Response to reviewer 2:

Review for ‘QBO modulation of the Asian Monsoon water vapour’ by Peña-Ortiz et al.

This work studies the mechanisms of how Quasi-Biennial Oscillation (QBO) will influence the tropical tropopause layer water vapor by regulating temperature and convection. This work focuses on the Asian Monsoon (AM) region, a region where it is important while there remains a lot of uncertainty in the water vapor budget. By analyzing observational data, the authors explain how QBO will influence the water vapor from a dynamics perspective, filling current knowledge gaps. Most of the analytical work in this paper is clear and logical, and the paper is well-written. I recommend the paper be accepted after considering the following suggestions.

Major comments:

1. It would be helpful for readers to better understand the processes involved if the authors include figures showing the climatology, QBO-w mean, and QBO-e means of water vapor, temperature, outgoing longwave radiation (OLR), wind fields. This additional visual representation could enhance comprehension.

Certainly, we agree on the need to show the climatological values for vapor, temperature, wind and OLR for a better understanding of the results and we are going to do so for the revised version of the manuscript in which these values will be added to the anomaly figures or, in some cases, figures will be added to show them. In the case of the mean values for QBO-E and QBO-W, because the anomalies associated with each of the QBO phases are small compared to the climatology, we think that they do not add additional information with respect to the climatology and so we have not added them.

2. Table 1 indicates the number of QBOe and QBOw cases but doesn't provide information on their strength. With a sample size of 5-9 cases, there remains substantial uncertainty in the results. For instance, the differences observed between July and August may be influenced by variations in QBO strength due to the limited record. To address this, consider:

a. When discussing the relationship between water vapor and temperature, use MLS water vapor data, and temperature over 2005-2020.

b. When discussing how QBO modulates the deep convection and thus temperature, use a longer record (ERAi, NOAA OLR, and Singapore QBO data all have a longer record).

c. Instead of counting the number of QBO events, consider presenting variables like wind (U) or the correlation between U and H2O to strengthen your analysis.

Although it is true that the availability of high-quality data for water vapor significantly limits the period of study (2005-2020), we believe that it contains a sufficient number of QBO-W and QBO-E cases (between 9 and 6) to perform a meaningful analysis. In our opinion,extending the study period including less reliable water vapor data from the 80s and 90s would not improve the significance of the results. On the other hand, the quality of the temperature, wind, OLR or diabatic heating rate data at UTLS levels can also be compromised as we go back in time.

In order to assess possible variations in the QBO strength for the QBO-W and QBO-E cases used in our study, figure 1 compares the QBO amplitude at different pressure levels according to the values of the Singapore sonde monthly zonal wind for QBO-W and QBO-E defined at 10hPa and 20hPa for July and August for the same time period used in the paper, 2005-2020, and following the same procedure for the phases definitions. The figure shows a slightly higher amplitude of the QBO at UTLS levels during July compared to August, and this may indeed contribute to the stronger QBO signal on temperature and cloudiness during that month. In fact, this is consistent with Sweeney et al. (2023), who show that deep intrusions of zonal wind anomalies into the upper troposphere are only visible during boreal spring and early summer, peaking during MJJ. They found that, in a synchronized way, QBO temperature anomalies penetrate to the lowest altitudes and the response of the cloud fraction reaches its maximum and extends from above tropopause to □12.5 km. Although this study used observational data for the period 2006-2020, they found, using ERA5 reanalysis, a similar seasonality of the zonal wind response to the QBO over the period 1979-2020. In the same way, figure 2 of the present document, which shows latitude-height cross sections of QBO-W minus QBO-E differences for ERA5 zonal mean temperature and zonal wind averaged for June 16th - July 16th and July 19th - August 18th for the period 1980-2020, also evidences slightly stronger QBO anomalies in the UTLS during Jun-Jul than during Jul-Aug. This would support the idea that the difference in the amplitude of the QBO signal in the zonal wind in the UTLS (and synchronously in all other variables) between July and August found for the period 2005- 2020 is not an artifact associated with the limited number of cases, but something related to the seasonality of the QBO strength in the UTLS. In any case, we consider this to be an obvious limitation of our work and will explain it in the new version of the manuscript.

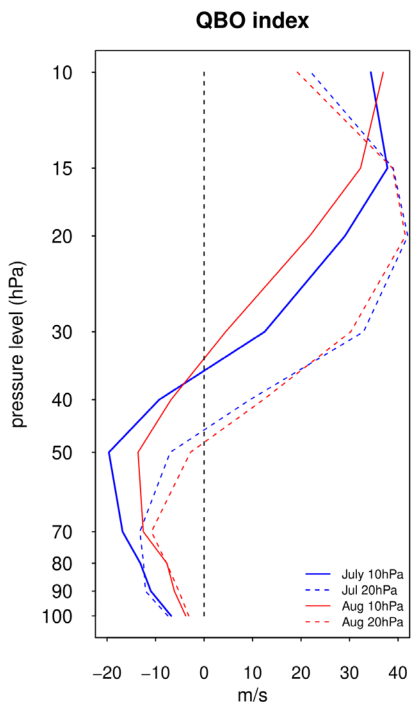


Figure 1: QBO-W minus QBO-E differences for the Singapore sonde monthly zonal wind at different pressure levels for QBO-W and QBO-E defined at 10hPa and 20hPa for July and August for 2005-2020. QBO phases defined at 20hPa/10hPa are shown as dashed lines/solid lines while values for August/July are shown in red/blue colors.

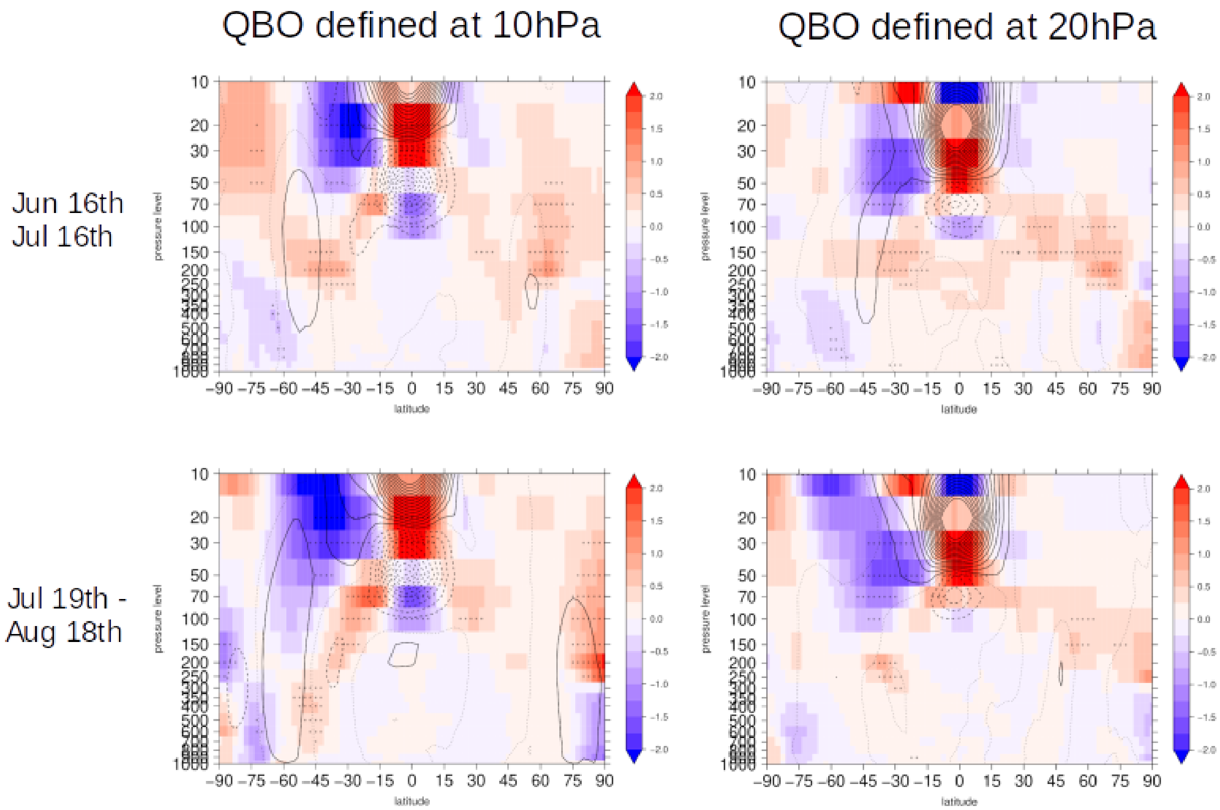


Figure 2: Latitude-height cross sections of QBO-W minus QBO-E differences for ERA5 zonal mean temperature (colors) and zonal wind (black contours) for June 16th - July 16th (top row) and July 19th - August 18th (bottom row) and for the period 1980-2020. QBO phases were defined at 10 hPa using the Singapore index for July (top left) and August (bottom left) and at 20hPa using the Singapore index for July (top right) and August (bottom right). Solid/dashed contour lines show positive/negative anomalies with contour intervals at every 2m/s from 1m/s/-1m/s for positive/negative anomalies. Dots indicate significance at the 95% confidence level.

Finally, we have performed some checks in order to test the sensitivity of our results to the period of study. Thus, to test whether the observed differences in temperature anomalies on the southern flank of the monsoon between Jun-Jul and Jul-Aug for the period 2005-2020 are also observed during the extended period 1980-2020, figure 3 depicts latitude-height cross sections of QBO-W minus QBO-E differences for ERA5 temperature and zonal wind averaged over 60E-120E and between June 16th and July 16th (a) and between July 19th and August 18th (b) for the period 1980-2020. Thus, it is equivalent to figure 4 in the manuscript but for a 41-year period. Consistent with results in the manuscript for 2005-2020, this figure shows no significant temperature anomalies in the UTLS (around 100hPa) over latitudes corresponding to the southern flank of the monsoon (20N-30N) during Jun/July while a significant warming, although weaker, of this region is observed during Jul/Aug. We mention the robustness of this result in the revised manuscript.

In any case, as we have said, we understand that the limited extension of the study period is an obvious shortcoming of this work and we will discuss this in the revised version of the manuscript. We will also add the information about the amplitude of the QBO at each level in table 1.

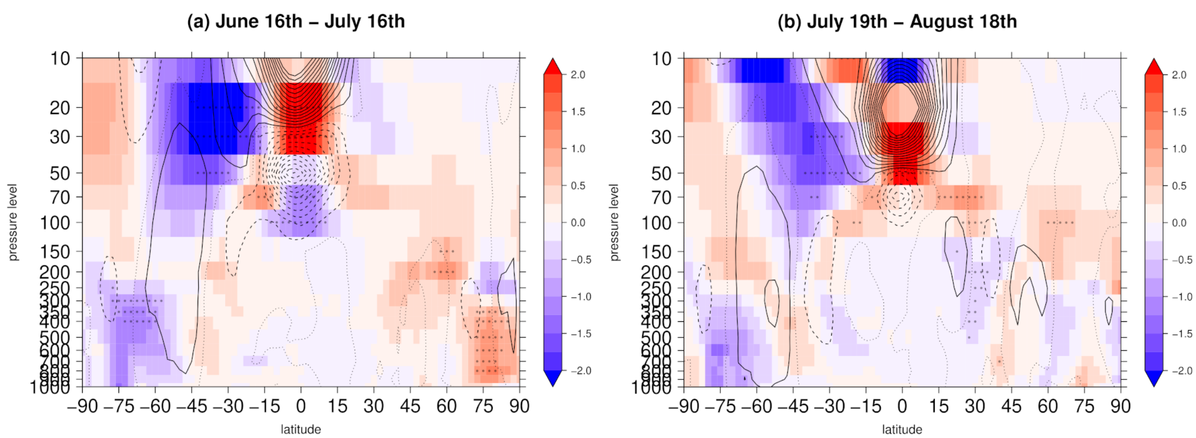


Figure 3: Latitude-height cross sections of QBO-W minus QBO-E differences for ERA5 temperature (colors) and zonal wind (black contours) averaged over 60E-120E and between June 16th and July 16th (a) and between July 19th and August 18th (b) for the period 1980-2020. In (a) differences correspond to the QBO index for July defined at 10hPa while for (b) we chose the QBO index defined at 20hPa for August. Solid/dashed contour lines show positive/negative anomalies with contour intervals at every 2m/s from 1m/s/-1m/s for positive/negative anomalies. Dots indicate significance at the 95% confidence level.

3. The paper currently discusses the choice of different QBO levels extensively, which may distract from the main topic. The conclusion that 10 hPa/20 hPa is the best proxy may be sample-size dependent and not universally applicable so can be removed from the result section. Consider consolidating this discussion with Table 1 and relocating it to Section 2, allowing Sections 3 and 4 to focus on scientific results.

In line with this comment we have simplified figures 1, 2 and 4 to show only those panels corresponding to the QBO phases defined at 10hPa for July and 20hPa for August and have moved the previous figures with all panels to the appendix. In this way we have also been able to simplify the text and reduce the discussion regarding the signal in the vapour and the temperature as a function of level for the definition of the QBO phases. Following the reviewer's recommendation and, as far as possible, we have moved the discussion on the dependence of the QBO signal in tropopause on the level at which the phases are defined to section 2, "Data and Methodology".

4. Need more discussion on using OLR as a proxy of the deep convection. Although Randel et al. (2015) conclude that deep convective cooling plays a main role in the water vapor budget over AM and North American regions, there are also many recent studies using radar with a much finer resolution to observe deep convection and overshooting over the North American regions, and conclude that the deep convection impact is moistening (Chang et al., 2023; Smith et al., 2017; Tinney & Homeyer, 2021; Yu et al., 2020). Asian monsoon region is different from the NA region and there is no very good coverage radar product over the AM region to test convective moistening/drying, so convective impact still could be cooling over this region. However, a discussion on the shortcoming of using OLR as a proxy is necessary.

In our study we observed that the modulation of cloudiness by the QBO plays a dual role. On the one hand, cloud modulation over the equatorial region contributes to a response in circulation and temperature over the southern flank of the monsoon that modulates the water vapor content of the monsoon. In this case, changes in equatorial cloudiness cause changes in diabatic heating and thus generate the dynamic response. To add further evidence to this result, in the revised version we have added the analysis of the ERA5 diabatic heating rate, which allows us to verify that changes in tropical cloudiness, even when occurring in the UTLS, are likely to cause the release of latent heat, which is essential to generate a response in the circulation.

On the other hand, changes in the circulation over the southern flank of the monsoon cause changes in convection and temperature over this region. In this case, we have only considered the impact of convection on temperature but have not analyzed the possible impact of direct water vapour injection over the monsoon. While it is true, as suggested by the reviewer, that several studies have pointed to the moistening effect of deep convection in monsoon regions, particularly over the North American monsoon, the contribution of these convective systems to the overall budget of water vapour transport over monsoon regions is still questionable (Ueyama et al. 2023). For example, while Ueyama et al. (2018) showed that deep convection within the Asian monsoon anticyclone can enhance water vapour in the lower stratosphere by 30%, Plaza et al. (2021) found no contribution from this mechanism despite using a similar approach.

Furthermore, the hierarchy of processes controlling the water vapour signal in monsoon regions may be monsoon dependent due to differences in thermodynamic structure between the Asian and North American monsoons. For example, Randel et al. (2012) found a maximum of δD only for the North American monsoon as evidence for different magnitudes of transport processes playing a role in monsoon water vapour signals. Therefore, it is not possible to directly extrapolate to the case of the Asian monsoon the conclusions drawn in the scientific literature for the observed wetting of the North American monsoon in relation to convection. We agree with the reviewer that to attend the full impact of convection within the Asian Monsoon region, it would be necessary to obtain new and more accurate observations of this region in addition to OLR. In this study we do not aim to quantify this impact and the causal links between the changes in temperature and cloud fraction in the Asian Monsoon region related to QBO phases should be further studied using a dynamical model for this purpose.

In the revised version, we will expand the discussion on this issue and explicitly clarify the limitation in determining the role of convection, not having considered its possible impact through direct water vapor injection.

Specific comment:

1. After first introducing the region, consider adding latitude information (e.g., Indian, tropical Indian Ocean).

Latitude information will be added in the revised version.

2. Line 16-18: The sentence is long and slightly challenging to comprehend. Consider breaking it into two or more sentences for clarity.

Corrected in the revised version.

3. Figure 3: This figure could benefit from subtitles and adding a significant level to figures b and d. Additionally, consider adding a second x-axis with lag dates to improve readability.

Corrected in the revised version.

4. Figure 5: The dots in this figure are unclear when overlapping with the wind field.

Corrected in the revised version.

5. Line 205: It's unclear how this paragraph differs from the one starting at line 140, as they both discuss Figure 3. Please clarify the distinction.

The dots have been enlarged and are more clearly distinguishable in the revised version of the figure.

6. Line 289: The sentence is unclear. Isn't the secondary circulation over the mid-latitudes, and this paragraph is discussing the equatorial region? Could you please explain more?

The secondary meridional circulation (SMC) is characterized by a sinking motion at the equator in westerly shear zones and rising in easterly shear areas. A maximum (minimum) in temperature at the equator in westerly (easterly) shear zones is necessary to maintain the thermal wind balance. The sinking (rising) motions produce adiabatic heating (cooling) to preserve positive and negative temperature anomalies against thermal damping (Baldwin et al., 2001). As Plumb and Bell (1982) illustrated in their 2-D model, the SMC is also distinguished by meridional convergence (divergence) zones over the equator coinciding with the location of maximum westerly (easterly) wind. The QBO temperature anomaly changes sign at approximately ±15° owing to rising (sinking) motions that compensate the sinking (rising) motions at the equator (Baldwin et al., 2001; Choi et al., 2002).

In the revised version, we will clarify that in line 289 we are referring to the equatorial branch of the SMC.

7. Line 359: In the sentence, "and a secondary meridional circulation of the QBO...," Is the secondary circulation transport the equatorial temperature anomaly?

What we intend to say in that sentence is that the warm temperature anomaly appears as a combination of two effects. The first one is the effect of the wave train observed between mid-July and mid August, characterized by a cyclonic gyre over the southeast flank of the Monsoon. This cyclonic gyre involves a weakening of the climatological rising motions (a downward anomaly) and also a weakening of the cloudiness northeast of India, which causes a warming over this region. This warming is observed in the eddy temperature field (corresponding to the total field minus the zonal mean) as well as a warming that is enhanced by the warm temperature anomaly associated with the secondary meridional circulation. This anomaly contributes to the Monsoon moistening.

We will clarify this sentence in the revised version.

Reference

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