

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

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Abstract. Stratosphere–troposphere exchange (STE) is a fundamental process in which ozone-rich stratospheric air enters the troposphere, modulating tropospheric ozone distributions and, under favorable conditions, influencing surface air quality. This study investigates an atypical STE event over North America from 6 to 14 March 2016, which coincided with a severe surface ozone pollution episode in Mexico City. Analyses using ERA5 reanalysis, potential vorticity (PV) diagnostics, ozone tracers, Lagrangian trajectories, and isentropic methods attribute the event to anticyclonic Rossby wave breaking, a cut-off low, and a persistent tropopause fold. Deep intrusions of high-PV air penetrated the troposphere, with maximum downward transport occurring approximately one day before the peak in surface ozone mixing ratios. Equatorward wave amplification facilitated coherent isentropic transport, enabling efficient descent of ozone-rich stratospheric air over the elevated basins of central Mexico. Backward trajectory analysis confirmed stratospheric origins, while isentropic advection quantified quasi-horizontal transport along 320–340 K surfaces. Tropopause folding, intensified by the subtropical jet and the elevated terrain of central Mexico, resulted in enhanced ozone mixing ratios of $8 \times 10^{-8} \text{ kg kg}^{-1}$ at 750–700 hPa, preconditioning background ozone levels prior to surface exceedance rather than serving as a direct surface source. The analysis identifies recurrent tropopause folds preceding high-ozone episodes, highlighting the persistent role of STE as a dynamical preconditioning mechanism for regional air-quality extremes. These results indicate that the location of cities in elevated tropical basins, in combination with Rossby wave dynamics and quasi-horizontal isentropic transport pathways, determines the depth, persistence, and significance of STE.

1 Introduction

Stratosphere-troposphere exchange (STE) is a crucial atmospheric process that transports air masses, including trace gases like ozone (Bates and Jacob, 2020; Holton et al., 1995; Martin, 1998; Wang and Fu, 2021), across the dynamic boundary that separates the stratosphere and troposphere, known as the tropopause. Tropopause folds are recognized as a primary mechanism for STE, which is often associated with upper-tropospheric jet streams and mid-latitude baroclinic systems. These tropopause folds facilitate the downward transport of stratospheric ozone into the upper and middle troposphere (Škerlak et al., 2014, 2015;

Sprenger et al., 2003). However, this mechanism has been observed over subtropical and tropical areas during the boreal winter (Barrett et al., 2019; Ogino et al., 2013; Toihir et al., 2018).

25 (Reviewer 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
30 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).)

35 (Reviewer 2)(The STE events can substantially modify tropospheric ozone distributions and, under favorable meteorological conditions, intensify surface air-quality episodes. Stratospheric ozone constitutes a primary natural source of background tropospheric ozone (Grewe, 2006), and its downward transport can significantly increase ozone mixing ratios in the lower troposphere. Previous research has shown that STE events may elevate surface ozone concentrations and, in certain instances, result in exceedances of air-quality standards (Knowland et al., 2017; Lin et al., 2015; Nguyen et al., 2022; Wang and Fu, 2021).
40 However, most existing studies have concentrated on mid-latitude regions and have primarily utilized Eulerian diagnostics. In contrast, relatively few investigations have explored the detailed Lagrangian pathways and isentropic evolution of stratospheric intrusions, especially within tropical and subtropical environments.)

Mexico city is a megacity located at a latitude of approximately 19°N and an elevation of approximately 2,300 meters above sea level in a basin surrounded by mountains. Climatological evidence suggests that these geographical conditions
45 make the region particularly susceptible to mid-latitude dynamical processes during the boreal winter (Binder and Wernli, 2025; Boothe and Homeyer, 2017; Škerlak et al., 2014). The southerly extension of the mid-latitude waveguide in this season allows baroclinic systems and upper-level troughs to reach subtropical and sometimes tropical latitudes (Hoskins and Karoly, 1981; Karoly and Hoskins, 1983; Nakamura, 1992; Trenberth, 1991), including central Mexico. (Reviewer 1)(The location of Mexico City also favours stable, dry atmospheric conditions during the boreal winter, resulting in reduced vertical mixing and
50 pollutant dispersion; under these conditions, local emissions accumulate and can lead to episodes of high near-surface ozone (O_3) mixing ratios .) ~~The location of Mexico City also favours stable and dry atmospheric conditions during boreal winter, significantly contributing to the O_3 mixing ratios as a pollution emission into the local atmosphere, triggering episodes of high O_3 mixing ratio near the surface.~~ In addition, significant pollution emissions can produce an environment in which atmospheric processes contribute to increase near-surface O_3 mixing ratios before high- O_3 mixing ratio episodes occur. However, detailed
55 case studies linking stratospheric intrusions with documented high-ozone episodes in Mexico City are limited.

(Reviewer 2)(Despite these favorable conditions for STE impacts, detailed case studies explicitly linking stratospheric intrusions, their dynamical evolution, and documented surface ozone exceedances in Mexico City remain scarce.) Barrett et al.

(2019) presented findings from surface observations and large-scale analyses on a tropopause fold over Mexico City. Although that study highlighted the important role of STE in driving extreme surface O_3 mixing ratios. (Reviewer 2)(However, the detailed dynamical pathways responsible for irreversible transport of stratospheric air into the lower troposphere, as well as the vertical and isentropic structure of such events over central Mexico, remain largely unexplored). In addition, there is a lack of detailed information regarding the structure and evolution of the synoptic system over Mexico, especially from a Lagrangian and isentropic perspective. Our present study addresses these gaps by combining reanalysis data with Lagrangian trajectory and isentropic analyses to characterize both the STE event and its impact on surface ozone.

65 An unusual STE event occurred over Mexico between 6 and 14 March 2016. This event was driven by a mid-latitude cyclone and characterized a RWB and deep tropopause folding, which was associated with a significant increase in near-surface O_3 mixing ratios in Mexico City and other Mexican urban centers. (Reviewer 1)(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- 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 (DMA, 2025).)~~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- O_3 mixing ratio events in Mexico City.~~

This study provides a dynamical analysis of the March 2016 event, focusing on the structure of the Rossby wave breaking, the evolution of the tropopause fold, and the spatiotemporal patterns of ozone tracers over Mexico City and other urban regions of Mexico. (Reviewer 1)(By combining reanalysis data from European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis version 5 (ERA5; Hersbach et al., 2020), 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.)~~By combining reanalysis data, isentropic analysis, Lagrangian trajectories and satellite products, we show that this large-scale STE event had measurable and regionally significant impacts on surface ozone, particularly in Mexico City, where it likely acted as a precursor to a multi-day high-ozone pollution episode.~~ (Reviewer 1)(In addition to this detailed case study, we examine whether similar tropopause folds and STE signatures have preceded other major high-ozone episodes over Mexico City, using a small set of additional events to contextualize the March 2016 episode within a broader dynamical and air-quality framework.)

(Reviewer 2)(These findings highlight the need to incorporate large-scale stratospheric processes into the interpretation and forecasting of air-quality variability in tropical and subtropical urban regions. Given ongoing urbanization and the persistent frequency of ozone exceedance days in Mexican cities, enhanced monitoring of Rossby wave breaking and related tropopause dynamics could improve early warning systems for severe pollution episodes during the boreal winter.)

This paper is organized as follows: Section 2 describes the study period, the selection of the March 2016 STE event, and the datasets and methodology used, including reanalysis data and Lagrangian isentropic analysis. In Section 3, we present a dynamical analysis of the event, which covers the structure of the Rossby wave breaking, the evolution of the tropopause fold, and the spatiotemporal distribution of stratospheric ozone tracers over Mexico City and other urban regions. Finally, Sections 4 and 5 provide a discussion and conclusions, respectively.

2 Data and Methods

2.1 ERA5 Reanalysis

95 The ERA5 global reanalysis was used at a horizontal resolution of $0.25^\circ \times 0.25^\circ$ with hourly output and vertical resolution of 37 levels. ERA5 provides fields of PV, wind, temperature, and specific humidity, which are essential for the analysis of the dynamical evolution of the upper troposphere and lower stratosphere during the STE event over Mexico in March 2016. The primary variables derived from ERA5 include: (1) PV on isentropic levels, used to identify stratospheric air masses and tropopause folds; (2) wind speed and geopotential height at constant pressure levels to characterize the synoptic-scale evolution
100 of the Rossby wave breaking and the associated cut-off low event over Mexico, and (3) ozone mass mixing ratio from ERA5 at constant pressure for the analysis of the downward transport of stratospheric ozone into the troposphere during the STE event. (Reviewer 1)(Beyond the detailed analysis of the 6–14 March 2016 event, a small set of additional high-ozone episodes over Mexico City was examined to provide a broader context for the STE mechanisms identified in this study. These events occurred on 25 December 2015, 14 April 2007, 10 April 2019, and 22 February 2024. Selection criteria included (i) documented surface
105 ozone exceedances reported by local air-quality authorities and (ii) the presence of synoptic-scale features consistent with STE in ERA5 reanalysis fields, such as tropopause folding, enhanced upper-level PV, and ozone mixing ratio.)

2.2 Observational Data and Reanalysis-Based Tropopause Identification

Ground-based ozone observations used in this study are provided by regional air quality monitoring networks across central and western Mexico, including Mexico City, Toluca, and the metropolitan area of Guadalajara (locations shown in Fig. S1).
110 Surface O_3 mixing ratios in Mexico City were obtained from the air quality monitoring system operated by the Secretaría del Medio Ambiente de la Ciudad de México (SEDEMA), while data for Jalisco and the Toluca Valley were retrieved from the Secretaría de Medio Ambiente y Desarrollo Territorial (SMCA) and the Red Automática de Monitoreo Atmosférico de la Zona Metropolitana del Valle de Toluca (RAMA), respectively, through the Sistema Nacional de Información de la Calidad del Aire (SINAICA). Together, these datasets provide continuous near-surface ozone measurements representative of urban
115 and regional air quality conditions during the study period. To support the identification of stratosphere–troposphere exchange (STE) events over the target regions, tropopause folds were diagnosed using ERA5 reanalysis by combining regions of low potential vorticity ($PV < 1$ PVU; $1 \text{ PVU} = 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$) with enhanced ozone mixing ratios. This combined criterion allows for a rapid and physically consistent identification of dynamical conditions favorable for stratospheric intrusions into the troposphere, which are examined in detail in the following sections.

120 2.3 Satellite ozone products

(Reviewer 1)(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) (Kramarova et al., 2021; Marshak et al., 2018). Tropo-

spheric 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 (Flynn et al., 2018).)

130 2.4 Lagrangian trajectories

Lagrangian trajectories were computed using the Lagrangian Analysis Tool LAGRANTO (Sprenger and Wernli, 2015; Wernli and Davies, 1997) to investigate STE over Mexico. LAGRANTO allows flexible and precise definition of trajectory starting positions based on geometrical or meteorological criteria. For this study, the trajectories were initialized equidistantly (50 km spacing) over a box covering Mexico City and its Metropolitan area (Longitude: 100°W to 98°W, Latitude: 18.5°N to 20°N) and on multiple vertical levels between 700 and 100 hPa, with the 700 hPa level chosen to account for the altitude of Mexico City (~2,300 m above sea level). Backward trajectories were calculated for 72 hours using ERA5 reanalysis meteorological fields as input. The trajectories were then selected based on dynamical criteria, specifically potential vorticity ($PV > 2$ PVU), to identify stratospheric air masses linked to the Rossby wave breaking and the cut-off low event over Mexico. The use of LAGRANTO enabled a detailed investigation of the downward intrusion of high-PV air along tropopause folds and its connection to the cut-off system over Mexico.

2.5 Rossby wave breaking identification

A RWB event was identified over Mexico in March 2016 using the Python package WaveBreaking (Kaderli, 2023), designed for detecting, classifying, and tracking RWB in atmospheric fields. The detection is based on analyzing the dynamical tropopause, represented by closed PV contours (e.g., the 2 PVU line), and applying three RWB indices. The Streamer Index identifies filamentous structures (streamers) in the tropopause contour that are geographically close but distant along the contour path (Sprenger et al., 2017; Wernli and Sprenger, 2007). The Overturning Index detects the overturning of the contour, defined as at least three intersections of the contour within the same longitude (Barnes and Hartmann, 2012). The Cut-off Index characterizes the decay of a wave breaking event by identifying streamers that separate from the main stratospheric or tropospheric body (Wernli and Sprenger, 2007). The algorithm calculates RWB characteristics such as area, intensity, and temporal evolution, allowing a systematic analysis of Rossby wave breaking and its connection to STE over Mexico.

2.6 Isentropic Analysis of Tropopause Fold Transport

To quantify the downward transport of stratospheric air over Mexico City, we calculated transport across the dynamical tropopause using ERA5 winds, PV, and ozone interpolated onto isentropic surfaces following Dethof et al. (2000). Air parcels with $PV > 2$ PVU were tracked to identify regions of tropopause erosion, and negative advection values were interpreted as

155 indicative of the export of high-PV stratospheric air into the troposphere. Ozone mixing ratios were also used to further distinguish stratospheric signatures. This approach allows the detection of quasi-horizontal and irreversible transport along isentropic surfaces (Dethof et al., 2000), providing a framework to relate stratospheric intrusions to enhancements of near-surface ozone during the 8–15 March 2016 tropopause fold event.

2.7 Tropopause Definition and Stratospheric Intrusion Diagnosis

160 (Reviewer 2)(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 (Hoskins et al., 1985). 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 (Postel and Hitchman, 1999).)

165 ~~Rossby waves arise from the latitudinal variation of the Coriolis parameter and the conservation of absolute vorticity. Rossby wave breaking (RWB) occurs when the wave amplitude grows to the point where the crest or trough overturns. It is characterized by the rapid, irreversible deformation of PV contours on isentropic surfaces and is commonly diagnosed by a reversal of the meridional PV gradient (Postel and Hitchman, 1999).~~

170 The RWB also implies the disruption of the westerly flow in the neighboring areas (Tyrllis and Hoskins, 2008) and it promotes blocking.

The dynamical tropopause is commonly identified on isentropic surfaces as the potential vorticity (PV) contour coinciding with the strongest meridional gradient, which acts as a barrier to cross-tropopause transport (Holton, 1997; Holton et al., 1995). Typical PV thresholds range from 1.5 to 5 PVU (Jing and Banerjee, 2018; Schoeberl, 2004), with the value associated with the maximum gradient generally increasing with potential temperature (Homeyer and Bowman, 2013; Turhal et al., 2024). In

175 extratropical and subtropical studies, the 2 PVU surface is widely used to separate stratospheric and tropospheric air masses and to identify tropopause folds (Holton et al., 1995; Sprenger et al., 2003; Tyrllis and Hoskins, 2008). Tropopause folds occur where the 2 PVU surface dips below 400 hPa and coincides with regions of large PV gradients and relative vorticity anomalies, marking zones of potential cross-tropopause exchange.

(Reviewer 2)(The PV value associated with the dynamical tropopause varies with latitude and potential temperature, with

180 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 1.5 PVU. Thresholds between 1.5 and 2 PVU have been 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; Gouget et al., 1996; Clain et al., 2010). Analyses using lower PV thresholds allow the interpretation of spatial and temporal distributions

185 of tropopause folding and transport.)

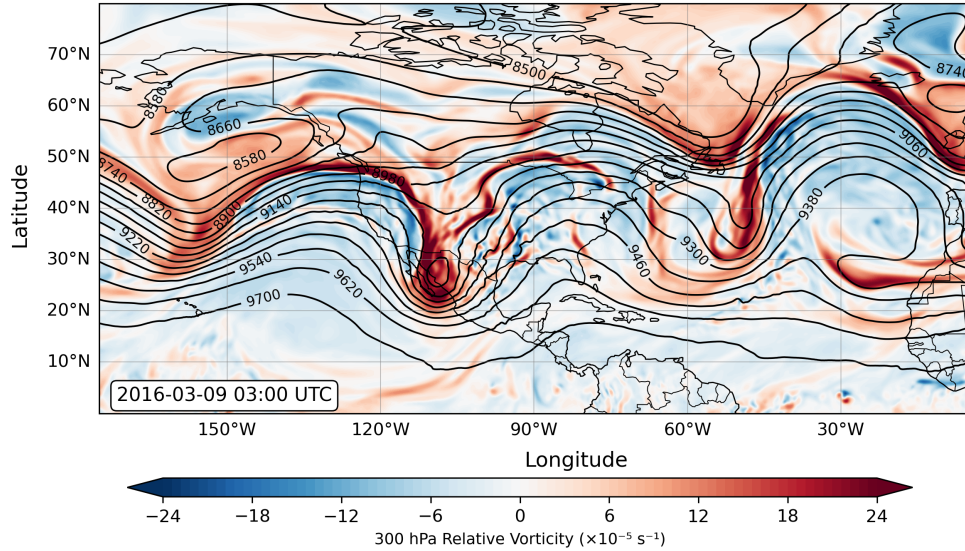


Figure 1. Relative vorticity (shading, $\times 10^{-5} \text{ s}^{-1}$) at 300 hPa at the time when the cyclone reached its minimum sea level pressure over Mexico (03:00 UTC, 09 March 2016). Solid black lines indicate geopotential height (m).

3 Results

3.1 Case Overview

(Reviewer 1 & 2)(Between 06 and 14 March 2016, a deep upper-tropospheric trough associated with a mid-latitude cyclone propagated equatorward into central Mexico, culminating in a stratospheric intrusion over Mexico City characterized by a pronounced tropopause fold (Fig. 1). ERA5 reanalysis fields show that the system exhibited a coherent vertical structure typical of an evolving baroclinic disturbance, with a surface geopotential height minimum and an upper-level trough identified by a relative vorticity maximum at 300 hPa.

On 8 March, the surface low was located near 29.75°N, 102.25°W (682.3 m geopotential height). The 300 hPa trough was centered at 24.75°N, 106.75°W and marked by a vorticity maximum of $2.87 \times 10^{-4} \text{ s}^{-1}$. This configuration resulted in a horizontal displacement of approximately 711 km between the low-level and upper-level features. Over the following two days (9–10 March), both features migrated poleward and eastward while maintaining a pronounced westward tilt with height, with displacements of 1170 km and 1028 km, respectively. The persistence of this tilted structure indicates a dynamically mature system that facilitated equatorward transport of high-PV air into the subtropics.

The surface geopotential height tendency reveals weak deepening on 8 March, followed by relatively minor temporal changes, suggesting a slowly evolving yet dynamically coherent cyclone. This synoptic configuration established a large-scale environment conducive to stratospheric air penetration into the upper and middle troposphere over central Mexico.

3.1.1 Dynamical coupling between tropopause folding and surface ozone enhancements

The stratospheric intrusion preceded a regional high-ozone episode observed between 12 and 14 March 2016 (Fig. 2). (Reviewer 1)(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.)~~Ground-based air quality observations indicate that near-surface O_3 mixing ratios in Mexico City exceeded the environmental contingency threshold, reaching up to 159 IMECA and remaining above 100 ppb for nearly five consecutive days.~~ Elevated ozone levels were also observed in Toluca and western Mexico (Jalisco), demonstrating that the event affected a broader region rather than a single urban area.

The timing of the ozone enhancement closely followed the development of a well-defined tropopause fold, identified in ERA5 by the descent of high-PV air into the troposphere (light blue shading in Fig. 2). This temporal alignment motivates a more detailed examination of the large-scale dynamics and transport pathways governing stratosphere–troposphere exchange during this event.

3.1.2 Diagnostic perspective on the intrusion

To characterize the vertical structure and evolution of the intrusion, the potential vorticity (PV) distribution is examined using both isobaric and isentropic perspectives. Figure 3a presents the March 2016 zonal-mean PV– θ structure over North America, while Fig. 3b highlights the case-specific configuration over Mexico on 10 March 2016. A pronounced PV maximum extends equatorward to near 20°N, with PV values between 1 and 4 PVU descending below 300 hPa, indicating strong tropopause deformation.

These features are characterized by sharp PV gradients and downward extensions of the 2 PVU surface, indicating deep penetration of stratospheric air into the upper troposphere. Complementary analyses on isentropic surfaces further show that air parcels predominantly follow potential temperature surfaces during this period (Animation 1). This finding emphasizes the relevance of an isentropic framework for diagnosing the subsequent dynamical evolution.

3.2 Synoptic-scale evolution and Rossby wave breaking of the March 2016 event

(Reviewer 2)(A pronounced upper-tropospheric trough amplified over the eastern North Pacific and propagated equatorward into central Mexico between 6 and 14 March 2016, in association with the development of a mid-latitude cyclone. By 8 March, the trough extended into the subtropics and tropics, coinciding with a significant equatorward displacement of the subtropical jet during boreal winter. This synoptic configuration enhanced meridional transport, reversed the meridional PV gradient, and established conditions favorable for anticyclonic Rossby wave breaking (RWB) (McIntyre and Palmer, 1983; Gabriel and Peters, 2008; Tyrlis and Hoskins, 2008). ERA5 analyses indicate that the trough evolution was dynamically coupled to the subtropical jet, with 300 hPa wind speeds exceeding 50 m s^{−1} in the jet entrance region (Fig. 4), which is indicative of strong upper-level deformation conducive to wave breaking.

The evolution and structure of the RWB event are diagnosed using isentropic potential vorticity (PV) fields. Figure 4 presents PV contours between 2 and 6 PVU on the 330 K isentropic surface during 9–11 March 2016. These contours display clear

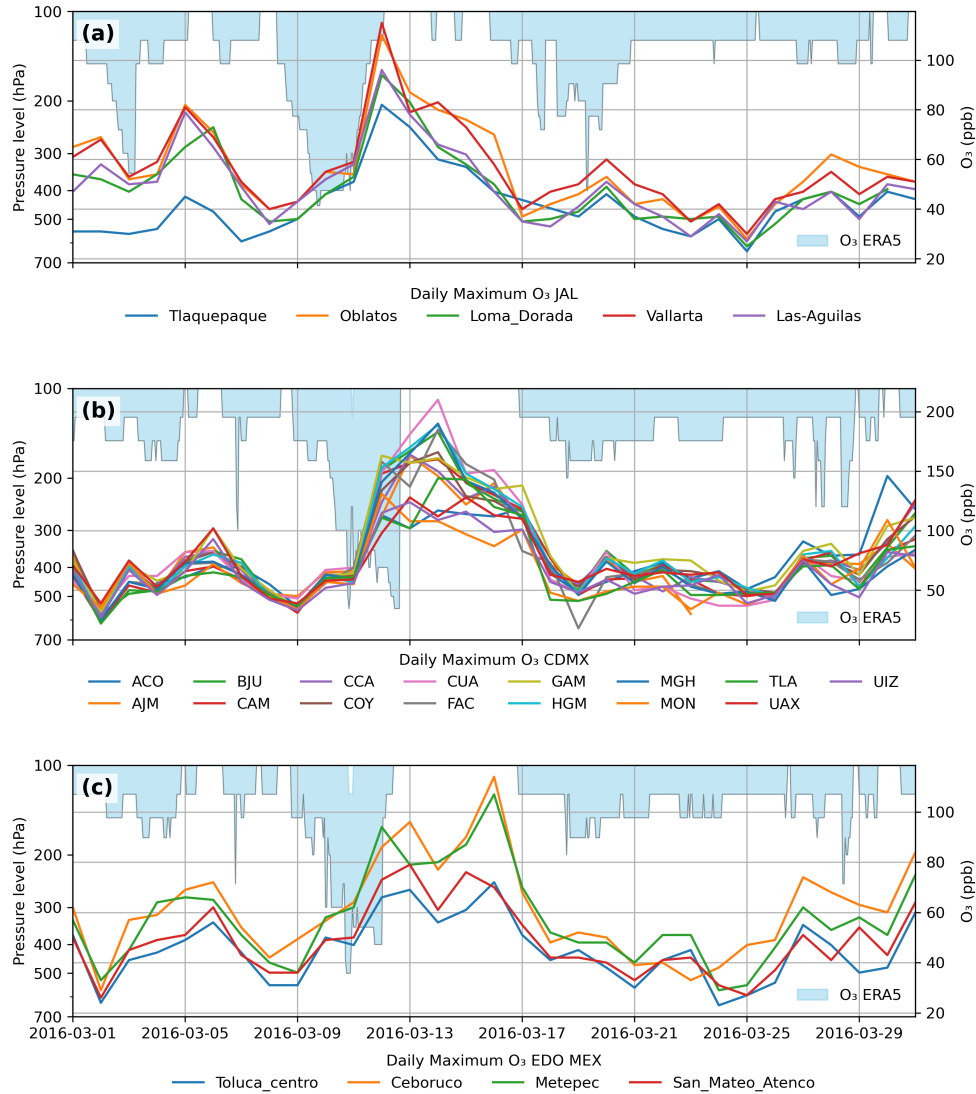


Figure 2. Observed and reanalysis evidence of the high-ozone event in Mexico during 12–14 March 2016. (a) Ground-based O_3 mixing ratios from the air quality monitoring network in western Mexico, Guadalajara, Jalisco, (b) Mexico City, and (c) Toluca (Locations are shown in Fig. S1). Three locations show sustained near-surface O_3 mixing ratios (ppb). Light blue shading denotes the tropopause fold identified from ERA5 reanalysis using potential vorticity values < 1 PVU combined with enhanced ozone mixing ratios, indicate conditions favorable for STE. Surface O_3 mixing ratios were retrieved from Calidad del Aire, Secretaría del Medio Ambiente de la Ciudad de México (SEDEMA), Mexico City (DMA, 2025). Data from Secretaría de Medio Ambiente y Desarrollo Territorial (SMCA), Jalisco, Red Automática de Monitoreo Atmosférico de la Zona Metropolitana del Valle de Toluca (RAMA) were retrieved through the Sistema Nacional de Información de la Calidad del Aire (SINAICA, 2025).

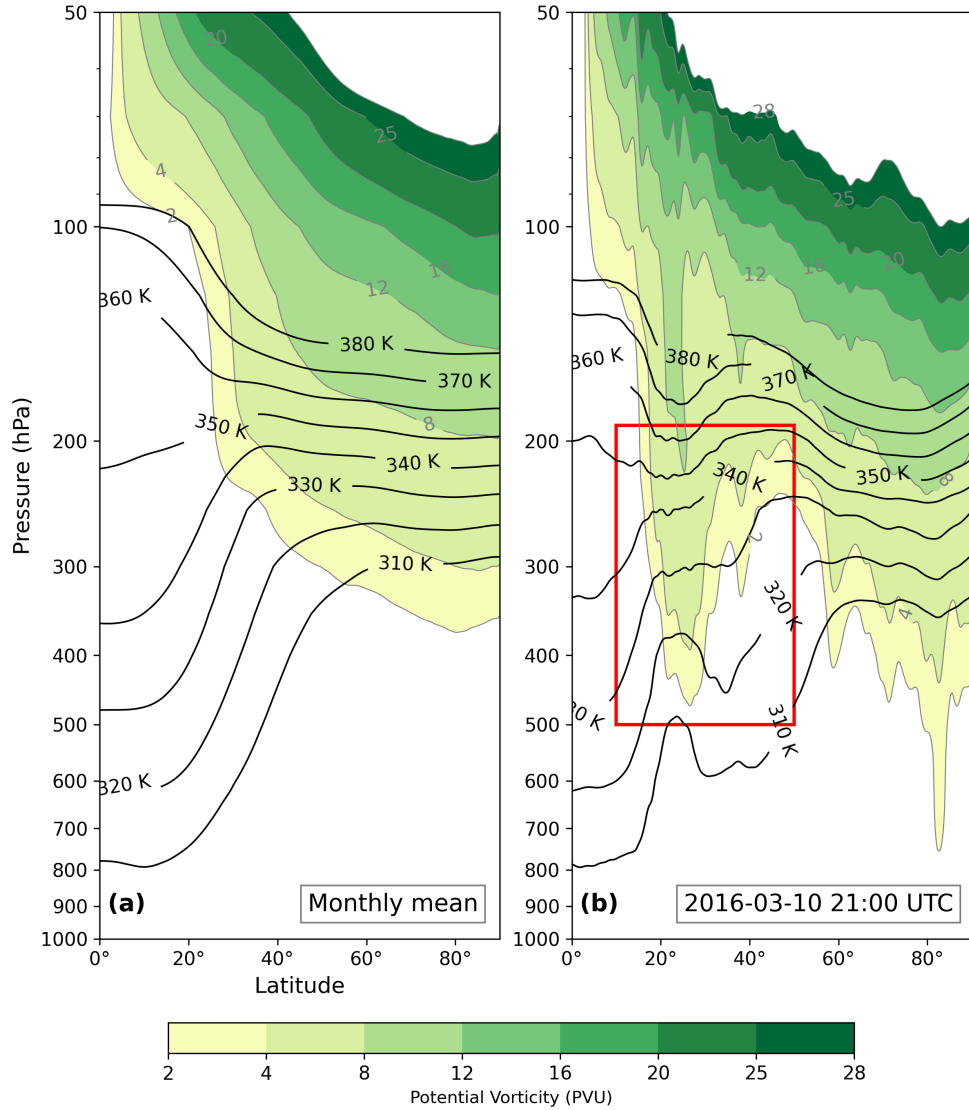


Figure 3. Zonal mean potential temperature (black contours, K) and potential vorticity (colour shading, PVU, $1 \text{ PVU} = 1.0 \times 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$) from ERA5. (a) March 2016 monthly mean over North America. (b) 21 UTC 10 March 2016 over Mexico, showing a PV maximum over the extratropic ($\sim 20^\circ\text{N}$) and downward extension of PV values between 1 and 4 PVU below 300 hPa, indicative of tropopause folding and potential cross-tropopause exchange (red box highlights region of interest).

overturning and equatorward amplification over North America and Mexico, which are characteristic features of anticyclonic
 235 RWB. Overturning is defined where a PV contour intersects a meridian, meeting both the geometric criterion illustrated in
 Fig. 4a and the 1,000 km longitudinal coherence threshold used to identify a single RWB event (Jing and Banerjee, 2018).

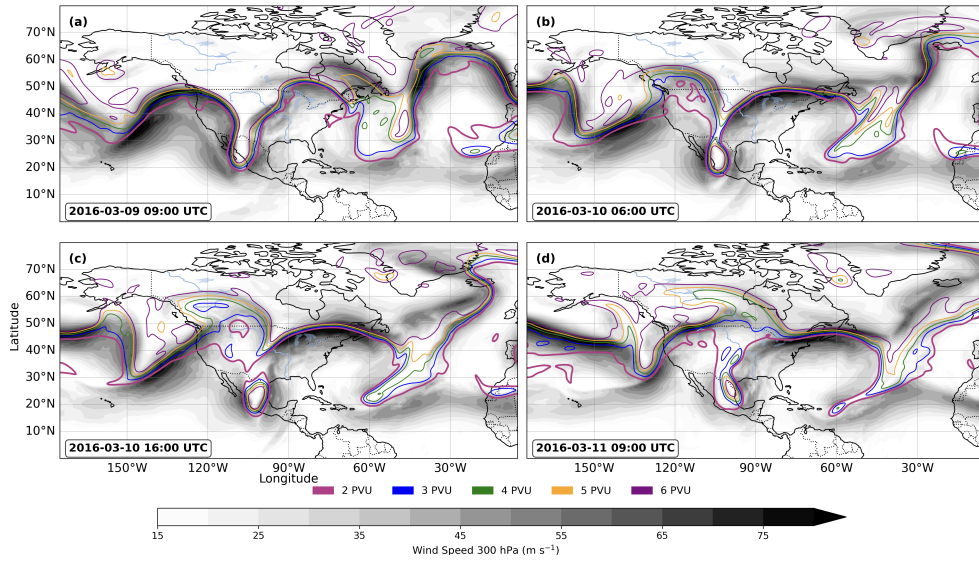


Figure 4. PV contours (2–6 PVU) on the 330 K isentropic surface and shaded 300 hPa wind speed (m s^{-1}) from ERA5 during 9–11 March 2016. Contours undergoing Rossby wave breaking (RWB) overturn across North America, the Pacific Ocean, and the Atlantic Ocean. Overturning is defined where a PV contour intersects a meridian and spans at least 1,000 km. Cyclonic RWB is evident over Mexico, with contours wrapping cyclonically and showing equatorward amplification, corresponding to tropopause folding and the development of low-pressure systems. Panels (a)–(d) show the temporal evolution of this event leading to a cut-off low event over Mexico.

Comparable overturning structures are observed across the 320–350 K isentropic layers (not shown), indicating a deep and vertically coherent wave-breaking episode.

During this period, a pronounced PV streamer extended southward from mid-latitudes into central Mexico, reaching latitudes below 20°N (Fig. 4a–d). Objective RWB diagnostics (Fig. 2) confirm the persistence of this streamer and indicate multiple crossings of the 2 PVU contour across several longitudes, consistent with a sustained regime of RWB lasting nearly three days. This duration exceeds the typical 1–2-day period for low-latitude intrusions. The longevity and coherence of the streamer suggest prolonged cross-tropopause exchange over central Mexico and establish a favorable environment for stratosphere–troposphere exchange (STE).

As wave breaking intensified, segments of the streamer underwent filamentation while others became dynamically isolated, resulting in the formation of a cut-off low. The dynamical influence of the upper-level PV anomaly in generating the closed cyclonic circulation is illustrated in Fig. 5, which overlays isentropic PV at 320 K with geopotential height at 500 hPa. The collocation of the high-PV anomaly with a closed mid-tropospheric geopotential contour demonstrates the balanced response of the mass field to the PV perturbation. Following the theoretical framework of Hoskins et al. (1985), the descent of high-PV, statically stable stratospheric air induces cyclonic vorticity, leading to the development of a cold-cored, closed circulation char-

acteristic of a cut-off low. This PV-induced circulation extends downward and intensifies as the intrusion deepens, particularly over the elevated terrain of central Mexico, where elevations exceed 2000 m above mean sea level.

Figure 1 documents the temporal evolution and classical synoptic signature of the cut-off low, while Fig. 5 explicitly highlights the dynamical connection between the upper-level PV anomaly and the induced mid-tropospheric circulation. Together with the PV-based RWB diagnostics in Fig. 4, these results delineate the pathway from large-scale Rossby wave amplification to streamer formation, PV isolation, and cut-off development. This sequence provides a dynamically consistent framework for interpreting the STE event over central Mexico.)

3.3 Tropopause fold depth and structure

The dynamical tropopause is a line of constant PV that separates the highly stratified stratosphere from the weakly stratified troposphere (Morgan and Nielsen-Gammon, 1998). It is identified using PV thresholds ranging from 1 to 5 PVU. Between 9 and 11 March, analyses reveal the development of a well-defined tropopause fold associated with the upper-level trough. The 2 PVU surface descended to altitudes below 400 hPa, a clear indicator of downward penetration of stratospheric air (Figs. 3b). A vertical cross-section at 00 UTC 12 March 2016 shows sharp PV gradients and a folded structure of the tropopause extending over central Mexico and Mexico City (Fig. 6), persisting for ~ 24 hours prior to the onset of high O_3 surface mixing ratios on 13 March 2016.

(Reviewer 2)(Figure 6 presents the temporal evolution of the tropopause fold through four successive cross sections (9–11 March 2016), enabling direct comparison with the PV evolution shown in Fig. 4. The figure illustrates the dynamical structure of the fold, where a sharp PV gradient is collocated with a pronounced increase in the squared Brunt–Väisälä frequency (N^2), which marks the tropopause. During the early stage (9 March; Fig. 6a), the fold remains shallow and is confined to the upper troposphere. Subsequent panels demonstrate progressive deepening and equatorward extension of high-PV air. The tropopause folding is characterized by high-PV air descending into low-PV air, locally reduced N^2 within the intrusion (indicating weakened stability), and strong N^2 above, consistent with a stratospheric intrusion extending into the mid- to lower troposphere below 400 hPa and near latitude $\sim 20^\circ\text{N}$. As the fold intensifies between 10 and 11 March (Fig. 6b–d), enhanced ozone mixing ratios are observed below the dynamical tropopause, lagging the initial PV intrusion and indicating delayed, stratosphere–troposphere exchange. A specific humidity threshold of $q = 0.1 \text{ g kg}^{-1}$ is also applied to distinguish stratospheric air from diabatically generated high-PV values in the troposphere (solid red line in Fig. 6). The combined use of PV, N^2 , ozone, and humidity diagnostics establishes a comprehensive framework for identifying STE during the March 2016 cut-off low event over low latitudes and mountainous regions.

The tropopause fold developed on the central to southern flank of a low-pressure system along the westerly jet stream. The multi-panel evolution in Fig. 6 demonstrates that fold formation and deepening occurred concurrently with the development and maturation of a cut-off low, which is a necessary dynamical condition for sustained stratospheric exchange. Three regions of folding were identified: over the United States ($\sim 40^\circ\text{N}$ and $\sim 30^\circ\text{N}$) and over Mexico ($\sim 20^\circ\text{N}$), all associated with the cut-off low centered between 15°N and 25°N (Fig. 6). The latitude–pressure structure clearly depicts a closed PV circulation in the mid- to upper troposphere by 10–11 March, confirming the presence of a fully developed cut-off low. These regions

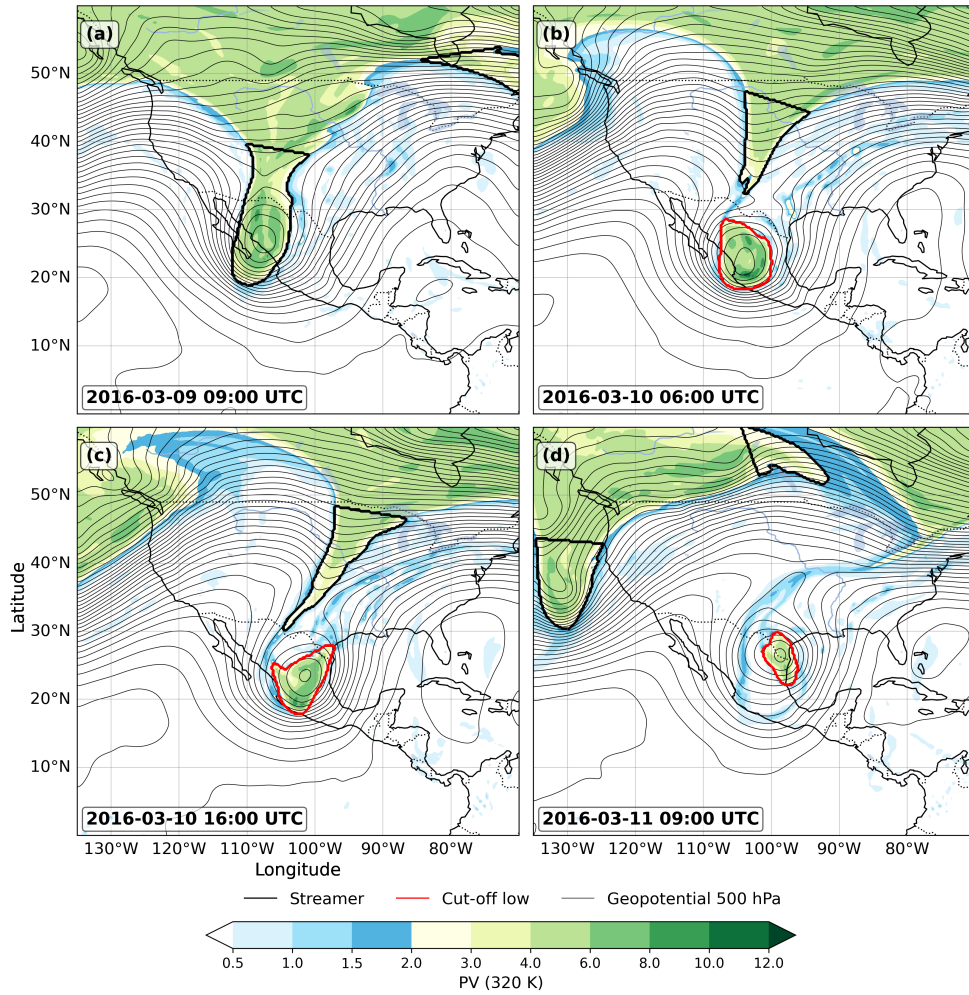


Figure 5. Isentropic potential vorticity in (shading, PVU) on the 320 K surface overlaid with 500 hPa geopotential (thin contours at 50 intervals, $\text{m}^2 \text{s}^{-2}$) for (a) 09 UTC 09 March 2016, (b) 06 UTC 10 March 2016, (c) 16 UTC 10 March 2016 and (d) 09 UTC 11 March 2016. A streamer of high-PV air extends equatorwards over Mexico (thick black contour), indicating strong tropopause distortion. Portions of this streamer roll up into an isolated structure, forming a cut-off low collocated with a closed 500 hPa circulation (red contours). This configuration highlights the dynamical coupling between upper-level PV and mid-tropospheric cyclonic development, a key mechanism of STE exchange for this case study.

285 exhibit a horizontally extensive, statically stable layer in the mid-troposphere, marked by a vorticity maximum induced by the cut-off low, which favors displacement of the system toward lower latitudes. Amplification of the isentropic PV contours illustrates the Rossby wave amplification process and the associated tropopause folding. In these regions, an upper-level trough develops (Fig. 1), supported by the intrusion of highly stable, high-PV stratospheric air that strengthens cyclonic circulation aloft and extends downward to induce surface cyclonic motion. As the intrusion deepens, this process intensifies, consistent

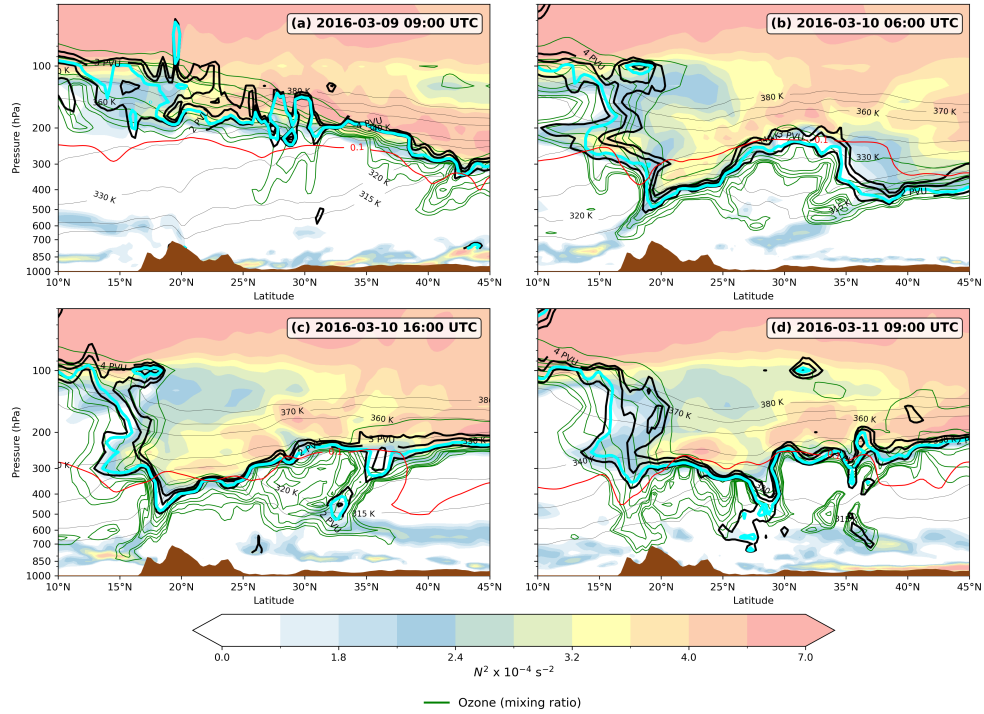


Figure 6. Tropopause fold over Mexico from (a) 09:00 UTC 9 March, (b) 06:00 UTC 10 March, (c) 16:00 UTC 10 March, to (d) 09:00 UTC 11 March 2016. The dynamical tropopause is defined using PV (solid thick black contours, PVU), with the cyan solid line indicating 2 PVU, and the squared Brunt–Väisälä frequency (colour shading, N^2 , $\times 10^{-4} \text{ s}^{-2}$). Section was average over longitudes between 99.1°W and 98.4°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 N^2 within the intrusion. The solid red line indicates the specific humidity threshold ($q = 0.1 \text{ g kg}^{-1}$). Thin solid lines indicate the potential temperature (K).

with the amplification patterns shown in Fig. 4. The concurrent amplification of the 1 PVU contour highlights the downward intrusion of high-PV stratospheric air, reflecting STE linked to baroclinic instability and Rossby wave amplification. The temporal correspondence between PV descent, cut-off low closure, and subsequent ozone enhancement supports the interpretation that effective stratosphere–troposphere exchange occurred only after the cut-off low became fully established. The intrusion deepened further between 10 and 12 March 2016, producing a closed circulation throughout the troposphere (Fig. 4). At the surface, a low-pressure system initially formed and then intensified during the day, coinciding with an amplifying trough in the mid- and upper troposphere.)

3.4 Transport pathways

(Reviewer 1)(Isentropic analyses on the 320–340 K surfaces reveal pronounced equatorward advection of high-PV air from the midlatitudes into central Mexico, consistent with the tropopause fold and streamer described in Section 3.2.) Backward

trajectories computed with LAGRANTO using ERA5 input fields confirm this intrusion. Parcels arriving near 700 hPa over Mexico City between 11 and 13 March 2016 originated from stratospheric levels above 250 hPa within the fold region. The three-dimensional trajectories capture the filamentation of a streamer, the subsequent development of a cut-off low, and the persistence of the fold, which together provided an efficient dynamical pathway for the downward transport of stratospheric air. This mechanism enabled ozone-rich, high-PV air to penetrate the lower troposphere above Mexico City (Fig. 7). Although ERA5 ozone tracer fields indicate enhanced ozone mixing ratios (Reviewer 1)(($\sim 8 \times 10^{-8} \text{ kg kg}^{-1}$ at 700 hPa)), the dominant signal was dynamical: a sustained Rossby wave breaking episode that facilitated STE at unusually low latitudes.

Ozone mixing ratios were interpolated along each trajectory, and only those with pressure differences (ΔP) exceeding 200 hPa between the initial and final positions were retained to diagnose descent trajectories. Most trajectories were located near 600 hPa at 12 UTC 12 March (Fig. 7a), with only a few extending down to 700 hPa above Mexico City (Fig. 7b) (surface pressure reference for Mexico City: 760 hPa). These parcels carried elevated ozone tracer values from the upper stratosphere that decreased gradually towards the surface, in agreement with the PV distribution showing 1–2 PVU air below 550 hPa (Fig. S2). By 00 UTC 13 March, the maximum density of descending trajectories shifted downward from 600 hPa to 700 hPa (Figs. 7c, 7d), coinciding with the observed peak in surface O_3 mixing ratios in Mexico City (Fig. 2b).

Two distinct groups of trajectories can be distinguished at 700 hPa (Fig. 7d). The first group experienced a rapid vertical descent with a clear ΔP from 350 hPa to 700 hPa within 48 hours, but with relatively low PV values (~ 1 PVU) near the surface (Fig. S2d), suggesting substantial dilution during transport, e.g., mixing with tropospheric air that reduces the original stratospheric PV. In contrast, the trajectories of the second group decreased more gradually during the first 48 hours, with PV decreasing smoothly from approximately 2 PVU aloft to about 1 PVU at 700 hPa. This gradual pathway provided a more efficient channel for transporting ozone-rich air into the lower troposphere, consistent with the enhanced surface ozone levels observed during the event.

(Reviewer 1 and 2)(The spatial distribution of the trajectories links the descent over central Mexico directly to the large-scale Rossby wave breaking and cut-off low embedded in the extratropical circulation (Section 3.2), confirming that the diagnosed STE is dynamically tied to the synoptic-scale configuration.) Parcels initially located in the stratosphere, with PV values exceeding 2 PVU, were traced back to the eastern Pacific and North America (Fig. S3), linking the fold to the Rossby wave breaking and the cut-off low embedded in the extratropical circulation. Their subsequent descent into the 300–700 hPa layer over central Mexico reflects the sloping geometry of the tropopause fold and the adiabatic descent forced by the cyclonic circulation on the anticyclonic flank of the breaking wave. Trajectories released between 500 hPa and 600 hPa reveal the evolution of the cut-off low over Mexico between 12 and 13 March 2016 (Fig. S3), emphasizing the dynamical coupling between stratospheric PV anomalies aloft and the development of cyclonic features near the surface.

Ozone transport from the lowermost stratosphere into the troposphere occurs in connection with tropopause fold event and the connection between the tropopause fold-STE and cut-off cyclone. Figure 8 illustrates the dynamical and ozone evolution of the STE event over Mexico City 8–16 March 2016. Tropopause folding is linked to upper level baroclinic waves and jet streams (Fig. 6). As the baroclinic wave develops near the tropopause, strong subsidence occurs over Mexico, accompanied by a downward tilt of the isentropes, facilitating the intrusion of stratospheric air into the troposphere between 10 and 13 March

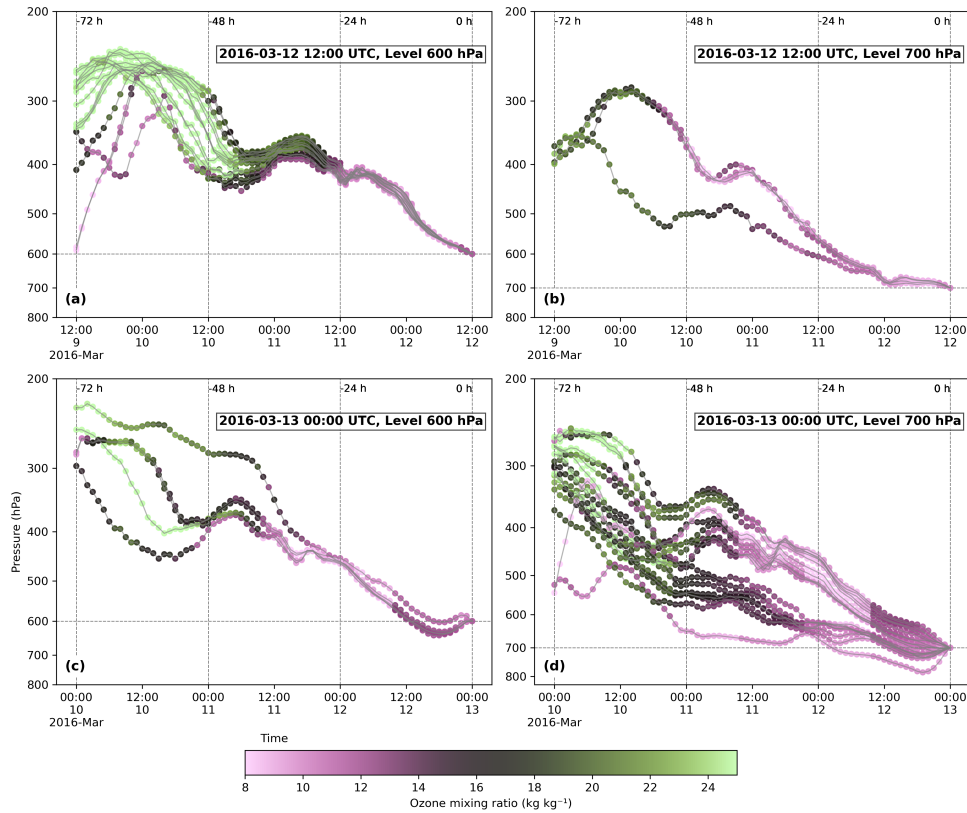


Figure 7. Backward trajectories initialized over Mexico City and its metropolitan area during 12–13 March 2016, computed with LA-GRANTO using ERA5 fields. Panels (a–b) show trajectories arriving at 600 hPa and 700 hPa at 12 UTC 12 March, while panels (c–d) illustrate the evolution at 00 UTC 13 March at the same levels. Ozone mixing ratios ($\times 10^{-8} \text{ kg kg}^{-1}$) are shown as shading along the trajectories. Only trajectories with $\Delta P > 200 \text{ hPa}$ and $PV > 2 \text{ PVU}$ at upper levels were retained. Most parcels originated in the stratosphere above 250 hPa within the tropopause fold region, confirming stratosphere-to-troposphere transport.

335 2016, before the environmental contingency in Mexico City. This intrusion provides a pathway for stratospheric constituents, including ozone, to descend into the lower troposphere over Mexico City.

Coinciding with the tropopause fold, ERA5 ozone tracer values reveal elevated ozone mixing ratios of $\sim 8 \times 10^{-7} \text{ kg kg}^{-1}$ between 150 and 400 hPa on 11 March 2016 (Fig. 8), indicating significant enhancement of ozone in the mid-troposphere over tropical latitudes. The spatial and temporal alignment between ozone mixing ratio and PV anomalies confirms the strato-
 340 spheric origin of the descending air mass. PV extends from the mid-latitudes into the subtropics by 9 March, with descending motion evident from increasing PV values and downward-shifting ozone tracer (Fig. 8). This multi-day progression indicates large-scale subsidence linked to baroclinic wave breaking, emphasizing the role of tropopause folding in driving STE and ozone transport into the lower troposphere. These processes ultimately influence O_3 mixing ratios over densely populated and industrial regions of Mexico (Fig. S4).

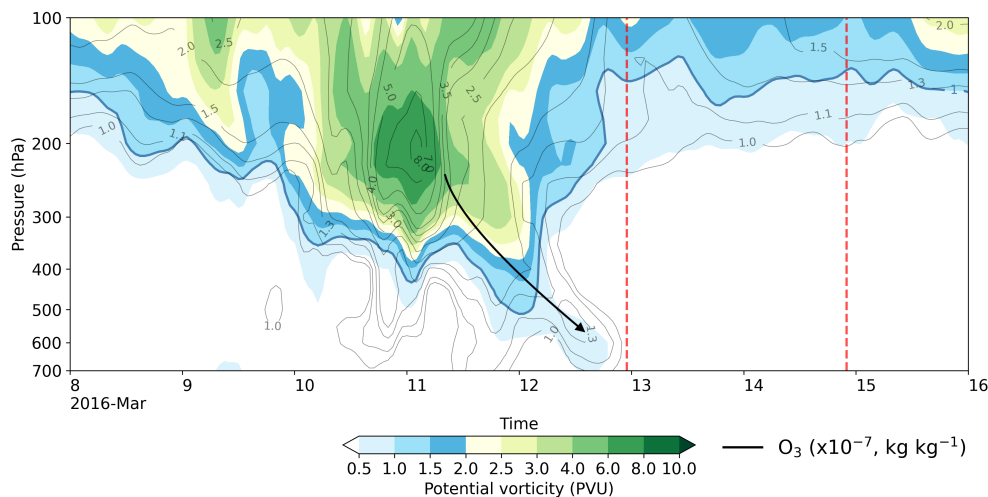


Figure 8. STE over Mexico City, 8–16 March 2016. ERA5 ozone mixing ratio ($\times 10^{-7} \text{ kg kg}^{-1}$) are shown in black contours and potential vorticity (PV) in shading. Ozone mixing ratio and potential vorticity were average over latitudes from 18.5°N to 20°N and longitudes from 99.5°W to 98.5°W . Tropopause folding linked to an upper-level baroclinic wave and jet stream drives the intrusion of stratospheric air into the troposphere between 10–12 March, prior to the environmental emergency (start and end days indicated by vertical red dotted lines). This event represents an unusually strong and unusual STE episode for the tropical latitude of Mexico City.

345 (Reviewer 1)(Satellite-derived products were utilized to supplement ozone tracer analysis and to investigate the evolution of total and tropospheric ozone columns during the tropopause fold and the associated stratosphere–troposphere exchange event over Mexico (Fig. S5). EPIC total column ozone data indicate an enhancement across Mexico, whereas tropospheric ozone columns reveal an increase over eastern Mexico on 10–11 March 2016, coinciding with the development of the tropopause fold. In contrast, the tropospheric ozone signal over central Mexico is weaker, which aligns with the influence of high-elevation

350 terrain and reduced satellite sensitivity in the upper troposphere–lower stratosphere. Although the daily averages reflect specific satellite scan times, the observed spatial patterns remain robust and are supported by independent OMPS–Suomi NPP total column ozone observations (Flynn et al., 2018), which exhibit similar large-scale features.)

To complement the ozone tracer analysis, satellite-derived products were used to assess the evolution of the total and tropospheric ozone columns during the tropopause fold and STE event over Mexico (Fig. S5). Data from The Deep Space

355 Climate Observatory (DSCOVER) Earth Polychromatic Imaging Camera (EPIC) were employed to generate a sequence of daily averaged ozone fields between 7 and 11 March 2016, with tropospheric ozone column and total column. The EPIC total column ozone shows an enhancement across Mexico. Tropospheric ozone signatures reveal a distinct increase over eastern Mexico on 10–11 March 2016, coinciding with the development of the tropopause fold. However, the tropospheric signature is not evident over central Mexico. Although the daily averages represent specific satellite scan times, the structures are robust and supported

360 by the Ozone Mapping and Profiler Suite (OMPS)–Suomi National Polar-Orbiting Partnership (NPP) total column data, which display similar spatial patterns.

3.5 Downward transport over Mexico City

Quasi-horizontal isentropic advection was quantified by interpolating ERA5 winds, PV, and ozone to isentropic surfaces. ~~This approach provides a direct measure of the horizontal transport of PV anomalies along isentropic layers.~~ In the context of the tropopause fold event described above, the analysis highlights regions where stratospheric air masses are irreversibly mixed into the troposphere. For simplicity, the analysis assumes one-way flux, although exchange can occur in both directions. Emphasis is placed on negative advection values, which correspond to the export of high-PV stratospheric air, indicating erosion of the tropopause and the downward transport of stratospheric signatures into the troposphere. The 2 PVU threshold was used to delineate the dynamical tropopause, and areas with $PV > 2$ PVU experiencing negative advection reveal the quasi-horizontal, irreversible transport of stratospheric parcels into the troposphere, consistent with the mechanism described by Dethof et al. (2000).

Figure 9 illustrates the detection of air parcels undergoing downward transport over Mexico City and its Metropolitan Area on isentropic surfaces between 310 K and 360 K during 8–15 March 2016. Downward-moving stratospheric parcels are identified by markers with ozone mixing ratios exceeding $5 \times 10^{-7} \text{ kg kg}^{-1}$ and $PV > 2$ PVU (triangles indicate parcels descending in the stratosphere, while stars display parcels descending in the troposphere). The erosion of the tropopause is particularly evident below the 320 K isentrope (starts), marking the region where stratospheric air intruded into the troposphere. This transport was strongest between 10 and 13 March 2016, descending to shallower isentropes (~ 310 K) during 12–13 March. This period coinciding with the environmental contingency in Mexico City. Independent calculations of cross-tropopause transport following (Siegmund et al., 1996) confirmed a similar footprint over the region (not shown), providing a robust evidence that the tropopause fold directly contributed to the enhancement of near-surface ozone levels.

3.6 Observed Tropopause Folds Preceding High-Ozone Events in Mexico City

(Reviewer 1)(To contextualize the 6–14 March 2016 event and evaluate the recurrence of the documented mechanisms, four additional cases were analyzed in which major high-ozone episodes in Mexico City were preceded by tropopause folding. These events (25 December 2015, 14 April 2007, 10 April 2019, and 22 February 2024) were identified using the same PV–ozone diagnostics as in the March 2016 case, combined with surface air-quality records indicating exceedances of Mexico City’s ozone contingency thresholds.

Figure 10 summarizes the dynamical structure of these events. The 25 December 2015 event (Fig. 10a) featured a shallow intrusion, associated with enhanced PV and ozone mixing ratios in the upper troposphere, and coincided with a pronounced surface pollution episode. In contrast, the 14 April 2007 (Fig. 10b) and 10 April 2019 (Fig. 10c) events involved deeper, consecutive tropopause folds, with PV values exceeding 1–2 PVU extending downward toward the mid–lower troposphere. These structures closely resemble the March 2016 event in both fold depth and the co-location of high-PV air with elevated ozone mixing ratios above central Mexico.

The 22 February 2024 event (Fig. 10d) also exhibited a deep tropopause fold, with elevated ozone mixing ratios between 700 hPa and 600 hPa. This pattern indicates that stratospheric air reached altitudes near the planetary boundary layer over Mexico

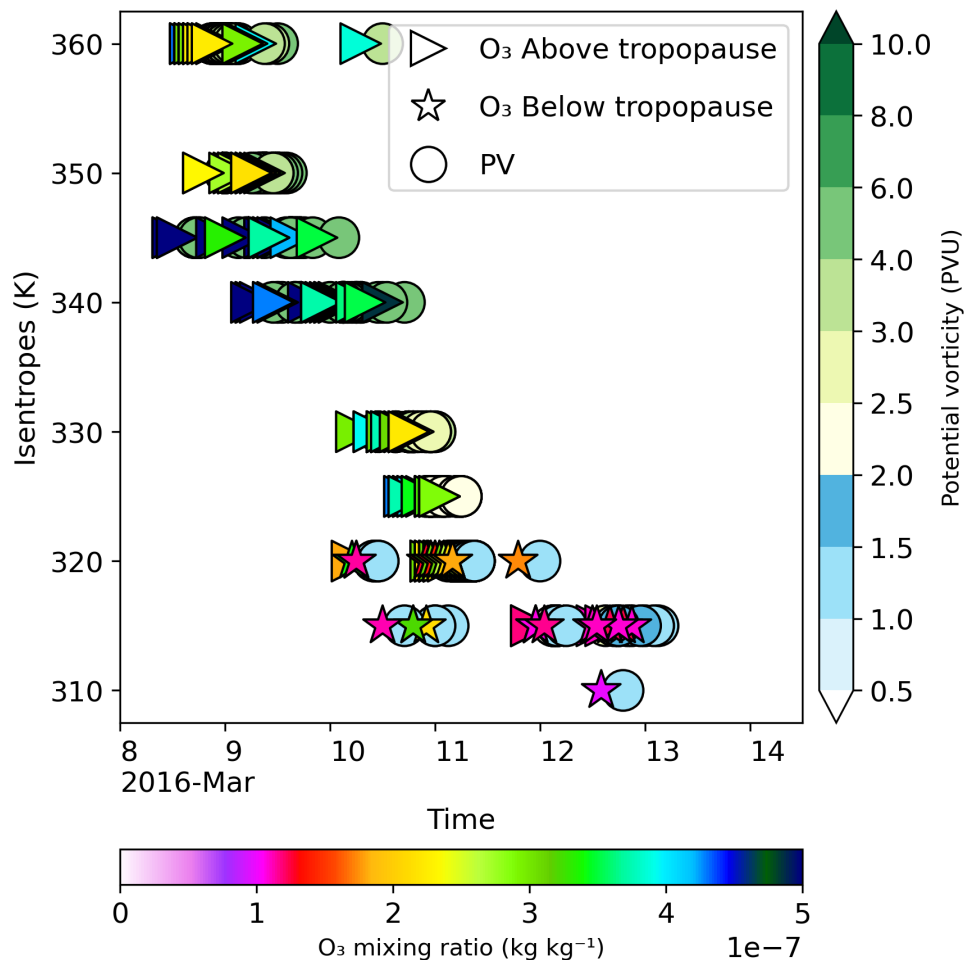


Figure 9. Air parcels detected using quasi-horizontal isentropic advection during the tropopause fold event over Mexico City and its Metropolitan Area between 8 and 15 March 2016. Downward-moving stratospheric parcels are indicated by markers with ozone mixing ratios ($\times 10^{-7} \text{ kg kg}^{-1}$), triangles and stars indicating air parcels above and below of the dynamical tropopause respectively and circles displays PV (PVU) on isentropic surfaces from 310 K to 360 K. Each marker displays the daily average of all pixels detected in the 24 hours analyzed.

City. In all four cases, the folds occurred within a few days prior to major surface ozone enhancements over the Mexico Megacity. This timing is consistent with the dynamical pathway documented for March 2016: Rossby wave amplification and cut-off development, tropopause folding, and subsequent downward transport of ozone-rich, high-PV air.

Although these additional events are not examined in the same detail as the March 2016 case, they provide supporting evidence that both shallow and deep tropopause folds serve as effective pathways for stratospheric ozone to influence near-surface O_3 mixing ratios over central Mexico. This finding suggests that STE associated with wintertime and early-spring

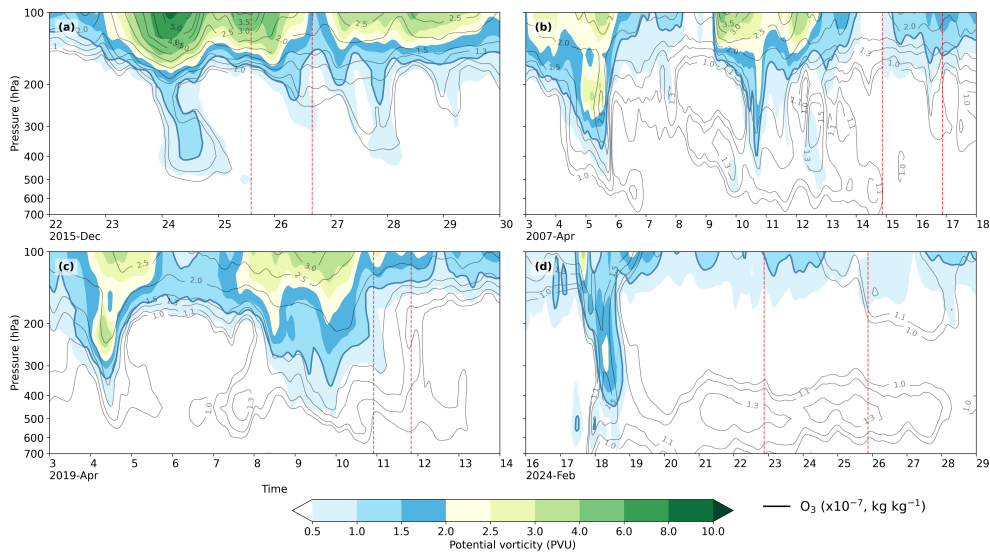


Figure 10. Examples of tropopause fold events over central Mexico associated with major air quality episodes. (a) shallow intrusion on 25 December 2015, ERA5 potential vorticity (PV) and ozone mixing ratio ($\times 10^{-7} \text{ kg kg}^{-1}$), (b) consecutive deep intrusions on 14 April 2007 and (c) 10 April 2019, and (d) 22 February 2024 event. These cases illustrate how both shallow and deep folds can act as effective pathways for stratospheric ozone, enhancing surface O_3 mixing ratios and contributing to extreme pollution episodes. Start and end days indicated by vertical red dotted lines).

baroclinic activity may systematically modulate extreme ozone episodes in the region. A more comprehensive climatological assessment of the frequency, intensity, and mechanisms of such events is beyond the scope of this study, but is clearly warranted for future research. Tropopause folds over central Mexico have preceded major air quality incidents, emphasizing the role of STE as a key mechanism modulating the contribution of stratospheric ozone to near-surface O_3 mixing ratios during boreal winter in the Mexico Megacity. For instance, four events were identified where the STE mechanism contributed to increase the surface O_3 mixing ratio in Mexico City. A shallow intrusion was linked to a pollution event occurred on 25 December 2015 (Fig. 10a), while deeper intrusions on 14 April 2007 (Fig. 10b) and 10 April 2019 (Fig. 10c) were associated with consecutive tropopause folding events that clearly indicate the effects of the STE mechanism in enhancing ozone transport prior to high O_3 mixing ratios over Mexico City. The event occurred on 22 February 2024, also transported ozone into the lower troposphere, with elevated mixing ratios observed between 700 hPa and 600 hPa (Fig. 10d), indicating that stratospheric air reached into the planetary boundary layer of Mexico City. These cases show that both shallow and deep tropopause folds are effective pathways for stratospheric ozone, increasing surface O_3 mixing ratios and contributing to severe pollution episodes over the region. Additional research is necessary to understand the frequency, intensity, and mechanisms of these events, along with their impact on local air quality extremes.

(Reviewer 1 & 2)(The March 2016 event over central Mexico was characterized by an unusually deep episode of stratosphere–troposphere exchange (STE), in which stratospheric air descended into the mid- and lower troposphere and reached near-surface levels over Mexico City by 13–14 March, resulting in surface ozone mixing ratios reaching up to 210 ppb. Dynamical analyses in Section 3.2 demonstrate that Rossby wave breaking, a persistent tropopause fold, and associated isentropic transport pathways facilitated this descent. The following section examines the implications of this atmospheric configuration for surface ozone exceedances and regional air quality.)

While a precise quantification of the stratospheric contribution is not possible given the use of reanalysis data, we found a contribution of ozone mixing ratio of $\sim 8 \times 10^{-8}$ kg kg⁻¹ (Reviewer 1)(near the surface of Mexico City (750–700 hPa)). (Reviewer 1)(This enhancement resulted in elevated background ozone levels, providing conditions favourable for the subsequent ozone exceedance event.)~~Then, the ozone mixing ratio related to the intrusion was enough to serve as a temporary precursor to the exceedance event.~~ The stratospheric input should therefore be viewed as an additional source that enhanced pre-existing anthropogenic background O₃ mixing ratios, driving them above the contingency threshold, rather than as the dominant mechanism of the episode. The timing of the event is also notable. The intrusion reached the lower troposphere roughly one day before the environmental contingency began, suggesting a lag between the dynamical descent of ozone-rich air and the peak surface O₃ mixing ratios. This suggests that the stratospheric signature likely preconditioned the lower troposphere, which was then exacerbated by local photochemical ozone creation, resulting in the observed exceedances.

The dynamical evolution of the event involved streamer development, cut-off low formation, and slow-evolving baroclinic disturbances, consistent with known midlatitude-tropical interactions that facilitate stratospheric intrusions (Appenzeller and Davies, 1992; Wernli and Sprenger, 2007). Unlike more transient STE events, the persistence of the fold and its structured isentropic pathways not only favored unusually deep descent into the boundary layer over Mexico City, enhanced by its high altitude (~ 2300 meters above mean sea level) and the southward position of the boreal winter subtropical jet, but also enabled long-range meridional and zonal transport of ozone-rich air. These quasi-horizontal pathways connected midlatitude source regions with multiple destinations in central and northern Mexico, demonstrating how Rossby wave breaking can act as an effective pathway for trace gases and synchronize pollution events across distant metropolitan areas.

Local emissions and meteorological conditions contribute to tropospheric O₃ mixing ratios, while long-range stratospheric transport adds to the already high anthropogenic background. This finding aligns with previous studies on STE contributions to tropospheric ozone in North America and Europe (Lin et al., 2015; Trickl et al., 2020, 2023) but represents one of the few documented cases in Mexico (Barrett et al., 2019). Importantly, the STE influence extended beyond Mexico City, with elevated ozone mixing ratios also detected in Guadalajara, Monterrey, San Luis Potosí, and Torreón (Fig. S4). Such regional-scale transport compounds local emissions, creating simultaneous exceedances across multiple cities and turning a dynamical event into a broader national-scale air quality hazard.

(Reviewer 2)(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). Comparable STE-related ozone enhancements have been reported in North America and Europe (Škerlak et al., 2019), 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.) The role of topography and altitude also emerges as a key modulator of intrusion depth. Mexico City and Monterrey, situated in elevated basins, could be especially susceptible to stratospheric air moving close to ground level during tropopause folds, while regions at lower elevations might experience less intense surface effects. These findings indicate that the interaction between complex terrain and intrusion dynamics requires further investigation in the tropical region, where orography significantly influences circulation during the boreal winter and spring. This phenomenon has been discussed in other geographical areas, as noted in Chen et al. (2016), Lüthi et al. (2015) and Škerlak et al. (2019). While similar STE-related ozone enhancements have been reported in North America and Europe, fewer studies exist in tropical regions where weather is influenced from extratropical cyclones. Comparisons with the Mediterranean basin and East Asia suggest that complex orography combined with subtropical jet dynamics plays a central role in facilitating deep intrusions. In Mexico, the elevated basins of central and northern cities appear particularly susceptible, underlining the broader subtropical relevance of this case.

From a forecasting perspective, these results emphasize the value of monitoring Rossby wave activity, tropopause folding, and isentropic transport pathways as potential early-warning indicators of surface pollution episodes. Current operational forecasts and air quality management plans in Mexico primarily focus on local emissions and meteorological dispersion in the planetary boundary layer. However, forecast accuracy is likely limited by strong terrain–flow interactions and the complexities of basin circulations, which modulate how stratospheric air masses interact with the boundary layer. Incorporating dynamical precursors into high-resolution numerical weather prediction and coupled chemical transport models could enhance predictive capacity and support more proactive public health interventions, particularly in mountainous tropical and subtropical regions.

5 Conclusions

This study provides a detailed dynamical analysis of a stratosphere–troposphere exchange (STE) event over central Mexico during 6–14 March 2016, coinciding with a severe ozone pollution episode in Mexico City. Using ERA5 reanalysis, PV and ozone tracer diagnostics, Lagrangian trajectories, and isentropic analysis, we show that this event was driven by anticyclonic

Rossby wave breaking and a persistent tropopause fold, facilitating the transport of stratospheric air into near-surface layers over central area of Mexico. The key findings are listed below:

1. The amplification of Rossby waves toward the equator and the subsequent formation of a streamer contributed to the development of a cut-off low over Mexico. This process created coherent isentropic transport pathways that allowed ozone-rich air from the stratosphere to efficiently descend into the lower troposphere. The intrusion of this stratospheric air reached the lower troposphere about one day before the environmental contingency began, highlighting a temporal lag between the dynamical descent of stratospheric air into the lower troposphere and the peak of surface O₃ mixing ratios, consistent with STE acting as a dynamical preconditioning mechanism rather than a direct sole driver of surface ozone exceedances.
2. Persistence and depth of the tropopause fold were unusual compared to previous STE events, allowing stratospheric air to reach the boundary layer over Mexico City, unlike shallower or more transient intrusions reported in earlier studies (e.g., Barrett et al., 2019).
3. Dynamical coupling between PV anomalies and mid-tropospheric cyclonic circulation amplified the intrusion and sustained downward transport over multiple days, demonstrating a strong link between large-scale Rossby wave dynamics and regional air quality impacts.

mixing ratios were observed not only over Mexico City but also in urban centers, such as Guadalajara, Monterrey, San Luis Potosí, and Torreón, showing that STE events can modulate regional air quality by elevating background ozone levels, thereby increasing the sensitivity of surface ozone to local photochemical production. Intrusion depth was strongly influenced by topography and altitude, with elevated basins like Mexico City and Monterrey more prone to near-surface stratospheric air, while lower-altitude regions were less affected. While this study does not explicitly quantify orographic effects, comparisons with other subtropical regions, including the Mediterranean and East Asia, indicate that subtropical jet dynamics combined with complex orography facilitate deep intrusions, highlighting the vulnerability of central Mexican urban basins.

Limitations of this study include reliance on ERA5 reanalysis, which may underestimate the sharpness of small-scale folds and mixing layers, and the lack of direct in situ ozone measurements aloft during the event. In particular, we do not quantify the relative contributions of stratospheric ozone versus in situ photochemical ozone production at the surface; therefore, the observed exceedances cannot be attributed to STE alone. Future work should combine high-resolution chemistry-atmospheric simulations with targeted observational campaigns to quantify stratospheric contributions and better understand the dynamical-chemical mechanisms driving regional ozone exceedances.

Overall, the March 2016 case exemplifies how synoptic-scale Rossby wave dynamics and tropopause folding can directly influence surface air quality in tropical and subtropical urban centers. Recognizing these links is essential for attributing past pollution episodes, improving operational forecasts, and informing mitigation strategies. Beyond documenting a single event, this study advances the understanding of STE by demonstrating that the persistence, depth, and geometry of isentropic transport pathways, rather than tropopause folding alone, determine whether stratospheric intrusions become environmentally significant

515 in tropical and subtropical regions. High-resolution chemistry–climate simulations, combined with real-time monitoring of STE precursors, would improve the quantification of stratospheric contributions to surface ozone, providing actionable insights for environmental management and public health preparedness by treating STE as a large-scale dynamical modifier of background chemical conditions rather than as a primary surface ozone source.

520 *Data availability.* ERA5 reanalysis data Hersbach et al. (2020) are publicly available from the Copernicus Climate Data Store <https://cds.climate.copernicus.eu>. Tropospheric ozone data from the NASA Earth Probe Total Ozone Mapping Spectrometer (EPIC) instrument Kramarova et al. (2021); Marshak et al. (2018) and Ozone Mapping and Profiler Suite (OMPS) data from the Suomi National Polar-Orbiting Partnership (Suomi NPP) satellite Flynn et al. (2018) are both available through NASA’s Earthdata portal <https://earthdata.nasa.gov>.

Code and data availability. Lagrangian trajectories were computed using the LAGRANTO tool Sprenger and Wernli (2015), which is available upon request from the developers. The WaveBreaking detection package Kaderli (2023) is accessible at <https://zenodo.org/records/14214463>.

525 *Author contributions.* CLB and EC conceived the study; CLB analyzed data and wrote the manuscript draft; CLB, EC, and AFR reviewed and edited the manuscript

Competing interests. Authors declare that they have no competing interests related to this research.

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