between northern winter and summer. The seasonality of the water vapor QBO signal has been seldom studied." "Seldom" would not mean never, so what is known about the seasonality and what not? And why is the difference between northern winter and summer of specific interest? I'd further appreciate that the authors formulate a hypothesis on expected impacts of the seasonality which could be based on existing knowledge on the seasonality of stratospheric water vapor and circulation and on the mean imprint of the QBO on these two quantities. Additionally I think it would be good to be more specific about why a seasonality of the QBO imprint on stratospheric water vapor would matter.

Response: Thanks very much for your positive comments. We added why it is interesting/important to investigate the seasonal cycle of the QBO on water vapor.

- "Serva et al. (2022) found that there are seasonal differences in temperature and SWV in tropical regions. In the northern summer, the temperature at 100 hPa and the WV at 85 hPa reach their peaks, while in winter, they reach their lowest levels (Serva et al., 2022). The QBO is affected by the BD circulation, and it is stronger in northern winter than in summer (Butchart, 2014). Tegtmeier et al. (2020) found that the temperature amplitude of QBO was 2 K in February of northern winter and only 0.9 K in September of summer. Similar questions naturally arise: Does the amplitude of WV QBO also undergo a similar change? What are the differences between winter and summer? 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. This study uses more samples based on the long time series of the QBO signal in SWV and discusses the differences in SWV distribution between different QBO phases and between different seasons. Possible causes of those differences are diagnosed, and the performance of climate models in capturing the

QBO signal in WV is also evaluated (Ye et al., 2018; Ziskin et al., 2022)." (L70-81)

2a Datasets: What is the motivation for using ERA5 and SWOOSH? To which degree can these datasets be considered independent. Have observations used to build SWOOSH also been assimilated in ERA5? What may be the advantages of one or the other dataset?

Response: Thanks for your suggestion. The comparison between ERA5 reanalysis data and SWOOSH satellite observation data has been added. ERA5 reanalysis data are used because it has a longer time range.

- "In contrast to the troposphere, the WV content within the stratosphere is extremely low. Compared to the SWOOSH satellite observation data, the ERA5 reanalysis data provides a longer time span, which provides more samples for revealing the effect of QBO on SWV. There remains uncertainty regarding the performance of ERA5 reanalysis data in depicting SWV. In the ERA5 reanalysis, WV mainly assimilates in-situ humidity observations in the troposphere and satellite radiation observations that are only sensitive to humidity in the troposphere……" (L104-124)

L117: The authors write that divM "represents the eddy transport of water vapor" To my understanding it doesn't represent the full eddy transport, which is partly already included in the residual advection terms. It only appears in the case of tracers which are not inert. I have to admit my knowledge of this formalism is only partial, but other readers may also benefit from a more comprehensive discussion of these terms.

Response: You are correct.Thanks for your suggestion. This explanation has been added to the text.

- "In the case of a non-inert tracer, it doesn't represent the full eddy transport, which is partly already included in the residual term." (L156-157)

L134: "Since HALOE started from 1992, the water vapor QBO amplitude in the upper stratosphere between 1–5 hPa has increased, which is also shown in ERA5 reanalysis." To me this statement is unclear. Is the assumption that the assimilation of HALOE data is causing this increase in the datasets, or could the timing be accidental? This is related to the above comments on the independence of ERA5 and SWOOSH data. I also don't understand why the following sentence starts with "Alternately, …" Do you mean "alternatively"? But even then, it seems that the two sentences discuss different phenomena, changes in time in the first, and changes with altitude in the second sentence.

Response: Thanks for your suggestion. This part has been modified, and the original description has been deleted to clarify.

- "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). ERA5 reanalysis can well display the QBO signal of SWV below 10 hPa." (L164-166)

L164: The authors write that the "relationship between the QBO and water vapor [shown in Fig. 3] is to be expected" because the cold point temperature determines tropical water vapor. I'd agree that "a" relationship is to be expected, but why "this" relationship? Why would it be expected that both at 10 and 70 hPa there would be an in-phase relationship? Given the in-phase relationship at these two levels and the different vertical propagation directions of QBO winds and water vapor, would the relationship be out of-phase at levels inbetween (e.g. 20 or 30 hPa). If this is so, it would be good to mention it in order not to raise the false impression of an in-phase relationship everywhere. Please consider this issue also for point I of the summary section.

Response: Thanks for your suggestion. It has been removed in the latest revised version. 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. Places related to your concerns are listed as follows.

- "Figure 4 shows the lagged correlation coefficients between the QBO index at 30 hPa and the WV at each level……" (L199-)
- "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……" (L423-)

Fig. 10: I think the results of this figure are not sufficiently discussed. It is said that "the residual circulation explains partially the water vapor variation in the tropical stratosphere" which I find to vague. What means partially? What else is important? And is it horizontal or vertical advection that matters? If possible I'd like to see a conclusion from this analysis arguing if tropical water vapor anomalies are mainly related to the upward propagation of different amounts of water vapor entering the stratosphere in different QBO phases or some other phenomenon. Similar for extratropical anomalies. This would also be the place for an attempt to explain the analysed differences between hemispheres and seasons.

Response: Thanks for your suggestion. Here we added the analysis and supplemented the meridional and vertical advection terms (Fig. S6).

- "The change of mean advection of WV is basically consistent with the tendency of WV in the tropical region. Positive and negative anomalies are observed at the lower and upper stratosphere, respectively. However, in the tropical lower stratosphere, the positive anomaly of the mean advection is smaller than that of the WV tendency (Fig.9b)." (L331-)

4b: Factors affecting the water vapor distribution: The discussion of temperature anomalies is motivated by the relevance of the cold point temperature. However, the

following paragraph discusses temperature anomalies also elsewhere. What is the motivation for this? Furthermore: The QBO influence on cold point temperature has been discussed by other studies. It would be good to provide references and discuss to what extent this study provides similar or different results.
Response: Thanks for your suggestion. Here we added motivation for this and provide references.

- "By analyzing the stratospheric temperature anomalies at different QBO phases, it can be found that only the cold temperature at the bottom of the tropical stratosphere can affect the change of SWV, while the temperature change in the middle and upper stratosphere does not directly alter the WV content." (L258-260)

L218: "as expected from thermal wind balance" It may be useful to add a reference here as not every reader may be familiar with the concept of thermal wind balance in the tropical atmosphere.
Response: Added (Allen and Sherwood, 2008). (L197, L241)

Figs. 4, 6, 7, 10: Please use consistent vertical extensions in these plots to facilitate comparison of the figures.
Response: All four figures have been modified to 150-1 hPa.

Fig. 8: The seasonal dependence of QBO-related temperature anomalies in the tropopause regions has been analysed earlier, e.g. by Tegtmeier et al. (GRL, 2020) or by Serva et al. (QJRMS, 2022). I'm almost certain there are even more papers on this, but I haven't performed a proper literature survey. Please discuss to what extent your results agree or disagree with earlier studies.
Response: We learned and cited the two references. We further analyzed the impact of the 30 hPa QBO index on the 100 hPa temperature with a six-month lag.

- "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-)
- "This is consistent with the discovery by Tegtmeier et al. (2020) that the QBO temperature amplitude is stronger in winter than in summer……" (L270-271)

L298: "This combination suggests that the QBO might be able to influence convection in this region." There have been many earlier studies on the dependence of convection on QBO phases. Please discuss to what extent your results agree or disagree with earlier studies. As the main goal of this study is to analyse the QBO-dependence of stratospheric water vapor, I'd like to see a discussion if the dependence of convection might impact the water vapour distribution. If not I'd suggest to remove this part.
Response: Thanks for your suggestion. This part has been moved to the Supplementary Materials.

Section 5: Figures 1 and 11 use different color scales. This may be useful to show the simulated signals more clearly, but it should be mentioned explicitly. Related to that

I'd find it useful to state clearly very early that for all models the signal is too weak. Potential reasons for that should be discussed. I understand the analysis presented in Fig. 14 as an attempt to identify an explanation, but I don't see a clear conclusion presented by the authors. If the tropopause temperature anomaly is crucial for the water vapour entry, wouldn't it be more straightforward to analyse how the strength of this anomaly in CMIP models relates to the simulation of the water vapour signal?

Response: As concluded earlier, variations in stratospheric water vapor are jointly influenced by the transport effect of the secondary circulation and the cold point tropopause temperature. Temperature is only one of the contributing factors. Thank you for your suggestions, we have made several revisions this time.

- "Given that the WV QBO signal in the CMIP6 models is generally weak, different color scales are used in Figures 2 and 10 to display the signal more clearly." (L352-353)
- Based on the feedback from the last reviewer, Figure 11 has been modified to depict the relationship between 30 hPa zonal wind and 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-)

L327: "Since stratospheric water vapor has important climatic effects, evaluation of the simulated water vapor QBO by CMIP6 models is helpful in diagnosing how to improve the performance of the models (Keeble et al., 2021; Ziskin Ziv et al., 2022)." This may provide some of the motivation I was missing in the introduction. However, I find the statement very vague. What do you have in mind? Model performance with respect to what? How would it help in diagnosing how to improve it?

Response: A discussion on the simulation performance of QBO in CMIP6 models has been added to the Introduction to clarify this.

- "However, it remains a challenge to simulate the QBO in general circulation models (GCMs), with only a few GCMs being able to reproduce it. The waves need to be correctly represented to simulate a realistic QBO. Many GCMs still cannot simulate a realistic spectrum of tropical waves because of their low resolution and their deficiencies in the parameterization of small-scale gravity waves forcing (Ricciardulli and Garcia, 2000; Lott et al., 2014). Studies have suggested that an adequately fine vertical resolution (vertical grid spacing of ~500–700 m) of the troposphere and lower stratosphere is also necessary to simulate the QBO due to the forcing of some resolved waves with small vertical wavelength and the need to capture the wind shear (Richter et al., 2014b; Geller et al., 2016). In CMIP5, only five models could generate the QBO internally (Butchart et al., 2018). In CMIP6, at least 15 models now able to simulate realistic QBO-like behavior during the historical period (Richter et al., 2020)." (L49-57)

L367: Is this statement really true for CESM-WACCM-FV2? The table indicates a winter correlation of only 0.29, not higher than 0.5.

Response: Changed.

- "Only one model (AWI CM-1-1-MR) can simulate the seasonal contrast in WV distribution with the pattern correlation exceeding 0.5, although the general WV anomaly patterns show biases from the ERA5 reanalysis (Fig. S2)." (L386-388)

L423: As mentioned above, a seasonality of QBO signals in tropopause temperature has been identified in previous papers. Please indicate to what extent your findings are new.

Response: Revised in several places.

- "Consistent with previous work (Tegtmeier et al., 2020)……" (L432-)
- We have also identified the impact of the 30 hPa QBO on the 100 hPa temperature with a six-month lag. "As the QBO signal propagates downward from the upper stratosphere, the 30hPa QBO index has a significant impact on the 100hPa temperature after six months, but the lagged temperature amplitude in northern summer is still smaller than that in winter." (L435-438)

L443: "This study … finds that BD circulation change related to QBO might be a mediator bridging the QBO and water vapor." I have difficulties to understand this statement. Please be more precise. What means mediator? Why might? Hasn't it been shown clearly in this and earlier studies that QBO and stratospheric water vapour are related? So what is actually new in this finding?

Response: Thanks for your suggestion. This sentence has been modified.

- "However, this study reveals the difference in SWV content regulated by QBO between northern winter and summer, and finds that QBO-related cold point temperature anomalies in the tropics affect WV distribution in the lower tropical stratosphere with a 6-month lag. QBO-related secondary circulation affects WV transport in the middle and lower tropical stratosphere, which provides a new perspective to better understand the SWV QBO signals." (L455-458)

L444: "It provides a new perspective to better understand the stratospheric water vapor QBO signals." Also this sentence is unnecessarily vague. What is this new perspective?

Response: See comments above.