We thank the reviewer for their valuable comments and for the positive evaluation of our work. We believe that addressing these comments has significantly improved 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.

Minor comments (in order of appearance)

L48 "…models and observations (Kunkel et al., 2014), but…": In Kunkel et al. (2014) only results from idealized model simulations are shown. So here the observational reference is missing here.

Thanks for pointing this out, we have added the following two observational references at L57:

1. Moustaoui, M., Teitelbaum, H., Van Velthoven, P. F. J., & Kelder, H. (1999). Analysis of gravity waves during the polinat experiment and some consequences for stratosphere–troposphere exchange. *Journal of the atmospheric sciences*, *56*(8), 1019-1030.
2. Kunkel, D., Hoor, P., Kaluza, T., Ungermann, J., Kluschat, B., Giez, A., ... & Riese, M. (2019). Evidence of small-scale quasi-isentropic mixing in ridges of extra-tropical baroclinic waves. Atmospheric Chemistry and Physics Discussions, 2019, 1-34.

L60: What is the vertical grid spacing of the WRF simulation, especially in the UTLS?

The vertical grid spacing follows the one used in Kruse et al. (2022) and has a vertical grid spacing of about 400 m in the region 12 - 18 km. This information has been added at L75 in the revised manuscript.

Reference:

Kruse et al. (2022). Observed and modeled mountain waves from the surface to the mesosphere near the Drake Passage. Journal of the Atmospheric Sciences, 79(4), 909-932.

L112: Can you please include the criterion for the LRT detection here? I guess it is the one with 2K/km and the 2 km thick layer above? And also Lapse Rate Tropopause; why are the words capitalized?

In FLEXPART-WRF, the LRT is computed as the lower boundary of a layer in which the temperature lapse rate is less than 2K/km for a depth of at least 2 km (as described in Hoinka, 1997). This information is now reported in the revised manuscript at L129 – 131.

The capitalization was a typo; it has been corrected.

L149: Can the OGWs be more specifically shown, e.g., using a cross section through the region of the OGWs.

We thank the reviewer for this suggestion. For this, we have expanded the description of Figure 3a, which shows imprints of GWs and orographic GWs in a horizontal plane (L178 – 182). Besides this, the cross-section through the OGW field was already present in the manuscript as Figure 3c. We also highlight this aspect more in the revision.

And more importantly: the connection of these OGW should be made more clearly to the low Ri values shown in Fig. 6. I would value it, if this connection would be shown in more detail in the manuscript; in the current version it might not be too obvious for many reader to see the OGW signals.

We agree with the reviewer that including additional figures to illustrate the connection between OGW and the dynamic or convective instabilities, which underlay the observed intrusions into the TTL/stratosphere, will improve the clarity of the manuscript.

To address this, we have added two new figures in the revised manuscript (Figure 5 and 6) for the R2 and R4 target regions (shown in Figure 4) and three figures in the supplementary materials for R1, R3 and R5 where the intrusions are categorized by their specific stability regimes. This categorization allows us to better differentiate between varying atmospheric conditions using the following criteria:

- Convective Instability: Ri < 0;
- Dynamic Instability: 0 =< Ri <= 0.25;
- Stable Conditions with Non-Negligible Turbulence: Ri > 0.25 and TKE > 0.1 m^2s^{-2};
- Stable Conditions with Negligible Turbulence: Ri > 0.25 and TKE <= 0.1 m^2s^{-2}.

This later two criteria are introduced, because it is known from the literature that in coarsely sampled model data the criterion of Ri <= 0.25 is overly sharp for coarse datasets and may result in missing some of the dynamic instability events occurring in the model (Kaluza et al., 2022). The threshold value of 0.1 m^2s^{-2} for TKE is established based on the domain-averaged TKE within the 16–19 km layer during the first 10 hours of the simulation, restricted to the calm region west of 129 °E (Figure S4). 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.

As a representative example, in target region 4 (located in the northern Philippines where OGW activity is most intense), the new Figure 6a demonstrate that air parcels influenced by orography consistently experience elevated turbulence before entering the TTL, even when the Richardson number alone suggests a stable layer. The signature of dynamical instability or enhanced TKE in otherwise stable Ri regimes are key indicators of OGW-induced mixing, which motivated our original approach in the previous Figure 6 (in the original version of the manuscript) to combine both metrics.

Furthermore, the absolute number of air parcels associated with turbulent conditions are considerably higher over land than over the ocean (Figure 6a and Figure 6c), further substantiating the link between orographic wave activity and the observed low-Ri and high-TKE signals.

These changes can be found at L220 – 252 in the revised manuscript, alongside the new Figures 5 and 6.

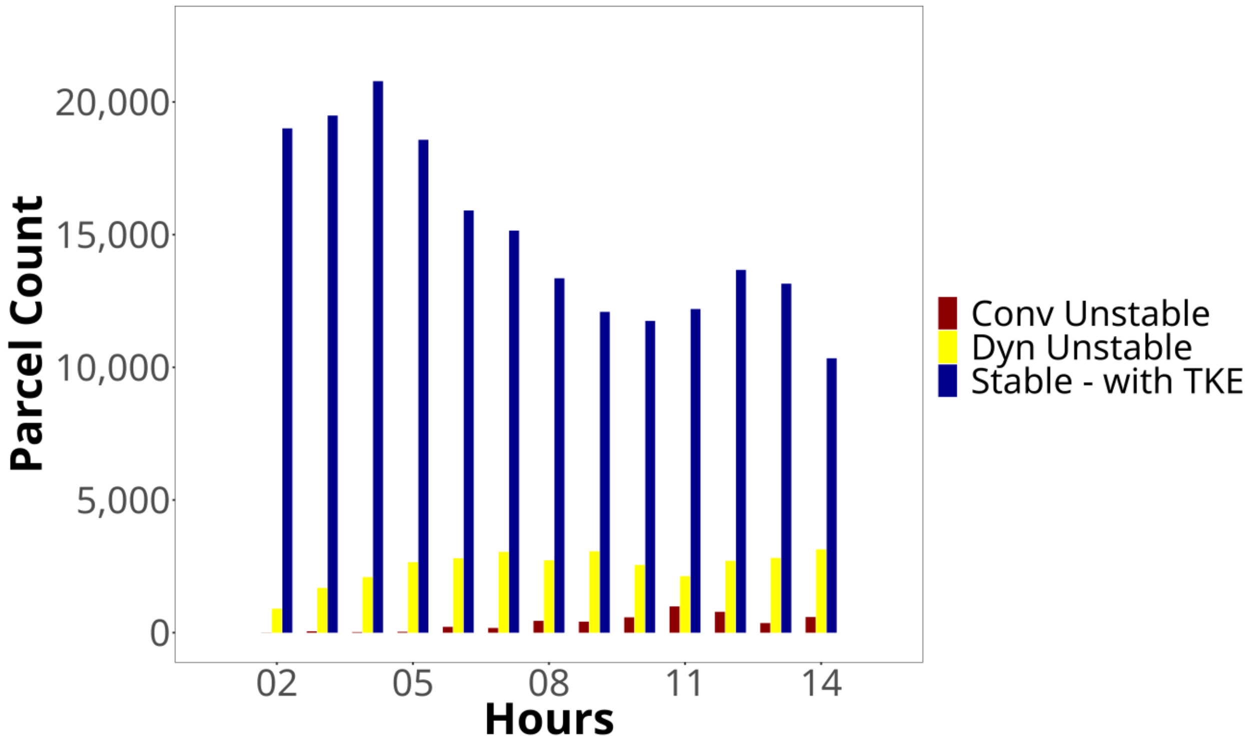

Figure 6a – Intrusions per hour entering the TTL across the R4 target region on the 26 October 2020 over the land, categorized using stability regimes. The bars indicate the absolute parcel counts categorized into four distinct environmental regimes based on their Richardson number (Ri) and Turbulent Kinetic Energy (TKE): convective instability (Ri < 0, dark red), dynamical instability (0 <= Ri <= 0.25, yellow), stable conditions with non-negligible turbulence (Ri > 0.25 and TKE > 0.1, dark blue), and stable conditions with negligible turbulence (Ri > 0.25 and TKE <= 0.1, light blue).

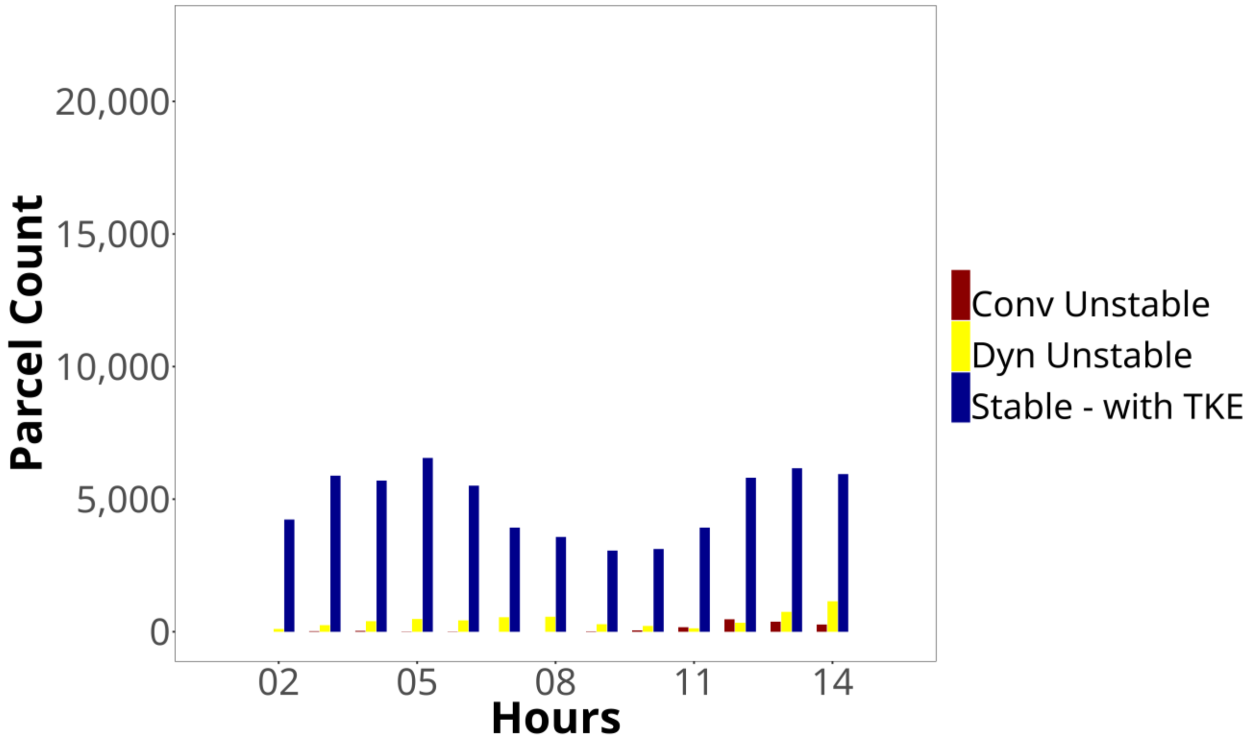

Figure 6c – Intrusions per hour entering the TTL across the R4 target region on the 26 October 2020 over the sea, categorized using the stability regimes. The bars indicate the absolute parcel counts categorized into four distinct environmental regimes based on their Richardson number (Ri) and Turbulent Kinetic Energy (TKE): convective instability (Ri < 0, dark red), dynamical instability (0 <= Ri <= 0.25, yellow), stable conditions with non-negligible turbulence (Ri > 0.25 and TKE > 0.1, dark blue), and stable conditions with negligible turbulence (Ri > 0.25 and TKE <= 0.1, light blue).

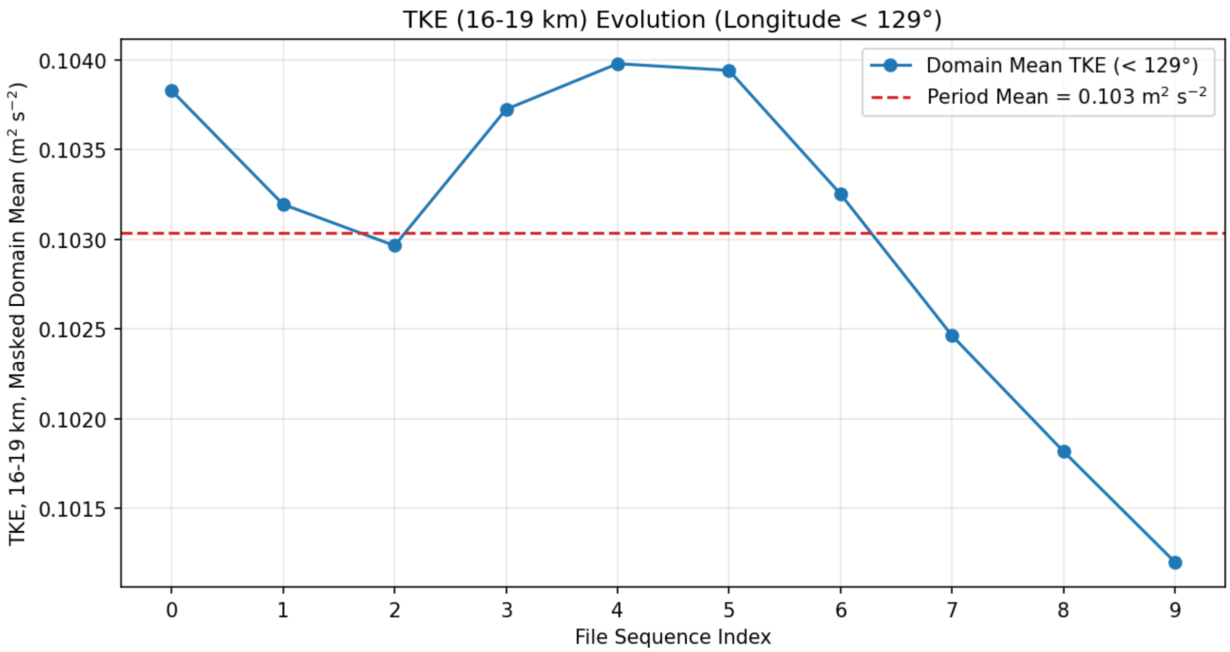

Figure S4 – Domain-averaged TKE within the 16 – 19 km layer for the region west of 129 °E during the first 10 hours of the simulation on 24 October 2020 (00:00--09:00 UTC). The red dashed line denotes the 10-hour mean TKE.

Reference:
Kaluza, T., Kunkel, D., & Hoor, P. (2022). Analysis of turbulence reports and ERA5 turbulence diagnostics in a tropopause-based vertical framework. Geophysical Research Letters, 49(20), e2022GL100036.

L158/159: Upper Troposphere–Lower Stratosphere => upper troposphere-lower stratosphere

Done, we used only the acronym UTLS (L192)

L184: The first discussion around the secondary intrusion and the concept of multiple tropopause crossing is very much like the transit time concept used by Wernli, H., and M.Bourqui, A Lagrangian “1-year climatology” of (deep) cross-tropopause exchange in the extratropical Northern Hemisphere, J. Geophys. Res., 107(D2), doi:10.1029/2001JD000812, 2002.

Bourqui, M. S.: Stratosphere-troposphere exchange from the Lagrangian perspective: a case study and method
sensitivities, Atmos. Chem. Phys., 6, 2651–2670, https://doi.org/10.5194/acp-6-2651-2006, 2006.

We really appreciate the two additional references you provided. While Bourqui (2006) was already cited in the introduction, we did not mention Wernli and Bourqui (2002).

We agree that there are similarities between the “secondary intrusions” concept presented in our manuscript and the “transit time concept” developed in Wernli and Bourqui (2002). Therefore, we modified the sentence as follows: “To capture this effect,

the secondary intrusions concept is introduced, similar to the transit time concept developed by
Wernli et Bourqui (2002), but without discarding shallow intrusions." (L256 – 257).

Furthermore, we included Bourqui (2006), along with James et al. (2003), as sources of inspiration for the development of the algorithm AirIntrusions used in this manuscript at L145.

L187ff (the discussion around Figure 5): Can you more clearly state what the difference is between Figures 5a and 5b and between Figures 5c and 5d, especially in the figure itself by using a title or in the figure caption? From the text I get: 5a, 5c are for intrusions into the TTL and 5b, 5d are for intrusions into the stratosphere?
Thank you for this suggestion regarding clarity.

The reviewer correctly interpreted the figures: 5a and 5c depict intrusions into the TTL (single and secondary intrusions, respectively), while in 5b and 5d air parcels move across the CPT (in our definition of the TTL) and enter the stratosphere (single and secondary intrusions, respectively). We have made slight changes to the text (L260 - 276) and the caption and added also self-explanatory titles to each plot as suggested (now Figure 7 in the revised manuscript). We now believe the meaning to be clearer.

Figure 5: When looking at Figure 5 I wondered whether you have the data for each trajectory available from the FLEXPART-WRF simulation and more specifically:
(1) Are any other quantities available along the trajectories? Especially, quantities which would help to show the presence of OGWs? Or to highlight the dynamic instability, in lines 133/134 it is stated that the Richardson number, the TKE and the Brunt-Vaisala frequency are available.
Yes, the Richardson number and Turbulent Kinetic Energy (TKE) are available along the air parcel trajectories. However, the mention of the Brunt-Väisälä frequency in the original manuscript was a typo, and this variable is not available; we have corrected the text accordingly (L164). Furthermore, we have now included additional figures using the Richardson number and TKE prior to entering the Tropical Tropopause Layer (TTL) or stratosphere (Figure 5 and 6). These new visualizations successfully highlight the roles of both dynamic instability and convective instability during the TTL/stratospheric intrusions. Please see our detailed response and the updated figures in the previous comments about L149.

(2) If OGWs play a role I would expect to see some undulations in the trajectories? Is this the case here? If so, where? If not, why?
Yes, the air parcels exhibit some undulations along their trajectories, which is particularly evident in Figures 5c and 5d (now Figure 7c and 7d). These figures show air parcels characterized by secondary intrusions into the TTL and stratosphere. As we can see from the standard deviation around the mean altitude of all parcels experiencing secondary intrusions, their trajectories are far from straight. Furthermore, the standard deviations of

the LRT and CPT are lower than that associated with the location of the air parcels, indicating that it is the oscillation of the air parcel trajectory that is responsible for penetration into the TTL/stratosphere, rather than oscillation in the location of the TTL/stratosphere.

We included this discussion at L281-286 in the revised manuscript.

L275 (and **L139**): I tried to follow the given link (https://github.com/MassiMart/FLEXPART-WRF_AirIntrusions.git) and it gave me a http 404 error. I only can reach https://github.com/MassiMart, maybe the repository is still private? And also the asset made available when submitting this review was expired.

We apologize for the inconvenience. Unfortunately, the temporary link pointing to the directory expired in April. You can have access to the temporary repository using this new link:
https://anonymous.4open.science/r/FLEXPART-WRF_AirIntrusions-B648/README.md
The repository will be made publicly available once the paper is accepted for publication.