Reviewer #2

Authors response:

We sincerely thank the reviewer for their comprehensive review and valuable feedback. We have carefully considered all suggestions and addressed each point in the revised manuscript. Our detailed responses are provided below. All line and page numbers refer to the track-changes version of the manuscript.

Review of **Stratosphere–Troposphere Exchange and Surface Ozone Pollution over Tropical Regions: A Case Study of Rossby Wave Breaking and Tropopause Folding** by

Clemente Lopez-Bravo, Ernesto Caetano and Armenia Franco-Díaz

Major Comments

I agree with the first reviewer that this manuscript is not suitable for publication in the state that it in at the moment. It needs to be significantly reorganised and redundant information to be removed. This constitute a major revision of the manuscript and below I present some comments for the authors to consider.

Authors response:

We appreciate the reviewer's assessment and agree that the original submission needed significant reorganization and removal of redundant material. In response, we have thoroughly revised the manuscript to improve clarity, logical flow, and scientific focus, and to better distinguish process-based insights from descriptive content. The major changes are summarized below:

1. **Reorganization**
   Previously, descriptions of case evolution, diagnostics, and interpretation were interwoven, which reduced clarity and caused repetition. The revised manuscript now follows a clearer progression from:
   - synoptic-scale dynamics and Rossby wave breaking,
   - tropopause fold structure and depth,
   - transport pathways and STE diagnostics, and
   - implications for surface ozone and air quality.

   This reorganization is most evident in the Results section, where content is now explicitly aligned with physical processes rather than a chronological narrative.

2. **Removal and consolidation of redundant material**
   The original manuscript repeated explanations of Rossby wave breaking, tropopause folding, and potential vorticity diagnostics across several sections. In the revision, methodological descriptions are limited to Section 2 (L:95-185,P:2-6), while the Results section focuses on interpretation and synthesis. Redundant text has been removed or consolidated, resulting in a more concise and readable presentation.

3. **Clearer separation between methods, results, and interpretation**
   Methodological explanations (e.g., PV thresholds, isentropic diagnostics, and trajectory criteria) were often repeated within the Results section. These elements are clearly separated, with interpretation moved to the Discussion section (L:188-414, P:720). This improves coherence and reduces redundancy.

4. **Improved focus and reduction of descriptive emphasis**
   The revised manuscript emphasizes the persistence, depth, and geometry of the STE event, rather than repeating descriptions of the same figures or diagnostics. This shift creates a more process-oriented narrative and clarifies the key physical mechanisms driving the event and its air-quality impacts.

5. **Contextualization beyond a single event**
   To avoid an overly descriptive single-case study, the revised manuscript now includes a concise analysis of additional high-ozone episodes preceded by tropopause folding. This section has been streamlined and repositioned to support broader interpretation rather than duplicate earlier content.

In addition to the re-organisation of the manuscript, in my opinion as reviewer, this paper does not clearly illustrate what the contribution is to the STE body of knowledge thus far. It merely describes the event but how does this event advance our understand of STE processes? This is not clear to me.

Authors response:

Thank you for your valuable comment. Although the manuscript addressed its contribution to the broader stratosphere–troposphere exchange (STE) literature, we recognize these points were not sufficiently emphasized. We have revised the text to clarify the study's contribution and expanded the discussion to provide clearer process-based insights, addressing the gaps you identified.

We have substantially revised the manuscript to clarify how this case study advances understanding of STE processes, particularly in tropical and subtropical regions. The revised manuscript now highlights the following key contributions:

1. **Extension of STE theory to low tropical latitudes and elevated basins.**
   Although STE associated with Rossby wave breaking and tropopause folding is well documented at midlatitudes, this study provides rare process-based evidence that persistent anticyclonic Rossby wave breaking can cause unusually deep stratospheric intrusions reaching the lower troposphere near 20°N. The March 2016 event demonstrates that STE mechanisms, typically considered midlatitude phenomena, can directly affect tropical urban regions when combined with subtropical jet displacement and the presence of densely populated areas atop mountain ranges. For example, Mexico City, home to approximately 23 million people, is exposed to frequent high pollution events, which directly impact health and quality of life (Sections 3.2-3.4; Discussion, L: 224-361, P:8-17).

2. **Identification of sustained, coherent isentropic transport pathways as a key mechanism.**
   By combining Eulerian diagnostics with Lagrangian trajectories and quasi-horizontal isentropic advection, we show that the depth and impact of this STE event depended not only on instantaneous tropopause folding, but also on the persistence and coherence of isentropic transport pathways over several days. This highlights the importance of transport geometry and duration, rather than event intensity alone, in allowing stratospheric air to influence near-surface layers (Sections 3.4-3.5, L:297-330, P:14-18).

3. **Demonstration of STE as a dynamical precursor to surface ozone exceedances.**
   The analysis shows that stratospheric air descended into the lower troposphere about one day before the surface ozone contingency in Mexico City, effectively preconditioning background ozone levels. This timing clarifies the role of STE as a dynamical precursor that enhances anthropogenic ozone production, rather than serving as the sole driver of exceedances, and advances current interpretations of STE–air-quality coupling (Section 4, L:415-477, P:21-22).

4. **Evidence of recurrence and broader relevance beyond a single case.**
   To move beyond a descriptive case study, we added an analysis of additional high-ozone events preceded by tropopause folds (2007, 2015, 2019, 2024). This context shows that the mechanisms identified in March 2016 are recurrent and structurally similar, supporting the broader relevance of the proposed STE pathways for subtropical air-quality extremes (Section 3.6, L:381-414, P:18-20).

Minor comments

Lines 28-29: The authors should clarify exactly how stratospheric air ends up in the tropopause. The occurrence of a RWB (or tropopause fold) event does not necessarily mean that STE occurs, what it guarantees is that the dynamical tropopause has been lowered. If no cut-off occurs so that a blob of stratospheric air is isolated in the troposphere below the tropopause, then how we would conclude that STE has occurred. If a tropopause lowers without a cut-off then stratospheric air remains above the dynamical tropopause. Please consider this issue as I find it to be consistently misunderstood right through the manuscript (as the comment on Fig 6 will illustrate this point).

Authors response:

We agree that, in the original manuscript, the distinction between tropopause deformation and irreversible stratosphere–troposphere exchange (STE) was not stated with sufficient precision.

In response, we have revised the manuscript to clearly distinguish between:

1. lowering or folding of the dynamical tropopause, which does not by itself imply STE, and
2. irreversible transport of stratospheric air into the troposphere, which requires isolation, mixing, or sustained descent below the dynamical tropopause.

For Lines 28–29, we revised the introduction to clarify that not all tropopause folds or Rossby wave breaking events result in STE. The new wording states that STE occurs only when stratospheric air is irreversibly transported below the dynamical tropopause, typically through processes such as cut-off low formation, filamentation, mixing, and sustained isentropic descent.

For the March 2016 case, we clarify that STE is inferred not only from Rossby wave breaking or tropopause folding, but from the combined evidence of:

- formation of a cut-off low that isolates stratospheric air within the troposphere,
- sustained isentropic transport pathways,
- Lagrangian trajectories showing descent from above the dynamical tropopause into the lower troposphere, and
- PV–ozone diagnostics indicating irreversible transport rather than reversible tropopause displacement.

The revised text reads as follows L: 25-30, P:2.

"Tropopause folds are frequently linked to Rossby wave breaking (RWB) events, where large-amplitude wave disturbances on the tropopause surface evolve into overturning structures, inducing potential vorticity (PV) anomalies and enhancing cross-tropopause mixing (Gabriel and Peters, 2008; Luo et al., 2019; Postel and Hitchman, 1999). However, the presence of RWB or tropopause folding alone does not necessarily indicate stratosphere–troposphere exchange. Dynamical deformation of the tropopause must be accompanied by irreversible transport processes, such as cut-off low formation, turbulent mixing, or sustained isentropic descent, to enable stratospheric air to persist within the troposphere and alter its chemical composition (Holton et al., 1995; Sprenger et al., 2003). Consequently, only a subset of observed tropopause folds result in meaningful STE, and the depth, duration, and thermodynamic characteristics of these events largely determine their impact on tropospheric ozone and surface air quality, exacerbating the already low air quality in cities and megacities around the globe (Chen et al., 2024; Li et al., 2025; Ni et al., 2024; Vazquez Santiago et al., 2024)."

General comment on the literature review in the introduction is that whilst it is well written, it does not go far in enough in reviewing STE issues and what this work attempts to close. Therefore, review of current STE knowledge needs to be significantly improved.

Authors response:

We appreciate the reviewer's comment. In response, we have substantially revised the Introduction to provide a more comprehensive review of current stratosphere–troposphere exchange (STE) knowledge and to clarify the specific research gap addressed by this study. The revised text now explicitly differentiates between dynamical tropopause deformation, such as Rossby wave breaking and tropopause folds, and effective STE, which requires irreversible transport processes including mixing and sustained isentropic descent. We have expanded our discussion of established STE impacts on tropospheric and surface ozone, underscored the predominance of mid-latitude and Eulerian-focused studies, and identified the scarcity of detailed Lagrangian and isentropic analyses in tropical and subtropical regions.

These revisions more clearly situate the present work within the existing literature and articulate its contribution to advancing understanding of STE impacts on surface ozone in a subtropical megacity. See the Introduction section L: 18-92,P: 1-3.

Lines 69 – 96: Section 1.1 does not belong to the introduction, where we normally present current knowledge, define hypothesis etc. It should be integrated into 3.1

Authors response:

We appreciate the reviewer's suggestion. Following this comment, we have reorganized Section 1.1 clearly separates data and methodological subsections. We also reordered the sections so that the methodology now appears before the results, which enhances clarity and readability. The revised text is available in Section 2.2 of the Data and Methods section (L:107-119 ,P: 4) and Subsection 3.1.1 of the Results section (L: 198-212,P: 7-8).

Lines 97 – 159: The data and methods section should only discuss the diagnostics and defer discussion about the case to the results section. For instance the discussion of Figs 2 and 3 is treated here and it should be in Section 3.

Authors response:

We agree that the original Data and Methods section included premature discussion of the case study. In the revised manuscript, Section 2 now focuses solely on datasets and diagnostics. All case-specific discussion, including interpretation of Figs. 2 and 3, has been moved to the Results section (Section 3) to ensure a clear separation between methods and results. The changes can be found in Section 3.1, L:198-221, P: 7-8.

Line 136 – 137: The authors are discussing breaking baroclinic waves and therefore should refer to potential vorticity conservation instead of absolute vorticity conservation, as the latter applied to barotropic Rossby waves. Also please consider the conditions under which PV is conserved and these should be mentioned explicitly here.

Authors response:

We thank the reviewer for this helpful comment and agree that breaking baroclinic Rossby waves should be described in terms of potential vorticity (PV) conservation. We have revised Lines 136–137 accordingly to describe Rossby waves in a stratified atmosphere using Ertel PV and to explicitly state the conditions under which PV is conserved (adiabatic, frictionless, large-scale flow; Hoskins et al., 1985).

The revised text characterizes Rossby wave breaking as the overturning and irreversible deformation of PV contours on isentropic surfaces. This process is associated with strong meridional PV mixing and a reversal of the meridional PV gradient (Postel and Hitchman, 1999). We have further clarified our rationale for selecting PV thresholds to define the dynamical tropopause. Although PV values at the tropopause vary with latitude and isentropic level, lower values (approximately 1–1.5 PVU) are typical in subtropical and tropical regions (Homeyer and Bowman, 2013).

The revised text reads as follows L: 160-168, P: 6:

“Rossby waves result from the latitudinal variation of the Coriolis parameter and, within a stratified atmosphere, are best described using potential vorticity conservation under adiabatic, frictionless conditions and large-scale flow conditions, Ertel potential vorticity is materially conserved following the motion \citep{hoskinsUseSignificanceIsentropic1985}. Rossby wave breaking (RWB) takes place when a baroclinic Rossby wave amplifies sufficiently for PV contours on isentropic surfaces to overturn and undergo irreversible deformation. This phenomenon is marked by intense meridional mixing of PV and is typically identified by a reversal of the meridional PV gradient \citep{postelClimatologyRossbyWave1999a}.”

The new text reads as follows L: 179-185, P: 6.

“The PV value associated with the dynamical tropopause varies with latitude and potential temperature, with higher values typically observed at higher latitudes and at isentropic levels (Homeyer and Bowman, 2013). In subtropical and tropical regions, the tropopause is often associated with lower PV values, typically 1 to 1.5 PVU. However, a thresholds between 1 and 2 PVU are employed in this study to maintain consistency with previous research on subtropical and low-latitude stratosphere–troposphere exchange and to ensure the identification of stratospheric air masses (Škerlak et al., 2019; Gougetet al., 1996; Clain et al., 2010). Analyses using lower PV thresholds allow the interpretation of spatial and temporal distributions of tropopause folding and transport.”

References

Gouget, H., Cammas, J. P., Marenco, A., Rosset, R., & Jonquières, I. (1996). Ozone peaks associated with a subtropical tropopause fold and with the trade wind inversion: A case study from the airborne campaign TROPOZ II over the Caribbean in winter. *Journal of Geophysical Research: Atmospheres*, 101(D20), 25979-25993.

Clain, G., Baray, J. L., Delmas, R., Keckhut, P., & Cammas, J. P. (2010). A lagrangian approach to analyse the tropospheric ozone climatology in the tropics: Climatology of stratosphere–troposphere exchange at Reunion Island. *Atmospheric Environment*, 44(7), 968-975.

Lines 151-158: Should be moved to the results where the case is described. For this plot (Fig 3), please specify the range of longitudes through which the zonal averages are calculated for the two panels.

Authors response:

Lines 151–158 and Figure 3 have been moved to the Results section, where the case study is discussed. The figure caption now specifies the longitude ranges used for zonal averages: 173°W–60°W for Fig. 3a and 120°W–80°W for Fig. 3b.

Sections 3.1 and 3.2. Some of the issues raised in 3.1 are repeated in 3.2, so these two sections should be combined and discussed using either Fig 4 or 5 but not both. My preference is the former and the streamers diagnostics could be implemented in Fig. 2. The geopotential heights and the appearance of the COL in the traditional sense has already been covered in Figure 1. Hoskins et al (1985) should also be invoked here as the PV anomaly induces the closed COL circulation

Authors response:

We agree with the reviewer that Sections 3.1 and 3.2 contained overlapping descriptions and have therefore merged them into a single subsection to eliminate redundancy. While we retain both Figs. 4 and 5, their roles are now clearly differentiated. Figure 4 is used exclusively to diagnose anticyclonic Rossby wave breaking and PV streamer evolution on isentropic surfaces, whereas Figure 5 is employed to illustrate the balanced mid-tropospheric response to the upper-level PV anomaly. In particular, Fig. 5 highlights the PV-induced closed cyclonic circulation in the sense of Hoskins et al. (1985), which is distinct from the synoptic evolution already documented in Fig. 1. We believe this separation clarifies the physical interpretation while preserving complementary diagnostics. The new section 3.1 reads in L: 224-257, P: 8-12.

Lines 215 – 233: Fig 6 should show the evolution of the fold that corresponds to Fig 4, so that the time lag between the PV intrusion and the steep rise in ozone concentrations may be better explained. Also this discussion should show what was raised earlier in this review and that is, for there to be stratospheric exchange, a COL should have happened. The lat/pressure plots should clearly show this.

Another advantage of presenting the evolution of these zonal profiles in that we will have a 3-D view of the event, as readers.

Authors response:

Figure 6 now includes four time-evolving latitude–pressure cross sections (9–11 March 2016) that correspond directly to the PV evolution in Fig 4. This update enables tracking the tropopause fold's progression from its formation through deepening and equatorward extension. The revised figure clearly shows a time lag between the initial descent of high-PV stratospheric air and the later increase in ozone mixing ratios. This supports the interpretation that stratosphere–troposphere exchange occurs after the dynamical intrusion is established, not at its onset. This behaviour is discussed in the updated text (L: 296-266, P: 12-14).

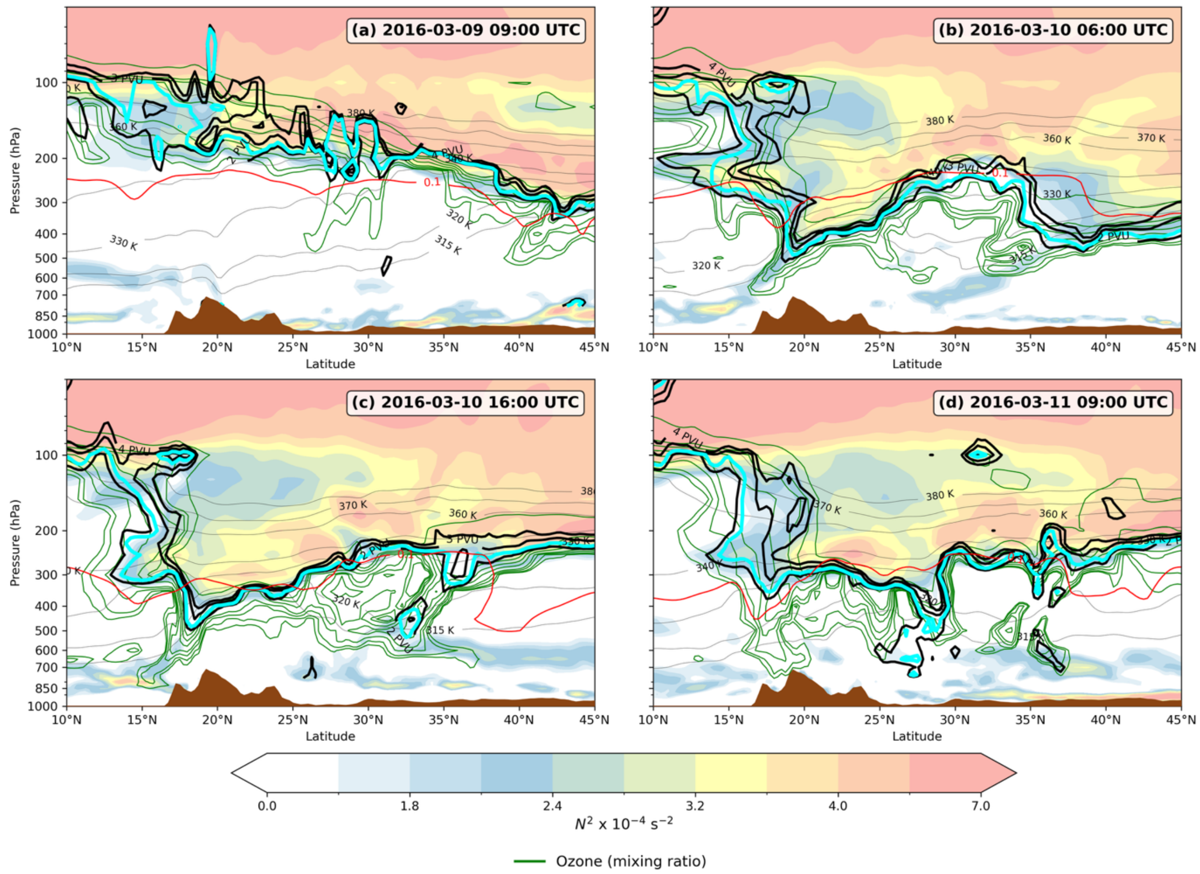

Figure 6. Tropopause fold over Mexico from (a) 09:00 UTC 9 March, (b) 06:00 UTC 10 March, (c) 16:00 UTC 10 March, to (d) 09:00 UTC 11 March 2016. The dynamical tropopause is defined using PV (solid thick black contours, PVU), with the cyan solid line indicating 2 PVU, and the squared Brunt–Väisälä frequency (colour shading, N2, × 10−4 s−2). Section was average over longitudes between 99.8°W and 98.5°W and displays latitudes from 10°N to 45°N. Tropopause folds extend from the upper to mid–lower troposphere, with high-PV stratospheric air descending into low-PV tropospheric air and locally reduced N2 within the intrusion. The solid red line indicates the specific humidity threshold (q = 0.1 g kg−1). Thin solid lines indicate the potential temperature (K).

Lines 275 – 278: Even though intuition is forcing me to agree with this statement. Fig 8 is not showing that the air that is associated with increased ozone concentrations and the tip of the curved arrow. Reason for this is that the PV values located near the surface are less than 2PVU, meaning that they cannot originate from the stratosphere. If anything, the air there originates from below the dynamical tropopause. The authors will have to explain.

Authors response:

We appreciate the reviewer’s careful and important observation and agree that Fig. 8 alone does not show PV values ≥ 2 PVU reaching the surface. This clarification has been explicitly incorporated into the revised manuscript.

Our interpretation does not rely on Fig. 8 in isolation to infer a stratospheric origin at the surface. Rather, Fig. 8 illustrates the vertical and temporal alignment between descending ozone-rich air and PV anomalies in the mid- and lower troposphere, while the stratospheric origin and transport pathway are demonstrated by the Lagrangian trajectory analysis (Fig. 7) and the quasi-horizontal isentropic transport diagnostics (Fig. 9).

Specifically:

- Backward trajectories (Fig. 7) show that air parcels reaching the lower troposphere originated above the dynamical tropopause and descended along constant equivalent potential temperature surfaces, confirming their stratospheric origin.
- Although the 2 PVU surface does not extend to the ground. Recent studies have shown that the tropopause PV value is flow-dependent rather than a universal threshold of 2 PVU, resulting PV threshold below of 2 PVU (Barnes et al., 2021, 2022; Bauchinger et al., 2025; Turhal et al., 2025). Additionally, the location of Mexico of City in the middles of mountains (2300 m) favours the proximity to the fold descending sufficiently close to the planetary boundary layer to facilitate stratosphere–troposphere exchange through mixing and erosion of the dynamical tropopause. This mechanism is consistent with classical observations of STE (Johnson and Viezee, 1981) and It is supported by our analysis in Figs 7, 8 and 9.
- In addition, observational evidence from Barrett et al. (2019) for the same March 2016 event shows that subsidence following the departure of the extreme cut-off low led to the development of a strong capping inversion between 600 and 650 hPa, located ~2,000 m above ground level, which correspond to the region of ~1.5 PVU in our analysis.
- Under these conditions, stratospheric ozone transported into the lower troposphere can influence near-surface concentrations even when PV values at the surface remain below the canonical 2 PVU threshold.

References:

Barnes, M. A., Ndarana, T., & Landman, W. (2022). Stratospheric intrusion depth and its effect on surface cyclogenetic forcing: an idealized potential vorticity (PV) inversion experiment. Weather Clim Dyn 3: 1291–1309.

Barnes, M. A., Turner, K., Ndarana, T., & Landman, W. A. (2021). Cape storm: A dynamical study of a cut-off low and its impact on South Africa. Atmospheric Research, 249, 105290.

Bauchinger, S., Engel, A., Jesswein, M., Keber, T., Bönisch, H., Obersteiner, F., ... & Schuck, T. J. (2025). The extratropical tropopause–Trace gas perspective on tropopause definition choice. EGUsphere, 2025, 1-29.

Turhal, K., Plöger, F., Clemens, J., Birner, T., Weyland, F., Konopka, P., & Hoor, P. (2024). Variability and trends in the potential vorticity (PV)-gradient dynamical tropopause. Atmospheric Chemistry and Physics, 24(23), 13653-13679.

Lines 352 – 354: The authors raise the issue of the role of topography without providing an analysis on these issues. In other words there is no analysis that suggest what the role of topography might be in this paper.

Authors response:

We have revised the discussion to clarify that the present study does not explicitly analysed or quantify the role of topography. The revised text now frames the influence of terrain and altitude as a contextual interpretation supported by the geographical setting of the affected sites and by previous studies, rather than as a direct result of our analysis. We also explicitly highlight the need for targeted future analyses to assess the role of orography in modulating stratosphere–troposphere exchange in tropical regions. The edited paragraph reads as follows L: 447-470, P: 21-22.

"While the present study does not directly quantify the influence of topography, the geographical context of the affected sites indicates that terrain and elevation likely modulate the surface manifestation of stratospheric intrusions. Mexico City and Monterrey, both situated in elevated basins, may be more prone to stratospheric air reaching the surface during deep tropopause fold events. In contrast, regions at lower elevations are likely to experience less pronounced near-surface impacts from comparable intrusions.

Interactions between complex terrain and stratospheric intrusion dynamics have been documented in regions such as the Tibetan Plateau and other midlatitude mountainous areas (Chen et al. 2016; Lüthi et al. 2015; Škerlak et al. 2019). While comparable STE-related ozone enhancements have been reported in North America and Europe, relatively few studies have examined these processes in tropical regions, where meteorological conditions are episodically influenced by extratropical cyclones. Comparisons with the Mediterranean basin and East Asia indicate that the combination of complex orography and subtropical jet dynamics can facilitate deep intrusions reaching lower tropospheric levels. In Mexico, the elevated basins of central and northern cities appear particularly susceptible, highlighting the broader subtropical relevance of this case and underscoring the need for targeted analyses that explicitly address the influence of orography and altitude on stratosphere–troposphere exchange, especially during boreal winter and spring when upper-level dynamics interact with complex terrain."

Conclusions: I am afraid I find that this study does not add to the body of literature to help us understand STE better in a convincing manner. It is highly descriptive in many areas and lacks a demonstration of how this case study helps us understand these issues. In addition to this, the paper requires very major restructuring. I am inclined towards rejection of the manuscript.

Authors response:

Thank you for your careful evaluation. We respectfully disagree with the assessment that this study does not contribute to the body of knowledge on stratosphere–troposphere exchange (STE). In the revised manuscript, we explicitly demonstrate that tropopause folding associated with persistent Rossby wave breaking is not only a synoptic feature but also a key dynamical mechanism linking upper-tropospheric dynamics to surface-level ozone pollution in a subtropical megacity. We have substantially revised the manuscript to emphasise this mechanistic focus. The updated Results and Discussion sections now demonstrate how the depth, persistence, and geometry of the tropopause fold determine the efficiency of stratospheric air transport into the lower troposphere, and how this process preconditions surface ozone exceedances rather than merely coinciding with them. By integrating isentropic analysis and transport, and Lagrangian trajectories, the study identifies the physical pathways through which STE affects an environmentally relevant outcome.

We submit that the revised manuscript provides a process-based contribution to understanding how tropopause folds serve as a dynamical footprint to air-quality extremes in tropical and subtropical regions. This aspect of STE remains underrepresented in the literature (tropical and populated cities).