Reviewer #1

Authors response:

We thank the reviewer for their detailed review and valuable feedback. We have carefully considered all your suggestions and have addressed them point by point in the revised manuscript. Please find our detailed responses below. All line and page numbers refer to the track-changes version of the manuscript.

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

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General comments

The manuscript describes the dynamic processes that led to a well-known ozone exchange process, i.e., STE, which primarily influences mid-tropospheric ozone and occasionally surface ozone, thereby impacting air quality. The STE event was thoroughly characterized using reanalysis data and Lagrangian trajectories. This case study is of great interest to the atmospheric science community; however, the manuscript requires major revisions in terms of its current structure and concise presentation of its results form before it can be accepted for publication in WCD.

I think sections 1.1 and 2 should be better organized by distinguishing clearly between subsections for data and method. Additionally, Section 1.1 presents some results before describing the methodology for obtaining those results, which could be remedied by reordering these sections.

Authors response:

We appreciate the reviewer's suggestion. Following this comment, we have reorganized Sections 1.1 and 2 to clearly separate 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 (L:106-199, P:4) of the Data and Methods section and Subsection 3.1 of the Results section (L: 198-212, P: 7-8).

The manuscript contains repetitive descriptions of the same event in multiple sections and subsections (3 and 4) of the manuscript. Some of the information described in these sections could be easily included in the introduction and discussed only when needed.

Authors response:

We thank the reviewer for this observation. In response, we have revised Sections 3.1 and 3.2, and 3.4, as well as the Discussion, to eliminate repetitive descriptions of the event. Redundant material has been removed or consolidated, and some of the background

information has been streamlined and, where appropriate, incorporated into the Introduction. As a result, the event is now described more concisely and discussed only where it is directly relevant, improving the overall clarity and structure of the manuscript. The revised text can be found in Sections 3.1-3.2 (L: 198-257, P: 7-12), and 3.4 (L: 298-361 P:14-17), as well as in the Discussion (L: 415-477, P: 21-22).

Although section 3.6 attempts to provide context, it feels out of place. In my opinion, this attempt to contextualize the STE event presents an opportunity to remedy one of the study's fundamental deficiencies, namely, a more thorough elaboration of its relevance (introduction), and to extend the study's period in a more systematic way (method), to later focus specifically on the 6-14 March 2016 event.

Authors response:

We acknowledge that Section 3.6 in the previous version could appear out of place. In response, we have revised the manuscript to better integrate this material by clarifying the study's scope and relevance in the Introduction, describing the selection of additional events in the Methods, and reframing Section 3.6. This section has been renamed and substantially revised. Its purpose is now clearly stated at the outset: to place the March 2016 event in a broader dynamical and air-quality context. The section highlights that the 6-14 March 2016 episode remains the study's primary focus, while additional events serve as illustrative examples to assess the recurrence of similar dynamical mechanisms. The new text can be found in the Data and Methods (L: 95-185, P: 4-6) and Result (L: 189-414,P: 7-20) sections.

Minor comment

Lines 38-40: This line is unclear, linking geography and local meteorology with an independent variable: emissions. I suggest rewriting this sentence.

Authors response:

We thank the reviewer for highlighting this lack of clarity. Our aim was to explain that the geographical setting of Mexico City creates meteorological conditions during the boreal winter that restrict ventilation and dispersion. These conditions allow locally emitted pollutants to accumulate, which in turn promotes high surface ozone episodes. We have revised the sentence to clearly distinguish the influence of meteorology from that of emissions and to avoid suggesting that emissions are directly determined by geography. The revised text reads as follows: L: 48:53, P:2.

"The location of Mexico City also favours stable, dry atmospheric conditions during the boreal winter, resulting in reduced vertical mixing and pollutant dispersion; under these conditions, local emissions accumulate and can lead to episodes of high near-surface ozone concentrations."

Line 53: Could you state the mixing ratio (by volume) value of this event?

Authors response:

Thank you for your suggestion. Our analysis shows that this episode resulted in very high ozone mixing ratios. As the cutoff low moved eastward, a pronounced low-level thermal inversion and reduced ventilation from 13 to 15 March increased concentrations of O_3 precursors. Strong UV radiation further enhanced photochemical ozone production, with peak O_3 mixing ratios reaching 210 ppb on 14 March at several monitoring stations in Mexico City. The new information reads as follows, L: 68-71, P: 3.

"An analysis of historical environmental reports on air pollution episodes by local authorities shows that this episode is significant as one of the major high-$\mathrm{O_3}$ mixing ratio events in Mexico City, with observed ozone mixing ratios reaching up to 210 parts per billion (ppb) by volume on 14 March at several monitoring stations \citep{DMA2025}."

Line 57: Satellite products are mentioned in the introduction as part of the analysis; however, the satellites used are not described in the methodology.

Authors response:

We appreciate this comment. To improve clarity, we have added a description of the satellite products used in the analysis to the Data and Methodology section. The new section reads as follows L: 120-129, P: 4-5.

"Satellite-based ozone observations provided a large-scale context for the stratosphere–troposphere exchange event examined in this study. Total and tropospheric ozone column data were sourced from the Earth Polychromatic Imaging Camera (EPIC) on the Deep Space Climate Observatory (DSCOVR) \citep{kramarovaEvaluationVersion32021, marshakEarthObservationsDSCOVR2018}. Tropospheric ozone columns were calculated using a residual-based approach, where an estimate of the stratospheric ozone column, defined relative to tropopause height from meteorological analyses, was subtracted from the total column. The limited vertical resolution, especially in the upper troposphere–lower stratosphere, means these products represent vertically integrated values and cannot resolve fine-scale structures. Uncertainty is further increased over regions with high-elevation terrain. EPIC total column ozone fields were qualitatively compared with independent measurements from the Ozone Mapping and Profiler Suite (OMPS) on Suomi NPP to verify the observed spatial patterns \citep{flynnNOAAJPSSOzone2018}.)"

Line 59: Clarify the term "precursor" here and throughout the manuscript.

Authors response:

We agree with the reviewer's comment regarding the ambiguity of the term "precursor." In this study, we use "precursor" in a dynamical and temporal sense, referring to a large-scale stratosphere–troposphere exchange event that raised background ozone levels and created conditions favourable for a multi-day high-ozone episode, rather than a direct chemical precursor. We have clarified this definition at first use and applied it consistently throughout the manuscript. The revised text reads as follows L: 74-80, P:3.

"By combining reanalysis data from European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis version 5 (ERA5), isentropic analysis, Lagrangian trajectories, and satellite products, this study demonstrates that the large-scale STE event produced measurable and regionally significant impacts on surface ozone. In Mexico City, the event acted as a dynamical precursor by enhancing ozone levels at surface prior to a multi-day high-ozone pollution episode."

The edited text reads as follows L: 423-426, P:21.

"This enhancement resulted in elevated background ozone levels, providing conditions favourable for the subsequent ozone exceedance event."

Line 89-91: For a general scientific community, I would not recommend using local indexes such as IMECA. The message would be the same and clearer if it just utilized nmol/mol (ppbv).

Authors response:

We agree that using local air quality indices such as IMECA may not suit a general scientific audience. We have revised the text to report ozone levels only as mixing ratios. The revised text reads as follows L: 204-207, P:8.

"Ground-based air quality observations indicate that near-surface O_3 mixing ratios in Mexico City reached up to ~210 ppb and remained above 100 ppb for nearly five consecutive days."

Line 91: The term "anomalies" is not clear. Do you mean high values, or was the ozone anomaly calculated?

Authors response:

In this context, the term "anomalies" was not intended to indicate a formally calculated ozone anomaly relative to a climatological mean, but rather to describe elevated ozone values observed during the event. To avoid confusion, we have replaced "anomalies" with "high ozone values". The edited text reads as follows:

“Similar high ozone values were observed across the monitoring networks of Toluca City…”

Figure 2: Note that you are using mixing ratios ppb (I assume by volume), which is the same as nmol per mol, instead of concentration. Please correct throughout the manuscript.

Authors response:

We thank the reviewer for pointing this out. We have corrected the terminology throughout the manuscript to consistently refer to ozone values as mixing ratios (ppb by volume) instead of concentrations. Figure 2 has been revised accordingly, and all relevant text has been updated to ensure consistency.

Line 203-204: This is just an example of many sentences that can be moved to the introduction: “*Cut-off cyclones of this type have been argued to play an important role in STE processes (Holton et al., 1995), as these structures can promote the irreversible descent of stratospheric air into the troposphere*”.

Authors response:

We agree that some sentences are conceptual and provide general background rather than event-specific results. Background-oriented statements elsewhere in the manuscript were also reviewed and, where appropriate, relocated or revised to ensure a clearer separation between background material and case-specific analysis in the Results section.

Line 242: mass mixing ratios. Between what level pressures?

Authors response:

The ozone mass mixing ratios are diagnosed near the surface over Mexico City at the 700 hPa pressure level (Fig. 7d), using Lagrangian trajectories and ERA5 ozone tracer fields. Figure 8 also supports this statement, showing the temporal evolution of the ozone mixing ratio over Mexico City. We have updated the text to clearly specify the pressure levels considered. The updated sentence reads as follows. L: 305, P: 15.

“Although ERA5 ozone tracer fields indicate enhanced ozone mixing ratios ($\sim 8 \times 10^{-8}$ kg kg^{-1} at 700 hPa)”

Line 281-289: If the authors want to include this text, it is first necessary to describe the methodology to estimate the tropospheric column ozone as well as to discuss the limitations of vertical resolution of satellite products, particularly in the UTLS. Consider that high elevation terrain also contributes to uncertainty. A full description

of the tropopause estimation is also necessary to include when satellite products are utilized.

Authors response:

We appreciate the reviewer's constructive feedback. In response, we have revised the Data and Methods section to provide a detailed description of the satellite ozone datasets and the methodology for deriving tropospheric ozone columns. We clarify that tropospheric ozone columns from DSCOVR/EPIC are derived using a residual-based approach, in which the stratospheric ozone column is subtracted from the total column ozone, defined relative to a tropopause height derived from meteorological analyses. We now discuss the limited vertical resolution of satellite ozone products, especially in the upper troposphere and lower stratosphere, and emphasise that these observations represent vertically integrated quantities without fine-scale vertical resolution. We also acknowledge the increased uncertainty in regions with high-elevation terrain, such as central Mexico. To improve clarity and reduce redundancy, methodological details are consolidated in the Data and Methods section, while the Results section focuses on observed spatial and temporal patterns and their interpretation.

Line 326: Instead of "Phase I Mexican environmental contingency," can the author just state the mixing ratio values reached at the surface level?

Authors response:

We have revised the text to specify the surface ozone mixing ratio values rather than referencing the "Phase I Mexican environmental contingency." L: 416-421, P:21.

Line 328: Temporal precursor? In another part of the manuscript, the terms "synoptic precursor," "synoptic dynamical precursor," and "precursor" are used interchangeably. Can the author define the term?

Authors response:

We thank the reviewer for raising this point. The use of the term "precursor" and related expressions has been clarified and harmonised throughout the manuscript in response to earlier comment. To avoid ambiguity, these terms have been removed or replaced with explicit descriptions of the temporal and dynamical relationships.

Line 330: Indicate the pressure levels where those ozone mixing ratios were identified.

Authors response:

The ozone mass mixing ratios are diagnosed near the surface over Mexico City at the 700 hPa pressure level (Please see Fig. 7d and Fig. 8). We have updated the text to clearly

specify the pressure levels considered. The edited text reads as follows L: 423-426, P21:

“we found a contribution of ozone mixing ratio of ∼8×10^{-8} kg kg^{-1} near the surface of Mexico City (750-700 hPa).”