REVIEW AND RECOMMENDATION

Lu et al. investigate the potential influence of the Hunga Tonga-Hunga Ha'apai (HTHH) eruption on the Quasi-Biennial Oscillation (QBO). Previous studies have examined related questions, including the effects of volcanic eruptions and stratospheric geoengineering scenarios on the QBO, often focusing on tropical warming associated with sulfate aerosols. Other studies have considered how the QBO may affect the circulation response to the HTHH eruption. The present study addresses an interesting question, how the HTHH perturbations including the large water-vapor injection modify the QBO.

However, the paper contains several unclear points, and its main conclusions are not adequately supported by the results presented. It has been argued that the HTHH perturbations altered the downward propagation of the QBO but did not affect the timing of its phase transitions. However, the timing of a phase transition may be related to the duration of each phase and the rate of downward QBO propagation. This point therefore requires further clarification. Two mechanisms "upwelling mechanism" and "thermal wind balance mechanism" are proposed to explain the role of Hunga perturbations on the QBO index, but the link between them is not sufficiently clear in the current analysis. In particular, the manuscript identifies the changes in tropical upwelling as a key pathway through which the HTHH perturbations may affect QBO winds, but the evidence presented does not clearly demonstrate this connection.

Therefore, I recommend rejection of the manuscript in its current form. Details of my recommendations are outlined below.

MAJOR COMMENTS

1. Clarifications for QBO-phase transition change and QBO-amplitude change in Section 3.2

In early 2022, the QBO was in its *easterly* phase below approximately 20 hPa before transitioning to a *westerly* phase (Fleming et al., 2024), consistent with the results presented here. However, the phase transition appears to be described in the *opposite* order in Lines 163 and 243.

Volcanic perturbations can affect QBO amplitude, the speed of its downward propagation, and the timing of phase transitions. In particular, the propagation speed (i.e., the duration of a QBO phase), appears to be closely related to the timing of the transition. However, the current interpretation focuses only on amplitude changes and does not account for the timing of the phase transition, as discussed below:

L243-247 The timing of the QBO phase transition is similar across all experiments and consistent with the observed evolution in 2022 (Fig. S1). … indicating that the combined injection of H2O and SO2 primarily enhances the amplitude and downward propagation of the QBO, rather than altering the timing of its phase transition.

Does this mean that the onset of the phase transition is unchanged, but that the westerly phase propagates downward more quickly once it begins, resulting in a shorter duration? If so, this would imply a faster transition from the westerly to the easterly phase for a following cycle. As currently written, the statement is unclear to interpret.

Also, Figure S5 shows that the QBO phase transition in 2022 occurs ~one month earlier in the sim_SO2+H2O simulation than in the control simulation. This is a significant change and

is consistent with the expected influence of reduced tropical upwelling on transition timing. This difference may be clearer if the zonal winds from the control simulation in Fig. S4a are overlaid as contours on the zonal-wind anomalies in Figs. 3b and 3d.

Another point is the interpretation of QBO amplitude changes. Line 301 states that "In sim_SO_2+H_2O, the 30 hPa QBO index perturbation strengthens relative to sim_control." This is not incorrect, however, at 50 hPa (a level also commonly used to define the QBO; Anstey et al., 2022), the anomalies are persistently easterly, implying a weakening of the easterly QBO index due to the Hunga perturbation, not strengthening the QBO index.

Because the QBO transitions from an easterly to a westerly phase during 2022, the westerly anomalies associated with the Hunga perturbation could weaken the easterly phase early in the year and enhance the westerly phase later. Thus, focusing on a single pressure level may provide an incomplete picture of the vertical structure of QBO changes. I suggest providing a supplementary figure similar to Figure 4 but for 50 hPa level, and noting that the interpretation of the amplitude response may depend on the pressure level used to define the QBO index.

Reference for Comment 1
Anstey, J. A., Osprey, S. M., Alexander, J., Baldwin, M. P., Butchart, N., Gray, L., ... & Richter, J. H. (2022). Impacts, processes and projections of the quasi-biennial oscillation. Nature Reviews Earth & Environment, 3(9), 588-603.

2. Simplifications for wave perturbations and EP flux diagnostic
Section 4.2 Modification of tropical upwelling: I found this section difficult to follow. The detailed discussion of extratropical planetary waves at two different wavenumbers does not seem necessary to explain the changes in the residual vertical circulation in the tropics.

I believe this section explores whether the changes in residual vertical circulation $\overline{\omega*}$ over the tropics can be largely explained by 1) changes in $\overline{\omega*}$ to compensate the diabatic heating $\bar{Q}$ or 2) changes in wave-driven circulation over the extratropics (associated with Fz) that is connected to the tropical circulation via mass continuity. However, this information from planetary waves and EP flux diagnostics largely focused on extratropics seems secondary compared to the radiative forcing over the tropics. I recommend substantially reducing the discussion of extratropical EP fluxes and waves, unless the authors intend to address their connection to the polar vortex.

Here are few examples of issues I found:
The EP-flux vectors and the divergence in Figure 8 already characterize net wave propagation and wave-mean-flow interactions, thus Figure S7 does not appear to provide more useful information. The amplitudes of wave activity seem difficult to reconcile across the figures: for example, wavenumber-1 amplitudes above 30 hPa appear larger in April than in July in Fig. S7, whereas the EP-flux diagnostics show larger amplitudes in July than in April. I therefore recommend shortening the discussion of wave perturbations in Fig S7.

I believe the wave propagation shown in Figure S7 is not necessarily consistent with what is shown in EP flux. For example, it has been stated:
L471-474: The enhanced Southern Hemisphere mid-latitude wave 2 propagates upward into

the stratosphere and is associated with EP flux convergence (Fig. 8b), contributing to increased residual vertical velocity in the tropical Southern Hemisphere between 5 and 20 hPa and thus strengthened upwelling (Fig. 9b).

However, in Fig. 8b, the vertical EP-flux vectors within the EP-flux convergence region (60–80°S, 100–10 hPa) do not appear to indicate upward wave propagation. Based on this figure alone, it is difficult to determine whether the increased residual vertical velocity over the tropics is driven by extratropical wave propagation or is a response that balances the tropical Q perturbations.

Lines 507–510 state that "Planetary wave 1 exhibits positive differences over most regions, except …" It is unclear what these positive differences in Figure S7d are relative to.

Figure 8d shows an EP-flux pattern that is consistent with, but stronger than, the pattern in Figure 8c. However, the planetary-wave patterns in Figures S7c and S7d appear quite different. This seems to indicate a discrepancy between the July wave patterns shown in Figures S7c–d and the EP-flux propagation shown in Figures 8c–d.

Lines 512–515 describe the relatively stronger wave-driven circulation in Figure 8d, compared with Figure 8c, as being connected to the stronger upwelling over the Southern Hemisphere subtropics in Figure 9d. However, the anomalous wave-propagation pattern in Figure 8d is opposite to the climatological pattern and is consistent with a weakening of the BDC, characterized by weaker tropical upwelling and weaker extratropical downwelling. Thus, it may be clearer to describe this as stronger anomalous wave forcing, while noting that it represents a weakening of the climatological wave forcing.

Similarly, on Line 515, consider changing "contributing to increased residual vertical velocity … and strengthened local upwelling" to "contributing to *an anomalously positive* residual vertical velocity … and *resulting in anomalous* local upwelling." However, in general this paragraph is a bit confusing because large downward residual-vertical-velocity anomalies also appear over the rest of the tropical stratosphere in Fig. 9d.

Again, I recommend authors to reduce the discussion of Figures 8 and S7.

3. Additional diagnostics of the "upwelling" mechanism

The extratropical wave activity shown in Fig. 8 and Fig. S7 do not seem to be the most direct diagnostic for assessing the forcing of tropical upwelling. I therefore suggest further examining the tropical residual vertical velocity and its role in the zonal momentum budget. Although the residual vertical velocity w* is shown in Figure 9, it is difficult to assess its contribution to the zonal-wind anomalies from this diagnostic alone, since w* is not itself a vertical flux of zonal momentum.

There are two main terms in the zonal-mean momentum equation (Holton 2004) that involves vertical velocity: 1) the mean vertical advection of zonal momentum ($\overline{\omega}^{*}\frac{\partial \bar{u}}{\partial p}$), and 2) the vertical divergence of the eddy momentum flux ($\frac{\partial(\overline{u'\omega'})}{\partial p}$). Aquila et al. (2014) found that the vertical advection of the mean flow was the main term balancing the zonal-momentum

tendency associated with parameterized gravity-wave forcing and driving the QBO's downward propagation.

Thus, I suggest that the authors examine this mean vertical-advection term.
For example, they could calculate the tropical average of the vertical advection of the mean flow. Then, integrate the resulting zonal-wind tendency over time to estimate the accumulated wind change associated with changes in tropical upwelling, and show in a similar format as in Figure S4. This will visualize the accumulated changes of tropical zonal wind associated with the changes in the tropical upwelling over time.

Similarly, since you already have EP flux divergence fields calculated, I suggest that the authors to examine the tropical zonal wind acceleration from wave forcing (D_F, the EP flux divergence term related to the acceleration of the zonal-mean zonal flow) and show in a similar format as in Figure S4. I suspect this term would be small.

$$D_F = \frac{1}{a\ cos\ \phi}\left(\frac{\partial F_p}{\partial p}\right) + \frac{1}{a\ cos\ \phi}\left(\frac{1}{a\ cos\ \phi}\frac{\partial\, F_\phi \cos\phi}{\partial \phi}\right) = \frac{1}{a\ cos\ \phi}\nabla \cdot \vec{F}$$

Here the QBO is defined within a narrow latitudinal band of 2°S–2°N, which was also used for the budget analysis in the previous study of Aquila et al (2014). I don't expect significantly different results with a larger band due to weak tropical temperature gradient. However, it seems the residual circulation anomalies show localized features extending beyond a 2° bandwidth in Figure 9, and the typical half-width of the QBO is ~12°. Thus, I believe it is worthwhile to double check for this budget analysis if using a broader latitudinal band (12°S–12°N) may better reduce the influence of smaller-scale disturbances compared to current 2°S-2°N domain.

4. Explaining causality using "Thermal wind balance" framework
I see that Franke et al. used the similar framework to show the zonal wind change associated with thermal wind balance. However, I do not think it is necessary to present separate plots of Ty and Tyy in two main figures, particularly if Tyy is included only to avoid numerical issues near the equator. Because Ty and Tyy are just intermediate steps in calculating the thermal-wind vertical shear (Uz), it may be more concise to show the vertically integrated Uz estimated from Ty (and maybe using Uz derived from Tyy to fill the equatorial region). This would make it easier to directly discuss about the zonal-wind change associated with thermal-wind balance.

Another point to consider is that attributing zonal-wind anomalies to temperature-gradient changes caused by stratospheric aerosol injections using the thermal-wind framework relies on several assumptions: The pressure gradient force (PGF) from increased height gradient is generated solely by the temperature response to aerosol heating, and that the PGF is in geostrophic balance with Coriolis force acting on the zonal wind, in order to be treated as the sole factor explaining dU/dt. And at tropical latitudes, geostrophic balance is difficult to be maintained due to the weak Coriolis force.

Thus, the thermal-wind framework may be more appropriate for the subtropics than for the 2°S-2°N latitude band used in this study to define the QBO. Even in the subtropics, examining the zonal-wind acceleration due to the Coriolis torque acting on the residual meridional circulation (fv*) may provide a more direct explanation of the wind changes than the temperature gradient.

MINOR COMMENTS

1) Fleming et al. (2024) also compared the difference in temperature anomalies induced by QBO and Hunga forcing based on different model, thus it would be nice to add some discussion/comparison with their results and current results based on WACCM.

Fleming, E. L., Newman, P. A., Liang, Q., & Oman, L. D. (2024). Stratospheric temperature and ozone impacts of the Hunga Tonga-Hunga Ha'apai water vapor injection. Journal of Geophysical Research: Atmospheres, 129(1), e2023JD039298.

2) Figures 3a and S1a appear to show the same results but use slightly different domains and color scales. I suggest using a less saturated color scale in Fig. 3a that is consistent with Fig. S1a. Finally, extending the vertical range of both panels in Fig. S1 to 5 hPa may help readers compare the patterns across the figures.

3) As noted in Major Comment 1:
L163: the QBO transitioned from a westerly to an easterly phase -> seems like at 30 hPa transitioned from an easterly to westerly (or westward to eastward) phase

L243: with a transition from westerly to easterly shear during the study period (Fig. S4) -> easterly to westerly

4) What is the unit of EP flux divergence in Figure 8?

5) L454: indicating enhanced wave convergence and strengthened wave forcing on the mean flow in the Antarctic stratosphere at 30-100hPa.

6) Figures 8 and 9: What is the statistical significance of these anomalies?

7) Anomalies in the residual stream function
The residual stream function could help visualize the changes in overturning circulation associated with the dynamical processes discussed above. I suggest adding these anomalies to Figure. 6, like the Figure 4 of Fleming et al. (2024).