Response to reviewer 1:

(1) The use of ERA5 “fraction of cloud cover” data

The authors use vertically resolved “fraction of cloud cover” data from ERA5 as a proxy of, in the end, tropical deep convection that provides source of large-scale diabatic heating to produce equatorial Kelvin and Rossby wave response (or the Matsuno-Gill response). First, reanalysis cloud data are product of forecast model, without observations assimilated, and thus in general less reliable compared to e.g. NOAA OLR data. Second, the authors focus on the region 150-100 hPa for these cloud data and discuss deep convection, but the clouds in this altitude region are primarily cirrus and anvil clouds, and may not be directly related to the core of deep convection that results in large-scale diabatic heating to produce the Matsuno-Gill type response. Because authors’ discussion very heavily relies on detailed structure/distribution in ERA5 fraction of cloud cover data at 150-100 hPa, and because (as discussed below) the features that the authors point out and emphasize are not very clear to me, I started to wonder whether the chosen cloud data set is appropriate or not.

We do indeed share the view that ERA5 fraction of cloud cover data may be less reliable than NOAA OLR data, so in the manuscript we add figure A2 in the appendix showing QBO-W minus QBO-E differences for NOAA OLR averaged between June 16th and July 16th (a) and between July 19th and August 19th (b). This figure serves to verify the signal observed in the "fraction of cloud cover" that we show in figures 6 and 7, from an independent observational data set. Also, in the new version of the manuscript we incorporate the analysis of the diabatic heating rate of ERA5. These new analyses and data corroborate the patterns and changes found in the ERA5 fraction of cloud cover.

It is true that our analysis does not allow us to determine which cloud types are affected by the QBO. Cirrus are the most common clouds at levels between 200 and 100hPa and, therefore, it is very likely that the QBO signal is mainly modulating the presence of this type of clouds. This result is consistent with Sweeney et al. (2023), who show that the QBO primarily affects cloudiness between 100hPa and 200hPa, mainly impacting cirrus clouds. However, also this study shows evidence of the QBO signal on cloudiness between 100hPa and 200hPa associated with opaque clouds, which are clouds often associated with deep convection and thick anvil. In fact, Giorgetta et al. (1999) argue that QBO acts primarily by raising the height of cloud tops, which, when the QBO causes a cooling of the tropopause, can more frequently reach levels between 100hPa and 150hPa rather than between 150hPa and 200hPa.

The possibility that changes in cloudiness in the upper troposphere may cause changes in circulation and excitation of wave trains was addressed in Slingo and Slingo (1990), Giorgetta et al. (1999) and Peña-Ortiz et al. (2019). These studies show that diabatic heating caused by cloudiness at the upper troposphere, including that associated with tropical cirrus clouds, can excite wave trains that can propagate to higher latitudes. Slingo and Slingo (1990) found that the major dynamical response to upper tropospheric diabatic heating is restricted to the tropics and the subtropical jets and that this response is characterized by an anticyclonic dipole to the north and south of the diabatic heating, with the possibility to excite wave trains propagating to higher latitudes.

We consider that this discussion is relevant and therefore, in the new version of the manuscript we show how the QBO signal on the diabatic heating rate in the upper troposphere is consistent with the signal in the cloudiness and, in turn, consistent with the observed response in the circulation which is characterized by the generation of divergence in the zonal wind with winds from the east to the west of the diabatic heat release zone and winds from the west to the east of it. At the same time, as described by Slingo and Slingo (1990), anticyclonic gyres can also be distinguished to the north and south of this region, being more intense to the north as the heat release is also displaced to the north.

However, we agree with the referee that the complete structure, typical of Matsuno Gill response, is not so clearly distinguishable and therefore in the revised manuscript we will not refer to it. It is also true that to demonstrate a cause-effect relationship between the diabatic heating and the subsequent generation of the wave train, a dynamic model would be necessary and, in the new version, we make it clear that this is an hypothesis suggested by the results but that its demonstration would require simulations that are beyond the scope of this article.

(2) The Matsuno-Gill response

In Section 4, in Figures 6-8, the authors show the ERA5 cloud data at 125-150 hPa and ERA5 temperature and wind anomalies, and mention that these are the Matsuno-Gill response. While it is well known that if we give diabatic heating at the equator or slightly off-equatorial region, we see the so-called Matsuno-Gill response in the wider regions of the tropical-to-subtropical atmosphere including the tropopause region, it is not clear to me in the current specific cases which group of deep convection, shown on the figures, is actually responsible for the specific 100 hPa temperature and wind anomalies over the Asian monsoon region. The authors need to clearly show the heating-response pair for each set of figures, and to show somehow (using e.g. a very simple model) the justification that they are actually the pairs.

In the new version of the manuscript, the use of diabatic heating has allowed us to more clearly delineate the regions where this heat is released and the circulation anomalies that respond to this heating. However, it is true that the Matsuno-Gill response is not so clearly distinguishable, primarily because it is difficult to distinguish the response in terms of a Kelvin wave to the east of the heating region. It is possible that either the heat released is not sufficient to generate this structure, or the area where positive latent heat release anomalies are observed sometimes appears to form a dipole next to a region where anomalies of the opposite sign are observed, preventing the Rossby-Kelvin pair from developing.

Studies by Slingo and Slingo (1991) and Giorgetta et al. (1999) that address the dynamical response to diabatic heating of the upper troposphere describe this response in terms of the formation of anticyclonic gyres to the north and south of the heating region and the excitation of wave trains. In the new version of the manuscript we emphasise these structures, which are clearly observable, and are more careful with references to the Matsuno-Gill response. In particular, we discuss that our analysis allows only the identification of consistency in the patterns with the Matsuno-Gill response but that for proving a causal relation a mechanistic model would be needed (see our answer to the previous question).

(3) The choice of QBO indices

The authors used monthly mean Singapore zonal wind data at 10 hPa, 20 hPa, 30 hPa, 50 hPa, and 70 hPa for (potential) QBO indices. While the authors' approach is understandable as first trials, I think that the final choice should be made in terms of direct relevance to the current problem. What we need here is e.g. vertical displacement, or temperature anomaly, or temperature gradient (static stability) anomaly around e.g. the tropopause over the tropics and over the Asian monsoon region due to the QBO and/or its secondary circulation. In other words, please explain the relevance (or the phase relationship) to the tropopause-level variables of the 10 hPa Singapore winds for July and the 20 hPa Singapore winds for August.

We fully agree that the aspects explaining the QBO signal on water vapour in the Asian Monsoon UTLS are related to the QBO signal on temperature and circulation at the tropopause level over the tropics and over the Asian monsoon region. However, Figures 1 and 2 show that the signal over the Monsoon water vapour is stronger when we define the QBO phases as a function of the zonal wind at 10hPa or 20hPa for July and August respectively. This signal is, of course, not due to what happens at these levels of the stratosphere but due to the impact of the QBO at the tropopause and its impact on temperature and circulation at this same level.

In fact, in the case of July, the water vapour signal for the QBO defined at 10hPa is practically the same but with the opposite sign to the one observed in the last row of figure 1, for the QBO defined at 70hPa. However, because the QBO signal over the zonal wind weakens in the lower stratosphere, the use of levels between 70hPa and 100hPa to define the QBO phases can be problematic and significantly reduce the number of cases.

We chose to show the signal over water vapour and temperature at 100hPa for the QBO defined at different levels to show the relationship between the signals over these two variables. However, in the new version we have simplified figures 1, 2 and 4 to show only the panels corresponding to the QBO phases defined at 10hPa and 20hPa for July and August respectively. In the revised manuscript, we will give a more detailed description of the characteristics of the QBO signal on temperature and circulation in the UTLS during these phases.

(4) The QBO secondary circulation, and then the potential Matsuno-Gill response

(This may be more like a comment, not a strong suggestion.) To me, it is more logical that the (zonal mean) QBO secondary circulation is first explained and analyzed, and then the anomalous Asian monsoon region is pointed out. Then, the tropical convection anomalies are analyzed in the Indian-Ocean and Indonesian sector. Then, the potential link of those convection anomalies to the Asian monsoon region through the Matsuno-Gill response is proposed.

The exact latitude where the subtropical part of secondary circulation maximizes might not be very clear in the past works, but the following paper may be a good starting point:

Hitchman et al., 2021, https://doi.org/10.2151/jmsj.2021-012

The one for specific months needs to be analyzed by the authors (and actually shown in the manuscript).

We share with the reviewer the need to illustrate more clearly the behaviour of the secondary meridional circulation of the QBO (zonal average) and then point out the anomalies over the Asian monsoon region. For this we will unify Figures 5 and A1 and expand the description of the secondary meridional circulation. We believe that this will allow a better understanding of the significance of the anomalies found over the monsoon.

Furthermore, it is not very clear to me what is the final process that mainly controls the water vapor in the Asian monsoon anticyclone. Is it local dehydration in association with the temperature anomalies or the wet/dry air transport changes in association with the wind anomalies, when the authors discuss the Rossby-wave part of the Matsuno-Gill response?

Our results, beyond showing the QBO signal in water vapor over the Asian Monsoon, attempt to explain this signal from the temperature anomalies associated with the QBO in the UTLS. In the case of water vapor in August, our results show that the QBO has a significant impact on temperature on the southern flank of the monsoon from mid-July to mid-August that modulates, through local dehydration, the water vapor content of the monsoon. Results suggest that in this region the temperature anomaly associated with the secondary circulation intensifies due to the wave train generated by the impact of the QBO on tropical convection in the previous weeks. Thus, this wave train is characterized, during QBO-W and with respect to QBO-E, by a cyclonic anomaly on the southeast flank of the AM that inhibits convection and favors subsidence in this region, generating a warm anomaly in July/August that intensifies the warming associated with the secondary circulation of the QBO and causes a moistening of the AM.

However, with respect to water vapor in July, our results show that it is the temperature over the tropical Indian Ocean that controls the interannual variability of water vapor in the monsoon. In fact, the QBO signal on monsoon water vapor in July is in phase with the signal in the equatorial UTLS. Thus a cooler and drier tropical UTLS coincides with a drier monsoon. Moreover, in this case, the QBO signal on temperature on the southern flank of the monsoon is very weak. It is therefore possible, as suggested in the manuscript, that the transport to the Asian monsoon of anomalously dry or moist air from the tropical Indian, is contributing to the signal that we find over the monsoon. In any case, in order to determine the separate effects of transport and temperature anomalies, we would need to analyze the trajectories of the air masses using a Lagrangian model, which is out of the scope of this manuscript. In the new version of the manuscript we will try to clarify this issue and also to explicitly discuss the limitations of our analysis.

(5) Different processes are proposed for July and August

Based on the analysis results, the authors suggest that different processes are operating in the month of July and August at the QBO time scales. I am not fully convinced whether this is possible/reasonable. If this were true, the seasonal progress of the Asian summer monsoon should be quite robust in each year, and the seasonal features are clearly different between July and August. Or, do I misunderstand something?

Our results reveal that indeed the QBO signal over water vapor has different characteristics in intensity and sign between July and August. While in July it is weaker and in phase with water vapor anomalies over the equator, in August it is stronger and shows a lag in relation to the signal over the equatorial moisture. One of the keys to this difference lies in the different impact of the QBO on the temperature of the southern flank of the monsoon (a region whose temperature is considered key to the modulation of monsoon vapor content) during Jun/Jul (mid-June to mid-July) and Jul/Aug (mid-July to mid-August). As explained in the answer to the previous question, in Jul/Aug significant temperature anomalies are observed over this region, which are consistent with changes in monsoon water vapor content. However, in Jun/Jul, temperature anomalies over this area are very weak, and therefore the monsoon vapor content seems to depend more on the temperature and moisture of the air over the equatorial region (figure 3a of the manuscript).

Results suggest that the seasonal evolution of the impact of the QBO on cloudiness in the tropical upper troposphere may explain these differences. Thus we see that during Jun/Jul there is diabatic warming, associated with QBO-W and with respect to QBO-E, over the tropical Indian Ocean which generates an anticyclonic gyre over India and a cooling observed in the temperature eddy field. This cooling is partially compensated by the warm anomalies of the zonal average (associated with the secondary meridional circulation of the QBO shown in figure A1), so that the actual temperature field shows very weak cold anomalies that have a limited impact on the water vapor content of the monsoon. However, in July/August, the QBO does not significantly modulate the cloudiness over the tropical Indian Ocean and thus there is not an intensification of the tropical easterly wind over this region and, as a consequence, the anticyclonic anomaly over India that appeared in June/July does not occur. Instead, we observe a wave train that is characterized by a cyclonic gyre over India, which inhibits cloudiness and generates a warm anomaly in this region, which, coupled with the warming of the secondary circulation of the QBO, causes a moistening of the AM during QBO-W relative to QBO-E. This is consistent with results of Giorgetta et al. (1999), which show that the latent heat released in June gives rise to a wave train observed in Jul, this wave train could be the result of the modulation of the upper tropospheric cloudiness during Jun/Jul, which in Jul/Aug gives rise to a wave train with the characteristics previously described. Furthermore, the evolution over the summer of the impact of the QBO on cloudiness in the tropics described in our study is also in agreement with Sweeney et al. (2023), which found that the strongest cloud fraction response to the QBO occurs in boreal spring and early summer, peaking during (May, June and July).

The evolution over the summer of the response to QBO of diabatic heating rate and circulation can be seen in figure 1 of this document. In this figure the differences between QBO-W and QBO-E have been calculated in all cases by defining the phases from the Singapore index for July at 10hPa. In this way we can follow the evolution of the QBO signal from mid-June (June 10th- July 10th, top row) to mid-August (July 19th- August 18th). This figure shows how, since the beginning of the summer, a diabatic warming has been observed in the equatorial region, reaching its maximum over the Indian Ocean, south of the Bay of Bengal. In fact, this warming is already observed throughout the month of June (not shown). This latent heat release increases in intensity until it reaches its maximum during the month of July (July 1st-July 31st) and then weakens rapidly. Associated with this heat release and only while it is occurring (until the period July 1st- July 31st), a circulation response is found, which is characterized by an acceleration of easterly winds to the west of the heat release region and the formation of an anticyclonic gyre over India, centered at 20N. This anticyclonic gyre intensifies the climatological anticyclone that dominates this region and, therefore, air rising motions, generating a cold anomaly associated with adiabatic cooling. It can also be observed how this anticyclone is part of a wave train that propagates northwards and southwards in the northern and southern hemispheres. As the diabatic warming weakens (last two rows in figure 1), the easterly wind anomaly over the equator also weakens and the wave train evolves so that the anticyclonic gyre over India gives way to a cyclonic gyre and a warm anomaly over the southern slack of the monsoon for the period Jul 19-Aug 18 (bottom row).

In the manuscript, and in order to optimize the QBO signal over the monsoon water vapor, we have made the analysis of the signal in July and August using a QBO index different from each month since in the case of July (August) we used July (August) winds. This has the counterpart that, in our case, the set of July and August months defined as QBO-E or QBO-W are not consecutive, they do not belong to the same years, and therefore the evolution of the signature over the summer is not straightforward. In any case, in the revised version of the manuscript we will include a figure (an improved version of figure 1 of this document) to show the evolution of the QBO signal on diabatic heating, circulation and temperature over the summer. We will also add an explicit analysis of the diabatic heating rates and will extend the latitudinal range in the figures showing the circulation response so that the generated wave trains can be better appreciated.

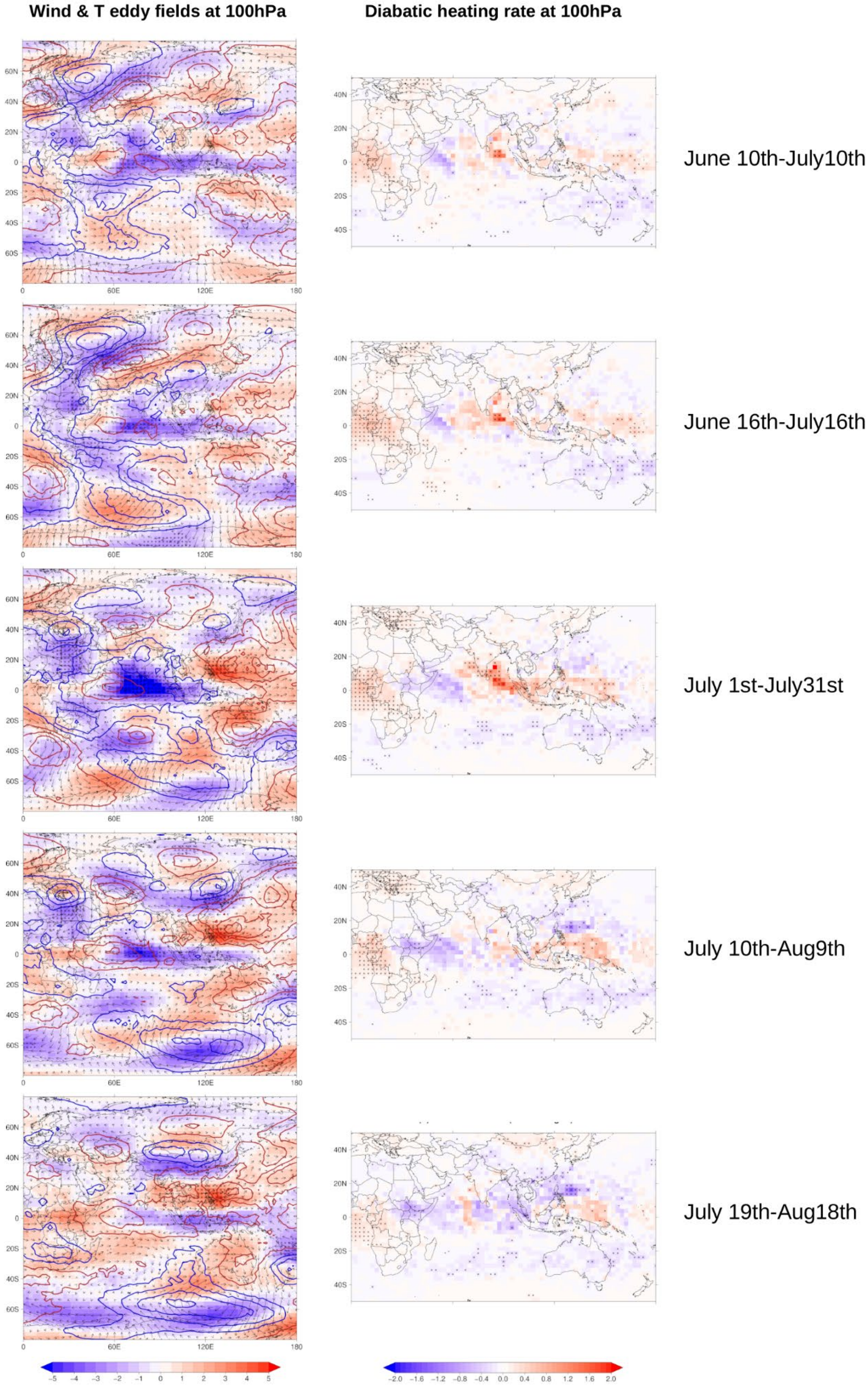
Wind & T eddy fields at 100hPa
Diabatic heating rate at 100hPa
June 10th-July10th
June 16th-July16th
July 1st-July31st
July 10th-Aug9th
July 19th-Aug18th
60N
40N
20N
0
20S
40S
60S
0
60E
120E
180
-5 -4 -3 -2 -1 0 1 2 3 4 5
-2.0 -1.6 -1.2 -0.8 -0.4 0.0 0.4 0.8 1.2 1.6 2.0

Figure 1: QBO-W minus QBO-E differences (phases defined from the July Singapore wind at 10hPa) for the eddy fields of zonal wind (color shades), horizontal wind (arrows) (b) and temperature (contours) (left column) and for diabatic heating rate (right column) averaged over the period between 10 June and 10 July, 16 June and 16 July, 1 July and 31 July, 10 July and 9 August and 19 July and 18 August. Blue/red contour lines show negative/positive anomalies of the temperature eddy field with contour intervals at every 0.5K starting at 0.25K and -0.25K for positive and negative anomalies respectively. Dots indicate significance at the 95% confidence level for zonal wind.

This leads me to the question (1). The features shown in the manuscript might be heavily dependent on the data set used, and ERA5 100-150 hPa fraction of cloud cover data might not be appropriate to be used as the observation of convective heating.

We agree that ERA5 fraction of cloud cover data is less reliable than NOAA OLR data (see the response to the first question). Thus, in the first version of the manuscript we already included the OLR analysis to verify the observed anomalies in the fraction of cloud cover. Additionally, in the revised version we have also added the analysis of the diabatic heating rate of ERA5, showing how the QBO signal on the diabatic heating rate in the upper troposphere is consistent with the signal in the cloudiness and, in turn, consistent with the observed response in the circulation.

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