We thank the reviewer for their valuable feedback and the overall positive evaluation of our work. In particular, we are thankful for the general comments because they enabled us to significantly improve the overall quality and clarity of our manuscript. Please find below our point-by-point responses to all specific comments, with our replies and manuscript revisions highlighted in blue.

General comments:

1) The authors use the instantaneous local tropopause levels (lapse-rate tropopause, LRT, for bottom of TTL; cold-point tropopause, CPT, for bottom of stratosphere) to determine whether parcels enter the TTL or stratosphere. At such a local, instantaneous level it is not completely clear whether this tropopause really acts as a transport barrier. Conceptually, one would need some sort of background tropopause from the surrounding area and/or time period to characterize it as a transport barrier. I appreciate that this would be complicated to implement and would result in additional uncertainties. But I'd like to see some discussion of this potential issue.

   Thank you for raising this fundamental point as the tropopause definition is a crucial aspect in order to identify properly the intrusions into the TTL and stratosphere. Below we give an additional reasoning for our approach and reflect this discussion also in the revised manuscript (L138 – 144).

   We assume that during an extreme event like the typhoon Molave, the location of the tropopause may be altered by the strong updrafts, overshooting convection and gravity waves. Therefore, determining the instantaneous location of the tropopause during such an extreme event is essential for capturing the precise moment of intrusions into the TTL or stratosphere. In our work, the TTL was consistently well-defined using the LRT and CPT, with depths ranging from 350 m to 4 km. The instantaneous tropopause has been used in previous studies, particularly in relation to the tropical tropopause, where the 2 PVU surface fails to accurately identify the tropopause (Stohl et al., 2003).
   The algorithm AirIntrusions constantly monitored the altitude of the air parcels with respect to the altitudes of the LRT and CPT taking into account shallow crossings due to oscillations in air parcel height or fluctuations in one of the tropopause boundaries (see also the comment line 124 below). We believe that using a background tropopause without considering the typhoon's influence on it would lead to overestimation or underestimation of the intrusions. For example, if the typhoon pushes the local troposphere upward, measuring parcel heights against a lower, undisturbed background tropopause would falsely register those parcels as entering the TTL or stratosphere.

   As for the question of how good a transport barrier the tropopause is – we agree with the reviewer that this is not that straightforward, because the tropopause cannot be viewed as some impermeable material line. In fact, systematic advective exchange of air across the tropopause exists within the Brewer-Dobson circulation. Still, one has to acknowledge that due to the strongly stable conditions in the TTL and stratosphere, the convection and upward advection get dampened here. Hence, the transport of air from the troposphere to the stratosphere is rather sporadic, which is reflected also in the differences of the tropospheric and stratospheric composition of air.

The transport barrier concept is not an important aspect for our study and hence we omit this phrase in the revised manuscript (before occurred on 3 occasions in the original manuscript).

References:

Stohl, A., Wernli, H., James, P., Bourqui, M., Forster, C., Liniger, M. A., ... & Sprenger, M. (2003). A new perspective of stratosphere–troposphere exchange. Bulletin of the American Meteorological Society, 84(11), 1565-1574.

2) The above potential issue is also related to the question of the fate of those air parcels that locally overshoot/enter stratosphere further downstream. In lines 194-196 the authors allude to the fact that many parcels in fact do not stay above the tropopause until the end of the simulation, which suggests that they did not conclusively cross the transport barrier. What does this mean for the actual net impact by the tropical cyclone on the composition of stratospheric air? Again, I'd like to see more discussion of this potential issue.

Thank you for the comment, we think that the answer has already been contained in the original manuscript, but based on your comment, we decided to add two new figures to the paper, which quantify the stability regime of the particles crossing the tropopause and elucidate the issue of fluctuating particles (Figure 5 and 6 in the revised manuscript).

Also, two additional tables are added in the revision, with information about the residence time and the time for reaching the TTL/stratosphere from the planetary boundary layer (Table 1 and 2 in the revised manuscript).

The stability regime figures (Figure 5 and Figure 6) reveal that a part of the particles crosses the tropopause as a result of instabilities (convective/dynamical) and turbulence, which would mix them with the ambient air. Another part of the particles is advected across the tropopause in a stable, turbulence free regime especially for secondary intrusions over the R1 target region (Figure S1) (wave induced vertical motions likely play an important role here) and fluctuate between the layers (see L220 – 252).

This is then reflected in the residence times of the air parcels (see L215 – 218). The majority of the air parcels reside in the TTL or stratosphere for up to 3 hours (76.8 % of the parcels for TTL and 85.3 % for the stratosphere). Still, a significant number of air parcels reside in the TTL and stratosphere for a long time (> 9 h; about 6 % for the

TTL and 5 % the stratosphere) increasing the possibility of chemical interactions leading to local changes in the atmospheric composition. Furthermore, the rapid transport of planetary boundary layer air towards the TTL and stratosphere could impact the local chemical composition even for the short residence times of about 3 h, if very reactive short-lived tracers are transported.

Finally, beyond the question of impact for the stratospheric composition, our results document that also the air parcels that only fluctuate between the layers were able to escape the boundary layer and reach the upper troposphere – lower stratosphere region in a very short time and reside in this region until the end of the simulation. Hence, these air parcels may as well be subjected to long-range transport and impact locations far away from the source area located in the Philippines (see L336–341 in the revised manuscript).

3) Yet another related, and more technical question is to what extend parcels fluctuate above/below the tropopause due to fluctuations in the parcel position itself or fluctuations in the tropopause level? This could be quantified and would provide a feeling for the transient nature of the local tropopause itself and its potential role in the studied transport pathways.

   We thank the referee for raising this point. This information was already implicitly contained in the Fig. 5 of the original manuscript and we now discuss it more explicitly in the revision. Particularly, Figures 5c and 5d (now Figure 7c and 7d) make evident how the air parcels characterized by secondary intrusions fluctuate along their mean position. The figure also shows the standard deviations of the LRT and CPT altitude and makes clear that the tropopauses fluctuate to a much smaller extent than the air parcels. This indicates that it is the vertical oscillations of the air parcels that are primarily responsible for the crossings, rather than oscillation in the location of the tropopauses, which can, however, also play a minor role (see L281 – 286).

4) Importance of tropical cyclones for overall TST across the entire tropical tropopause is debatable - I'm not aware of evidence that this component of TST is substantial (measured relative to TST by other transport pathways, such as planetary-scale overturning circulations, equatorial waves, "regular" deep convection). From that perspective one might question the importance of orographically enhanced TST via the associated gravity waves, which may represent a small portion of all tropical cyclones. So the motivation in the context of tropics-mean TST seems questionable. Do the authors agree? Or do you see stronger motivation? In either case it'd be nice to spell this out more explicitly.

   Thank you for the comment, however, we agree only partially at this point.

   For one, the TST via gravity waves and the transport from the planetary boundary layer enhanced by the interaction between TCs and orography is a novel mechanism that has not been described in the literature before, according to our knowledge. Hence, we think that highlighting this novel process has a scientific value of its own and quantifying the overall importance of this mechanism goes beyond the scope of our manuscript and should motivate follow-up studies.

Regarding the overall importance of tropical cyclones for TST, it has recently been pointed out that much remains unknown about the occurrence of total stratosphere-troposphere exchange in TCs (Gordon & Homeyer, 2025). For instance, 10-15 % of the global lower stratosphere H2O budget can be associated with overshooting convection in the tropics (Dauhut & Hohenegger, 2022; Tinney & Homeyer, 2021; Ueyama et al., 2023) and it has been found that approximately 15% of overshooting convection in the tropics occurs in TCs (H. Jiang & Tao, 2014; Romps & Kuang, 2009). Therefore, it is imperative to investigate this understudied STE mechanism as the accurate representation of the H2O budget is an important goal for earth system models (see L31 – 40 in the revised manuscript). Furthermore, in our study we observe that the typhoon can transport air parcels from the planetary boundary layer to the upper troposphere – lower stratosphere region in about 2-3 hours. As the Philippines are located in a highly polluted region, this rapid exchange of air can have a potential significant impact on the chemical composition of the UTLS if short-lived chemical species are captured from the lower troposphere (see L336 – 341 in the revised manuscript)

References:

- Gordon, A. E., & Homeyer, C. R. (2025). Examining stratosphere-troposphere exchange in an idealized simulation of a tropical cyclone. Journal of Geophysical Research: Atmospheres, 130(21), e2025JD044044.
- Dauhut, T., & Hohenegger, C. (2022). The contribution of convection to the stratospheric water vapor: The first budget using a global storm-resolving model. Journal of Geophysical Research: Atmospheres, 127(5), e2021JD036295. https://doi.org/10.1029/2021JD036295
- Tinney, E. N., & Homeyer, C. R. (2021). A 13-year trajectory-based analysis of convection-driven changes in upper troposphere lower stratosphere composition over the United States. Journal of Geophysical Research: Atmospheres, 126(3), e2020JD033657. https://doi.org/10.1029/2020JD033657
- Ueyama, R., Schoeberl, M., Jensen, E., Pfister, L., Park, M., & Ryoo, J.-M. (2023). Convective impact on the global lower stratospheric water vapor budget. Journal of Geophysical Research: Atmospheres, 128(6), e2022JD037135. https://doi.org/10.1029/2022JD037135
- Jiang, H., & Tao, C. (2014). Contribution of tropical cyclones to global very deep convection. Journal of Climate, 27(11), 4313–4336. https://doi.org/10.1175/JCLI-D-13-00085.1

- Romps, D. M., & Kuang, Z. (2009). Overshooting convection in tropical cyclones. Geophysical Research Letters, 36(9). https://doi.org/10.1029/2009GL037396

Minor comments:

line 11 (last sentence of abstract): this seems like a strong overstatement to me (see general comment above); I recommend to instead add a sentence about potential implications for TST in other tropical cyclones

We agree on stating the implications of our results for other tropical cyclones more explicitly, but we preferer to keep the note on the potential implication for the long-range transport of pollutants (see L11 – 14). As discussed in our response to the related general comments, our results show that air parcels that can penetrate the TTL/stratosphere continue to travel close to the tropopause, even when they re-enter the troposphere, which increases the possibility of long-range transport for these air parcels.

Introduction: I'm missing some motivation as to why you chose to provide another study of Molave (beyond Huang et al., who already studied STE associated with gravity wave activity for this particular typhoon). To be sure, I'm not saying that there aren't sufficiently novel insights here, but given the broader question of importance of the findings (see general comment above) it seems desirable to provide more/different motivation.

We thank the reviewer for this comment and have clarified the novelty of our work in relation to that of Huang et al. (2020) more effectively. While both studies investigate Typhoon Molave, our study focuses strictly on the period from the 24th to the 26th of October, specifically capturing the typhoon landfall and interaction with the complex orography of the Philippines. In contrast, Huang et al. (2020) investigate a later period starting from October 27th, focusing on the gravity waves generated after the typhoon had already crossed the Philippines and moved into the South China Sea. Furthermore, the Philippines is a well-documented regional pollutant hotspot. By focusing on the exact window of landfall over this domain, our study provides unique insights into how complex terrain-typhoon interactions may impact local and regional pollutant dispersion, which is an aspect not addressed by Huang et al. But, already in the original version of the manuscript, we acknowledge the work by Huang et al., who brought the typhoon Molave into our attention. We extended the original introduction to better motivate our research at L31 – 40 and L 59 – 64 in the revised manuscript.

line 63: please add information whether this is a one-moment or two-moment scheme?

The Goddard scheme (Tao et al., 2016) for microphysics is a single-moment scheme. This information is now included in the manuscript (see L77).

line 90: please state here which configuration you actually did include (passive?)

We considered passive tracers and we stated it more clearly in the text (see L114).

line 124: please clarify in which way you need/use the two time steps

An intrusion is identified by tracking the position of an air parcel across two contiguous time steps: the old location (time t) and the new location (time t+1). For example, a parcel might start below the LRT at the old location and move between the LRT and CPT at the new location. To confirm this, the old location must be compared against the LRT and CPT boundaries from that initial time step, while the new location must be evaluated against the boundaries at the subsequent time and position. Consequently, LRT and CPT values must be computed for both contiguous time steps. This text is reported at L148 – 154.

line 127: how do you define the top of PBL?

Thank you for the question. The PBL height is computed internally by FLEXPART-WRF using a Richardson number threshold set to 0.25. (see Brioude et al., 2013 and Stohl et al., 2005). We state this now explicitly in the revised manuscript at L157.

References:

- Brioude, J., Arnold, D., Stohl, A., Cassiani, M., Morton, D., Seibert, P., ... & Wotawa, G. (2013). The Lagrangian particle dispersion model FLEXPART-WRF version 3.1. Geoscientific Model Development, 6(6), 1889-1904.
- Stohl, A., Forster, C., Frank, A., Seibert, P., & Wotawa, G. (2005). The Lagrangian particle dispersion model FLEXPART version 6.2. *Atmospheric Chemistry and Physics*, *5*(9), 2461-2474.

line 158: please include more detail in which way the wave may become unstable and how you infer this from the plots

Thank you very much for highlighting a part of the manuscript that deserves more detailed explanation. Basically, there are two main instability sources for upward propagating OGWs in the troposphere/stratosphere: convective and dynamical instability. Convective instability occurs once the wave's amplitude is large enough and/or potential temperature isolines are steep enough that heavier air parcels are located above the lighter parcels causing an unstable stratification. In relation to gravity waves, such a state can be reached either through wave propagation to the UTLS, a region of lower air density that enables amplitude growth; or through the overturning of OGWs in case of near surface breaking. The dynamical instability refers to situations when the wave amplitude grows at the expense of the horizontal wind shear. The two instabilities can also act jointly (Sutherland, 2010), as indicated also by our results (Fig. 6b, now Fig. 8b, and also later time steps of the same transect; not shown), where a succession of initially dynamical and subsequently convective instability is present (see L191 – 192 in the revised manuscript).

Reference:

Sutherland, B. R. (2010). Internal gravity waves. Cambridge university press.

Fig. 4: it'd be helpful to have axes on the zoomed panels (e.g., upper left looks like it has longitude on x and latitude on y - correct?)

We thank the reviewer for the helpful suggestion. The reviewer is correct that the x-axis represents longitude, and the y-axis represents latitude. These axes are now explicitly included in the zoomed panels. Note that we decided to add an additional target region called R5 in order to consider an area over the sea less affected by the presence of orography and located along the typhoon path (see L205 - 208 and the new Figure 4 in the revised manuscript). While adding the R5 information to Table 4, we noticed a typo in the R1 results. We corrected this, but the conclusions remain unchanged.

line 196: missing "." at end of sentence after "simulation"
Thank you, done.

Fig. 5: it'd be helpful to label the panels in some way (e.g., "entering TTL, single intrusion" etc.)
Done. We added self-explanatory titles to each plot to increase readability (this Figure is now Figure 7 in the revised manuscript).

line 204: I don't understand how the remark in parenthesis fits the preceding statement "mostly affected by first intrusions" (btw, you could delete "(Table 2)" in this line - should be clear from previous sentence)
“First intrusion” refers to the first time in which air parcels enter the TTL/stratosphere. It does not mean that the air parcels enter the TTL/stratosphere just once; we refer to this situation as a “single intrusion” in the text. We have made this distinction clearer in the text (L261 – 264). Thank you for highlighting this potential source of confusion.

Fig. 7: I can't quite follow some of the plotting choices - why is there no shaded indication of convection for the "orographically enhanced updrafts"? What is the difference between the "overshooting updrafts" as part of the typhoon and the "overshooting convection" (gray) next to it? In what way should I be able to infer the interaction of the typhoon with orography (the surface winds look confusing to me - shouldn't they converge into the typhoon instead of flowing out)?
We thank the reviewer for checking Figure 7 carefully and pointing out these issues. The sketch has been revised as follows:

1. Regarding the shading, it is omitted for the "orographically enhanced updrafts" to visually distinguish them from the main typhoon-core and outer-core convection.
2. The “overshooting updrafts” refer to the convection occurring within the typhoon; whereas, the “overshooting convection” refers to the outer-core convection processes not strictly happening within the typhoon itself. For a more detailed discussion of the illustration of processes inside the typhoon, we refer the reviewer to Figure 1 in Gordon and Homeyer (2025), from which our schematic sketch was adapted.
3. To resolve the confusion regarding the surface wind field, we have revised the wind arrows in the sketch to illustrate the low-level typhoon circulation interacting with the orography.

We believe the revised schematic is now much more intuitive and accurately reflects the underlying dynamics. Additional text to describe the figure has been added at L333 – 335.

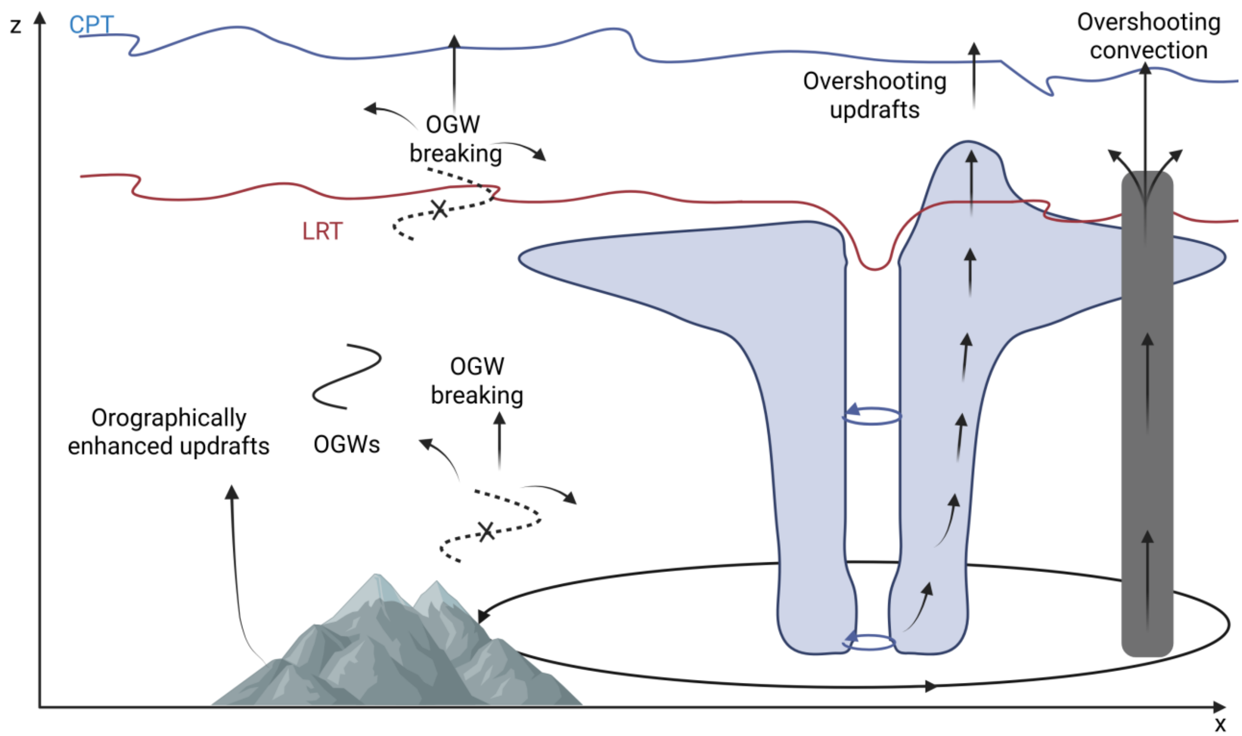

Figure 9 (previously Figure 7). Sketch of the troposphere-to-stratosphere transport arising from the interaction of a typhoon with orography based on the illustration by Gordon and Homeyer (2025) of a tropical cyclone cross section. It points out the significant contributions of orographic updraft enhancement and orographic gravity wave (OGW) breaking close to the tropopause and near the surface. The blue line represents the Cold Point Tropopause (CPT) and the red one the Lapse Rate Tropopause (LRT).