Dear Reviewer

First, we would like to thank you and the reviewers for your effort and the time spent to evaluate the manuscript entitled "**Ozone Downward Flux Revealed by High-Resolution Differential Absorption Lidar over Tibet during Stratosphere-Troposphere Exchange" (egusphere-2026-3261)**" We are sure that their valuable comments will improve the quality of our research work. We also would like to thank the editorial board for his guidance to proceed further. Following the reviewers' suggestions, we have revised this manuscript and highlighted the modifications in the revision. The point to point response to the comments are given below.

Response to Reviewer :

We would like to thank the reviewer for the efforts and time and appreciate the encouraging review. Thank you for pointing out our mistakes. We really believe that your feedback has helped us to improve the presentation of our manuscript and the quality of our paper.

Following your suggestion, we have revised the organization of the manuscript and updated the relevant figures. We have also expanded the methodological discussion and incorporated additional relevant references to improve the clarity and completeness of the manuscript. The specific revisions are as follows:

General Remarks

The manuscript describes the observation and analysis of the short-term structures above a region with complex terrain. The description of the tropopause oscillations and the most likely underlying wave activity is neither really clear nor convincing. Models are used without demonstrating their capability of reproducing the observed tropopause structures. I cannot suggest publication in the current state.

Our Response:

Thank you for your careful assessment and constructive criticism. In response to the reviewer's concerns, we have substantially revised the observational analysis, dynamical interpretation, methodological description, and relevant figures.

First, we now separate the direct lidar observations from their subsequent physical interpretation. The features T0-T6 are described as short-lived downward-displacement episodes of ozone-enhanced structures rather than as individual downward-transport events. Whether these features are related to transport is assessed only after considering the temperature, PV, and flux diagnostics. The corresponding revisions are provided in Lines 208-234.

Second, we have strengthened the simultaneous ozone-temperature analysis, which is a central observational contribution of this study. The identification of T0-T6 is now described more clearly, and the temperature profiles independently retrieved from the simultaneously measured 387-nm N_2 Raman return are compared with the ozone structures on an event-by-event basis. Six of the seven episodes are associated with temperature gradients exceeding 8 K km^{-1}, while T2 exhibits a gradient of 4.2 K km^{-1}. We now present this as an observed co-temporal and co-altitudinal correspondence, rather than as independent proof of irreversible transport.

Third, we have clarified the distinction between the regional tropopause fold and the shorter-timescale oscillations identified by the reviewer. The fold is diagnosed from the regional PV structure over approximately 25-28°N and 95-99°E, where a downward intrusion of high-PV stratospheric air is evident and spatially coincides with enhanced cross-tropopause mass flux in Figs. 9 and 10. The shorter-timescale variations near the lidar site are interpreted as wave-related tropopause oscillations superimposed on this regional folding structure. These processes are not mutually exclusive: observational studies have shown that jet-associated tropopause folds can be accompanied by inertia–gravity waves, wave breaking, turbulence, and related instabilities (Cho et al., 1999; Bertin et al., 2001; Stohl et al., 2003). The corresponding clarification is provided in Lines 378-385.

Fourth, we have clarified the role of ERA5. ERA5 is an observation-assimilating reanalysis rather than an unconstrained theoretical model field (Hersbach et al., 2020). We do not expect it to reproduce every sub-hourly structure resolved by the lidar. Instead, the lidar provides local, high-spatiotemporal-resolution ozone and temperature observations, whereas ERA5 supplies the regional three-dimensional dynamical fields required to define the tropopause, characterize the PV structure, and diagnose cross-tropopause fluxes. Figure 5 demonstrates that ERA5 captures the overall onset and recovery of the event and agrees well with the lidar in the magnitude and temporal evolution of ozone near the tropopause.

Finally, we have strengthened the robustness of the flux diagnosis. The uncertainty associated with the dynamical-tropopause definition is now evaluated through a PV-threshold sensitivity analysis and an examination of PV-surface continuity. On this basis, 3 PVU is adopted as a physically reasonable and representative threshold for this event rather than as a uniquely correct value. In addition, because Eulerian diagnostics in pressure coordinates can suffer from numerical cancellation among large terms (Wirth, 1995; Wirth and Egger, 1999), Wei's formulation has been reformulated in PV coordinates. The recalculated results are presented in the revised Fig. 10, with the methodological explanation provided in Lines 392-400.

The revised interpretation is therefore supported by several complementary lines of evidence: high-resolution ozone observations, independently retrieved Raman-temperature profiles, regional PV morphology, PV-threshold sensitivity analysis, event-scale consistency between ERA5 and the lidar, and cross-tropopause mass- and ozone-flux calculations. We believe that these revisions have substantially improved the clarity and robustness of the manuscript and have addressed the reviewer's principal concerns regarding tropopause oscillations, wave activity, and the use of ERA5 data. We respectfully ask the reviewer to reconsider the manuscript in light of these revisions.

Specific Comments

Comments and Suggestions #1

Introduction: In the Introduction also the international literature on a topic should be reviewed.

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions. We agree that the original Introduction focused mainly on studies over the Tibetan Plateau and did not sufficiently review the broader international literature on Stratosphere-Troposphere Exchange (STE).

We have therefore expanded the Introduction to include international studies on STE mechanisms and dynamical processes (Holton et al., 1995; Stohl et al., 2003), the global climatology of tropopause folds and cross-tropopause exchange (Sprenger et al., 2003; Škerlak et al., 2015), cross-tropopause mass and ozone fluxes (Olsen et al., 2004), and high-resolution ground-based ozone-lidar observations of stratospheric intrusions (Eisele et al., 1999; Kuang et al., 2012). These additions place the present study within a broader international context and provide a clearer transition to the remaining need for high-spatiotemporal-resolution observations over the Tibetan Plateau.

Changes in manuscript:

The corresponding additions are highlighted in yellow in the revised Introduction, particularly in Lines 29, 33, 35, 40, and 51. The relevant references have also been added or cited in the revised manuscript.

Comments and Suggestions #2

Lines 12-13: "It provides the first lidar-based detection of these rapid ozone descent events": I do not believe that you mean world-wide! There is a host of literature on this issue. Also "the evidence linking them to temperature variability in the tropopause region" is not new. You find this even in many radiosonde ascents

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions.

In the revised manuscript, we have replaced the original statement, "It provides the first lidar-based detection of these rapid ozone descent events and the evidence linking them to temperature variability…"with the following more precise description: "The high-spatiotemporal-resolution lidar observations resolve a series of short-lived, rapid ozone descent episodes … including temperature gradients generally exceeding 8 K km^{-1}."

We have also more carefully defined the distinctive contribution of this study. we now emphasize three specific aspects: (1) the high-spatiotemporal-resolution characterization of the short-lived ozone descent episodes labelled T0-T6; (2) the event-by-event correspondence between these ozone features and rapid temperature variations near the tropopause, independently retrieved from the Raman signals measured by the same lidar system; and (3) the subsequent quantitative estimation of cross-tropopause ozone flux by combining the lidar-derived ozone profiles with the dynamical flux diagnosis.

Changes in manuscript:

The corresponding revision can be found in Lines 12-16 of the revised manuscript. These revisions clarify the scope of the observational contribution and avoid overstating the novelty of the study.

Comments and Suggestions #3

Line 27: STT has been studied since the 1950s. Why do you prefer to cite just Chen et al? I would expect a citation of least the last review paper of Stohl et al (JGR 2003) in addition.

Our Response:

Thank you for this important comment. We agree that citing only Chen et al. (2006) in this general statement did not adequately reflect the long history of research on stratosphere–troposphere exchange or the extensive international literature in this field. Following the reviewer's suggestion, we have added the comprehensive review by Stohl et al. (2003) at the corresponding location. We have also expanded the Introduction to provide a broader review of international STE research, including its major dynamical mechanisms and related observational studies.

Changes in manuscript:

The corresponding revision is highlighted in yellow in Lines 27-29 of the revised manuscript. The corresponding sentence has been revised as follows: "Stratosphere-troposphere exchange (STE) has been investigated for several decades and is recognized as a key process controlling the budgets of ozone, water vapor, and other trace constituents in the upper troposphere and lower stratosphere (UTLS) (Stohl et al., 2003; Chen et al., 2006)."

Comments and Suggestions #4

Lines 30-34: You could add a few words about the role of the subtropical jet stream in this context. Sprenger et al (JGR2003) found an STT maximum in that area.

Our Response:

Thank you for this helpful suggestion. We agree that the subtropical jet and its associated dynamical structures provide important context for understanding cross-tropopause transport over the Tibetan Plateau and surrounding regions. We have therefore added a brief discussion of the role of the subtropical jet to the revised Introduction. In particular, we now explain that the strong horizontal and vertical wind shear associated with the jet favors dynamical disturbances, tropopause deformation, and tropopause folding, with the latter providing an important pathway for cross-tropopause exchange.

We have also cited Sprenger et al. (2003) and added the following text: "The subtropical jet is particularly relevant in this context because its strong horizontal and vertical wind shear favors tropopause deformation and folding. Global analyses by Sprenger et al. (2003) showed ..."The study by Sprenger et al. (2003) demonstrated that tropopause folds occur preferentially in the subtropics and that a substantial fraction of cross-tropopause exchange events within the 20°-40° latitude band are associated with such folds.

Changes in manuscript:

The corresponding revisions are highlighted in yellow in Lines 36-40 of the revised manuscript.

Comments and Suggestions #5

Line 57: high resolution in time or in space?

Our Response:

Thank you for pointing out this ambiguity. Here, "high resolution" refers to both the temporal and spatial (vertical) sampling capabilities of the USTC Ozone Lidar. We have therefore revised the wording to "high-spatiotemporal-resolution observations" to make this point explicit.

During routine operation, the lidar records one raw signal profile every 1 min, with a vertical range-bin spacing of 61.44 m. For the stratospheric ozone retrievals used in this study, the photon-counting signals were accumulated over 30 min to ensure an adequate signal-to-noise ratio and were subsequently processed using a moving time-window method. Accordingly, the original expression "high-resolution observations" has been revised to "high-spatiotemporal-resolution observations."

Changes in manuscript:

The corresponding revision is highlighted in yellow in Lines 85-86 of the revised manuscript.

Comments and Suggestions #6

Section 2: The lidar specifications are missing.

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions. The USTC Ozone Lidar used in this study is an established mobile differential absorption lidar (DIAL) system developed by our group. Its system configuration, technical specifications, and performance characterization have been described in detail in our previous instrumental paper (Fang et al., 2019). Because the focus of the present study is the application of this existing lidar system to the investigation and quantitative diagnosis of an STE-related ozone transport event, rather than the development or technical characterization of the lidar itself, we have avoided repeating the complete instrumental description provided in Fang et al. (2019).

Nevertheless, following the reviewer's suggestion, we have revised Section 2, particularly Lines 116-137, to provide a clearer summary of the key specifications directly relevant to the present observations. These include the transmitted and received wavelengths, telescope configuration and apertures, measurement altitude ranges, vertical range-bin spacing, and data-acquisition and accumulation intervals.

Changes in manuscript:

The key system specifications are provided in Lines 116-137, and the temporal and vertical sampling characteristics are described in Lines 144-148 and highlighted in green in the revised manuscript.

Comments and Suggestions #7

Lines 73-74: It is nice that you provide this capability. However, also lidar systems devoted to STT studies should be mentioned (e.g., Ancellet et al, Langford et al, Eisele et al, 1997, Kuang et al, Trickl et al, 2020).

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions. We agree that the original description did not sufficiently acknowledge previous ozone lidar observations specifically devoted to stratosphere-to-troposphere transport (STT) and stratospheric intrusion studies. We have therefore expanded Section 2 to place the USTC Ozone Lidar observations in the context of these earlier international lidar studies.

In the revised manuscript, we now cite representative studies by Ancellet et al., Eisele et al., Langford et al., Kuang et al., and Trickl et al., which have demonstrated the capability of ground-based ozone lidar to resolve ozone-rich stratospheric intrusion layers and to investigate their descent, evolution, and mixing in the troposphere. These references provide a more complete context for the application of high-resolution ozone lidar observations to STT studies.

Changes in manuscript:

The following text has been added to Section 2(lines105-113): "Ground-based ozone lidar has also been extensively applied to studies of stratosphere-to-troposphere transport (STT) and stratospheric intrusions. Early studies demonstrated the capability of ozone lidar to resolve ozone-rich layers associated with cross-tropopause exchange and tropopause-folding events (Ancellet et al., 1991; Eisele et al., 1999). Subsequent lidar observations have been used to investigate the descent, evolution, and mixing of stratospheric ozone intrusions in the free troposphere (Langford et al., 2009; Kuang et al., 2012). More recently, long-term ozone lidar observations have further demonstrated the frequent occurrence and substantial influence of stratospheric intrusion layers in the free troposphere (Trickl et al., 2020)."

Comments and Suggestions #7

Lines 78-81: Although lidar details are not ultimately essential for this study, a few more words could be added. For instance, it should be briefly explained why so many wavelengths are required and how they are generated (including citations).

Our Response:

Thank you for this helpful suggestion. We agree that, although the detailed instrumental design is not the main focus of the present study, a brief explanation of the purpose and generation of the different wavelengths is useful for understanding the measurement strategy. We have therefore expanded Section 2 accordingly and added relevant references.

The different wavelength pairs are employed to accommodate the large difference in ozone abundance between the troposphere and stratosphere and the corresponding requirements for differential-absorption sensitivity and measurement range. For tropospheric ozone measurements, the 289/299-nm DIAL pair is used to provide sufficient differential ozone absorption sensitivity at relatively low ozone concentrations. These wavelengths are generated through stimulated Raman scattering by pumping D_2 and H_2 Raman cells, respectively, with 266-nm radiation obtained from the fourth harmonic of a Nd laser (Papayannis et al., 1999; Fang et al., 2019). For stratospheric ozone measurements, where ozone abundance is substantially higher, the 308/355-nm DIAL pair is employed. The 308-nm wavelength is generated directly by a XeCl excimer laser, while the 355-nm wavelength is obtained through third-harmonic generation of the 1064-nm fundamental output of a Nd laser (McDermid et al., 1991; Godin-Beekmann et al., 2003; Fang et al., 2019). In addition, the N_2 vibrational Raman returns at 332 and 387 nm, corresponding to excitation at 308 and 355 nm, respectively, are simultaneously detected (McGee et al., 1993) to reduce aerosol/backscatter-related effects.

Changes in manuscript:

We have incorporated the above explanation and the corresponding references into Section 2 of the revised manuscript. The relevant revisions are highlighted in yellow in Lines 116-130.

Comments and Suggestions #8

Line 79: This wavelength pair does not allow for good vertical resolution unless there is a very strong ozone peak.

Our Response:

Thank you for your careful evaluation of our study and for your valuable suggestion. In the original manuscript, we stated that the USTC Ozone Lidar uses 289/299 nm for tropospheric measurements and 308/355 nm for stratospheric measurements.

Because ozone abundance differs significantly between the troposphere and the stratosphere, the USTC Ozone Lidar uses different wavelength pairs for measurements in these two altitude regions. For the troposphere, where the ozone number density is relatively low, the system uses the 289/299-nm DIAL wavelength pair (Papayannis et al., 1999; Kourtidis et al., 2002; Fang et al., 2019). The sufficiently large absorption cross sections at these wavelengths, together with the sufficiently large difference in absorption cross section resulting from the 10 nm wavelength separation, ensure adequate differential-absorption sensitivity. To maintain good signal quality over a relatively broad measurement range, the system employs two receiving configurations: a low-altitude channel covering approximately 5-10 km and a high-altitude channel covering approximately 8-19 km.

For stratospheric measurements, where ozone abundance is significantly higher, the system uses the 308/355-nm wavelength pair (McDermid et al., 1991; Godin-Beekmann et al., 2003), which enables the ozone-profile measurement range to be extended to higher altitudes. In addition, the system simultaneously detects the 332 nm and 387 nm nitrogen (N_2) vibrational Raman scattering signals generated by excitation with the 308 nm and 355 nm lasers, respectively (McGee et al., 1993). These Raman channels provide complementary information, helping to reduce the effects of aerosols and backscatter during the ozone retrieval and to improve the reliability of the measurements, particularly in the upper-tropospheric and stratospheric regions.

Changes in manuscript:

The corresponding explanation has been added to Lines 116-130 of the revised manuscript and is highlighted in yellow.

Comments and Suggestions #9

Line 83: Please, add a reference such as (McGee et al, 1993).

Our Response:

Thank you for this helpful suggestion. We agree that a reference to the established Raman lidar technique is appropriate here. Following the reviewer's suggestion, we have cited McGee et al. (1993) in the corresponding description of the N_2 Raman backscatter measurements in Section 2, and the full citation has been added to the reference list.

Changes in manuscript:

The corresponding revision can be found in Line 128 of the revised manuscript.

Comments and Suggestions #10

Line 88: Are the heights specified above the ground or above sea level?

Our Response:

Thank you for pointing out this ambiguity. The heights reported here are measured above sea level, rather than above mean ground level. We have clarified this in Section 2 by explicitly specifying "above sea level" for the corresponding height ranges.

Changes in manuscript:

The corresponding revisions can be found in Lines 134-138 of the revised manuscript.

Comments and Suggestions #11

Line 110: Please, cite the appropriate chapter in that book. This chapter, however, does not fully describe the state of the art of ozone lidar systems. What about aerosol and cloud interference? What about lidar calibration and uncertainty? References are needed.

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions. We agree that the description in the original manuscript was too brief and that the general citation to Weitkamp (2005) did not adequately address the retrieval issues specific to ozone DIAL measurements. We have therefore substantially revised the corresponding part of Section 2 and added more targeted references.

First, following the reviewer's suggestion, we now cite the specific chapter by Gimmestad (2005), entitled "Differential-Absorption Lidar for Ozone and Industrial Emissions," rather than referring only to the book as a whole. We have also clarified the major factors considered in the ozone retrieval, including the temperature dependence of the ozone absorption cross-sections, absorption by interfering atmospheric species, and the wavelength dependence of molecular and aerosol backscatter and extinction.

Second, we have expanded the discussion of aerosol and cloud interference. Differences in aerosol backscatter and extinction between the online and offline wavelengths can introduce systematic errors, particularly when strong vertical gradients in aerosol loading are present. We have therefore added ozone-DIAL-specific references addressing these effects (Browell et al., 1985; Kovalev and Bristow, 1996). We further explain that the N_2 vibrational Raman returns at 332 and 387 nm provide complementary information that helps reduce aerosol- and backscatter-related effects in upper-tropospheric and stratospheric ozone retrievals.

Finally, we have clarified the treatment of system characterization, retrieval uncertainty, and validation. The detailed system characterization, retrieval methodology, and uncertainty assessment of the USTC Ozone Lidar have been presented in our previous instrumental study, Fang et al. (2019). For the measurements used in the present study, the retrieved ozone profiles are further evaluated through comparisons with ERA5 and independent Aura/OMI and Aura/MLS observations, as shown in Fig. 3. We emphasize that these comparisons provide independent validation of the retrieved ozone profiles rather than serving as an absolute instrumental calibration.

Changes in manuscript:

The above discussion and the corresponding references have been added to Section 2 of the revised manuscript, particularly Lines 153-165.

Comments and Suggestions #12

Line 115: Please, add citations for the satellites.

Our Response:

Thank you for this helpful suggestion. We have added appropriate references for the Aura satellite mission and for the satellite instruments and ozone-profile products used in this study. Specifically, Schoeberl et al. (2006) is now cited for the EOS Aura mission, Liu et al. (2010) for the OMI ozone-profile retrievals, and Waters et al. (2006) for the Aura MLS instrument.

Changes in manuscript:

The corresponding revision can be found in Lines 170-171 of the revised manuscript. The corresponding sentence has been revised as follows: "The merged profile was then compared with ERA5 data for the corresponding time and further cross-validated against ozone-profile observations from the Ozone Monitoring Instrument (OMI; Liu et al., 2010) and the Microwave Limb Sounder (MLS; Waters et al., 2006) aboard the Aura satellite (Schoeberl et al., 2006), as shown in Fig. 3(b)."

Comments and Suggestions #12

Line 128: How fine?

Our Response:

Thank you for pointing out that the term "fine-scale" was too qualitative. We have revised the corresponding text to provide a quantitative description based on the temporal scales actually resolved in our observations. Specifically, during this event, the USTC Ozone Lidar resolved short-lived downward-displacement episodes of ozone-enhanced structures occurring on sub-hourly to 1-2 h timescales, as further presented and discussed in Section 3.1.

The corresponding text has been revised as follows: "Moreover, the high spatiotemporal sampling capability of the lidar allows it to resolve vertically confined and short-lived ozone structures that are often missed by other datasets, since satellite profile data typically contain only about a dozen vertical points and ERA5 records only slightly more than 30 pressure levels. In particular, the lidar observations resolve short-lived ozone descent structures occurring on sub-hourly (approximately 30 min) to 1-2 h, as discussed in Section 3.1. This capability is particularly valuable for detecting and analyzing transient cross-tropopause ozone transport events."

Changes in manuscript:

The corresponding revisions are highlighted in yellow in Lines 183-187 of the revised manuscript.

Comments and Suggestions #13

Figure 3: An explanation of the inserts RAYLEIGH, RAMAN and MIE/RAYLEIGH is missing in the caption.

Our Response:

Thank you for pointing this out. We agree that the labels "RAYLEIGH," "RAMAN," and "MIE/RAYLEIGH" in Fig. 3(a) were not adequately explained in the original caption. We have therefore revised the caption to define these labels and clarify the backscatter-detection schemes and wavelength channels associated with the different ozone-profile segments.

Specifically, "MIE/RAYLEIGH" denotes the elastic Mie and Rayleigh backscatter signals at 289 and 299 nm used for the tropospheric ozone measurements; "RAYLEIGH" denotes the elastic Rayleigh backscatter signals at 308 and 355 nm used for the stratospheric ozone measurements; and "RAMAN" denotes the N_2 vibrational Raman backscatter signals at 332 and 387 nm, corresponding to excitation at 308 and 355 nm, respectively. The associated wavelengths have also been specified in the revised figure caption.

Changes in manuscript:

The corresponding revisions can be found in Lines 190-194 of the revised manuscript.

Comments and Suggestions #14

Lines 160-161: What justifies to name these ozone features as representing downward transport? With one exception I see just modulations of the tropopause. At this point I would just describe the observations and then relate them to the analysis if this really yields a proof of vertical transport and not just tropopause dynamics (which would be interesting as well).

Our Response:

Thank you for this important comment. We would first like to clarify that our interpretation of STE refers to the overall ozone episode spanning 18-19 October, rather than to each individual short-lived feature. The blue and orange arrows indicate the downward evolution and subsequent recovery of the ozone-enhanced structure, respectively. Considering the duration and vertical extent of this episode, together with the dynamical and flux evidence presented later in the manuscript, we interpret the overall event as an STE/STT event. No comparable episode was identified in the other available lidar observations during that month.

Nevertheless, we agree that the original manuscript interpreted the lidar-observed ozone features as downward transport too early in the analysis. A downward displacement of an ozone-enhanced structure in a time-height cross-section alone is not sufficient to demonstrate irreversible cross-tropopause transport, because such an apparent displacement may also result from temporal variations or undulations of the tropopause.

Following the reviewer's suggestion, we have revised Section 3.1 to distinguish clearly between the direct lidar observations and their subsequent dynamical interpretation. In the revised manuscript, we first describe the evolution of the ozone field in Fig. 4 strictly in observational terms. Specifically, the ozone-enhanced structure on 18 October is described as exhibiting a downward displacement in the time–height cross-section, whereas the structure on 19 October exhibits an overall upward displacement. Similarly, the short-lived features T0-T6 are now described as "short-lived downward-displacement episodes of ozone-enhanced structures" rather than as individual "downward-transport events."

We have also explicitly stated that, at this stage of the analysis, these features are interpreted only as vertical displacements of ozone-rich structures near the tropopause. Whether they represent irreversible cross-tropopause transport or primarily reflect displacement or undulation of the tropopause is subsequently assessed using the dynamical and flux diagnostics presented later in the manuscript. Accordingly, our interpretation of the overall event as stratosphere-to-troposphere transport is not based solely on the apparent downward displacement in the lidar observations. It is supported by the combined analysis of the ERA5 meteorological fields, tropopause evolution, Wei cross-tropopause mass-flux diagnosis, the spatial relationship between the diagnosed mass flux and tropopause folding, and the estimated cross-tropopause ozone flux. We therefore no longer treat each individual T0-T6 feature as direct evidence of irreversible vertical transport.

We thank the reviewer for this suggestion, which helped us distinguish more clearly between the directly observed ozone variability and its subsequent dynamical interpretation.

Changes in manuscript:

The corresponding revisions are highlighted in yellow in Lines 208-228 of the revised manuscript.

Comments and Suggestions #15

Fig. 4: Please, explain the arrows.

Our Response:

Thank you for pointing this out. Although the meanings of the arrows were described in the corresponding discussion in Section 3.1, we agree that the figure caption should be self-contained. The blue arrow in Fig. 4(a) indicates the observed downward displacement of the ozone-enhanced structure on 18 October, whereas the orange arrow in Fig. 4(b) indicates the overall upward displacement of the ozone-enhanced structure during its subsequent evolution on 19 October.

Changes in manuscript:

We have added an explicit explanation of both arrows to the caption of Fig. 4. The corresponding revisions can be found in Lines 221-224 of the revised manuscript.

Comments and Suggestions #16

Line 164: "Previous studies have given limited attention to such events." This remark is important! It also would also be valid for features e.g. caused by tropopause oscillations.

Our Response:

Thank you for this insightful comment. We agree that, in the original manuscript, the term "such events" could be interpreted too narrowly as referring specifically to short-lived downward-transport events. As noted in our response to the preceding comment, the lidar observations alone do not establish that each of the T0-T6 features represents irreversible cross-tropopause transport.

We have therefore revised this discussion to refer more generally to short-lived ozone structures near the tropopause and to explicitly acknowledge that rapid tropopause oscillations or undulations can also produce apparent vertical displacements of ozone-rich layers. We agree with the reviewer that these short-timescale features are scientifically relevant regardless of whether they ultimately reflect irreversible transport, tropopause dynamics, or a combination of the two.

The revised text reads: “Previous studies have given comparatively limited attention to such short-lived ozone structures near the tropopause. Importantly, these features should not necessarily be interpreted as individual cross-tropopause transport events, since rapid tropopause oscillations or undulations may also produce apparent vertical displacements of ozone-rich layers. Their repeated occurrence on sub-hourly to hourly timescales nevertheless provides a useful observational perspective on fine-scale ozone variability and tropopause dynamics. The relationship of these features to tropopause variability and cross-tropopause transport is examined further using the temperature, dynamical, and flux diagnostics presented below.”

Changes in manuscript:

The corresponding revisions can be found in Lines 228-234 of the revised manuscript.

Comments and Suggestions #17

Line 253: USSA1976 model

Line 253: Please, specify USS1976 and add a reference.

Our Response:

Thank you for pointing this out. In the revised manuscript, we have clarified both the full name and the role of USSA1976 in the temperature-retrieval procedure. Specifically, USSA1976 refers to the U.S. Standard Atmosphere 1976. The temperature specified by this standard atmosphere at 50 km was adopted as the upper-boundary reference for the Raman temperature retrieval, and the temperature profile was subsequently retrieved downward from this reference altitude. The corresponding reference to the U.S. Standard Atmosphere 1976 has also been added to the reference list.

Changes in manuscript:

The revised text reads: “The temperature retrieval, shown in Fig. 8(b), was initialized at 50 km using the temperature from the U.S. Standard Atmosphere 1976 as the upper-boundary reference (U.S. Standard Atmosphere, 1976), and the temperature profile was subsequently retrieved downward from this reference altitude.” The corresponding revision can be found in Lines 343-345 of the revised manuscript.

Comments and Suggestions #18

Figs. 9 and 10: What does the red asterisk mean? Please, add information on the method to the caption.

Our Response:

Thank you for pointing this out. The meaning of the red symbol and the method used to calculate the cross-tropopause mass flux were already described in the main text, but we agree that this information should also be included in the figure captions so that the figures can be interpreted independently.

We have therefore revised the captions of Figs. 9 and 10 to clarify that the red asterisk marks the location of the USTC Ozone Lidar at Yangbajing (29°N, 99°E). We have also added that the cross-tropopause mass fluxes were diagnosed using Wei’s formulation together with ERA5 meteorological fields, and that the displayed fields represent 6-h means of the instantaneous mass flux over the corresponding time intervals. For Fig. 9, the individual contributions from tropopause motion, horizontal advection, and vertical motion, as well as the total mass flux, are now explicitly identified in the caption.

Changes in manuscript:

The corresponding revision can be found in Lines 387-389 and 433-435 of the revised manuscript.

Comments and Suggestions #19

Line 209: How did you determine the temperature lapse rate for all times?

Our Response:

Thank you for this question. We apologize that the calculation procedure was not described sufficiently clearly in the original manuscript. In this study, the temperature lapse rate and the corresponding thermodynamic tropopause were determined independently at each available ERA5 time step, rather than deriving them from a single time and extrapolating the results to other times. Specifically, for each ERA5 time step, the temperature lapse rate was calculated from the corresponding vertical temperature profile, after which the WMO lapse-rate criterion was applied to identify the thermodynamic tropopause.

Changes in manuscript:

We have clarified this calculation procedure in Lines 241-245 of the revised manuscript.

Comments and Suggestions #19

Line 220: PV is derived from model analyses. How can you expect that the models match your rather detailed observations? See line 248.

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions. We agree that, because of the substantial difference in spatial and temporal resolution, the ERA5-derived potential-vorticity (PV) fields cannot be expected to reproduce the short-lived, fine-scale ozone structures resolved by the lidar. It was not our intention to imply a point-by-point or event-by-event correspondence between the ERA5 PV fields and the individual lidar-observed features. We have clarified this point in the revised manuscript.

In this study, the ERA5-derived PV fields and the lidar observations serve different but complementary purposes. The lidar provides local, high-spatiotemporal-resolution observations of the evolution of ozone structures near the tropopause. In contrast, the ERA5-derived PV fields provide an observation-constrained and dynamically consistent description of the regional-scale atmospheric environment. They are used to define the dynamical tropopause, characterize the broader dynamical evolution of the STE event, and provide the framework required for the subsequent cross-tropopause mass-flux diagnosis. Accordingly, the PV-threshold analysis in Section 3.2 is intended to identify a physically reasonable dynamical-tropopause definition for the regional flux calculation, rather than to reproduce the individual short-lived features T0-T6 observed by the lidar.

This distinction is also consistent with the discussion around Line 248 of the original manuscript. The hourly ERA5 fields are suitable for characterizing the event-scale evolution of the tropopause, the regional tropopause-folding structure, and the associated cross-tropopause transport during this approximately one-day STE event. They cannot, however, resolve all of the sub-hourly to hourly variability detected by the lidar. For this reason, the individual short-lived ozone features are not interpreted solely on the basis of the ERA5-derived PV fields. Instead, their detailed temporal evolution is examined independently using the high-resolution lidar observations, including the temperature profiles retrieved from the simultaneously measured 387-nm N_2 vibrational Raman return. For the reviewer's reference, we show below the diagnosed cross-tropopause mass-flux field for 17 October. This figure is provided only in the present response and has not been added to the revised manuscript. Before the event observed on 18-19 October, neither the ERA5-based flux diagnosis nor the available lidar observations indicated pronounced cross-tropopause activity. In contrast, from 18 October onward, both datasets captured the onset and evolution of the STE event illustrated in Fig. 4. Thus, the ERA5-based diagnosis and the lidar observations consistently identify the occurrence and overall timing of the event at the event scale, while the lidar additionally resolves the finer vertical and temporal structures embedded within the event.

Our analysis therefore considers two complementary spatial and temporal scales. ERA5/PV provides the regional dynamical framework and the cross-tropopause flux diagnosis used to identify and interpret the overall STE/STT event, whereas the lidar resolves the local fine-scale ozone and temperature variability embedded within that larger-scale event. We have revised the manuscript to make this distinction explicit and to avoid suggesting that the ERA5-derived PV fields should reproduce the detailed lidar observations.

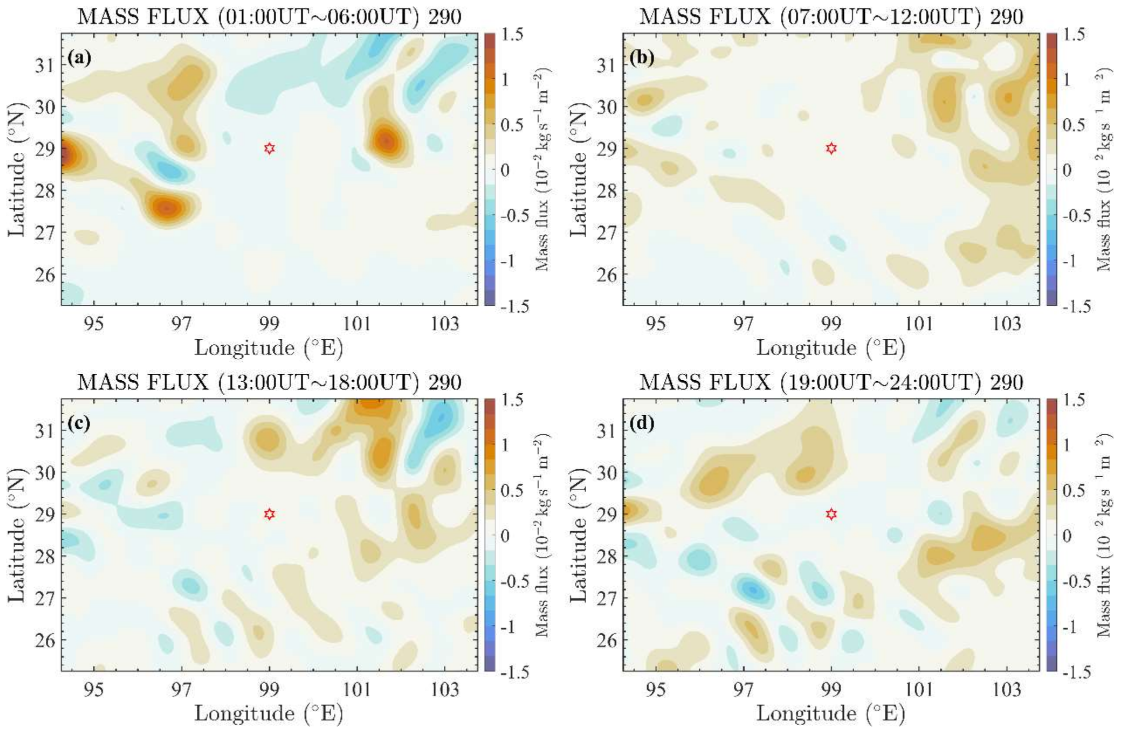

Figure.response19: The diagnosed cross-tropopause mass-flux field for 17 October

Changes in manuscript:

The corresponding revisions can be found in Lines 291-298 and 336-339 of the revised manuscript.

Comments and Suggestions #20

Fig. 7: Consider moving the data to line 1 of the caption since it seems to be representative for all panels.

Our Response:

Thank you for this suggestion. We agree that the date applies to the figure as a whole and is more appropriately stated at the beginning of the caption. We have therefore moved the date to the first line of the Fig. 7 caption and revised the descriptions of the individual panels accordingly.

Changes in manuscript:

The corresponding revision can be found in Lines 321-324 of the revised manuscript.

Comments and Suggestions #21

Lines 242-243: How accurate is this theoretical wind field? Does it represent the observations?

Our Response:

Thank you for this important comment. We would like to clarify that the wind fields used in this study were obtained from the ERA5 reanalysis rather than from a purely theoretical model. Because the lidar system did not provide simultaneous real-time wind measurements during the observation period, ERA5 served as an appropriate alternative source of wind information for the present analysis. ERA5 assimilates a wide range of atmospheric observations and provides observation-constrained, dynamically consistent three-dimensional meteorological fields (Hersbach et al., 2020). In the present study, the ERA5 wind fields are used at the regional dynamical scale to characterize the atmospheric circulation and to provide the horizontal and vertical wind components required for Wei's cross-tropopause mass-flux diagnostic. We neither expect nor require the ERA5 fields to reproduce every short-lived, fine-scale structure resolved by the lidar. Rather, the two datasets serve complementary purposes: the lidar provides local observations of ozone variability at high spatial and temporal resolution, whereas ERA5 supplies the observation-constrained three-dimensional dynamical fields required for the regional-scale analyses of the tropopause structure and cross-tropopause fluxes.

Figure 5 shows that ERA5 captures the overall onset and recovery of the event and agrees well with the lidar in the magnitude and temporal evolution of ozone near the tropopause. Although this does not directly validate the ERA5 wind fields, it supports the applicability of ERA5 to the event-scale analysis.

Changes in manuscript:

We have revised the corresponding text to clarify the nature and specific role of the ERA5 wind fields in the present analysis. The relevant revisions can be found in Lines 326-330 of the revised manuscript.

Comments and Suggestions #22

Lines 278-279: Again: How accurate is the tropopause?

Our Response:

Thank you for raising this important point again. The dynamical tropopause is a diagnostically defined transition surface rather than a directly observed boundary with a uniquely determined geometric height. Its diagnosed position depends on the selected PV threshold and the spatial resolution and structure of the meteorological fields. Therefore, an absolute vertical accuracy cannot be assigned from the available observations.

To evaluate this uncertainty, we explicitly tested the sensitivity of the diagnosed cross-tropopause transport to a range of commonly used PV thresholds. As shown in Fig. 6, lower thresholds produce larger upward and downward fluxes, whereas higher thresholds produce substantially smaller fluxes. We further examined the spatial continuity of the corresponding PV surfaces in the zonal and meridional cross-sections in Fig. 7(a-b). The lower-PVU surfaces are discontinuous in some regions,

while their continuity and stability improve markedly for thresholds of 2 PVU and above.
Based on both the flux-sensitivity results and the spatial continuity of the PV surfaces, we adopted 3 PVU as a physically reasonable and representative dynamical-tropopause threshold for this event, rather than as a universally optimal or uniquely defined value. The uncertainty associated with the tropopause definition is therefore addressed through the PV-threshold sensitivity analysis.

Changes in manuscript:

The corresponding clarification can be found in Lines 315-319 of the revised manuscript.

Comments and Suggestions #23

Line 286: I do not see the typical picture of a tropopause fold; please, explain.
Line 298 (and the following lines): I do not see "tropopause folding", but an oscillating tropopause. In lines 307 and 308 a wave activity is mentioned!

Our Response:

Thank you for these important comments. We would, however, like to clarify that these two phenomena are not mutually exclusive. In a strongly sheared jet-front environment, a regional tropopause fold can coexist with, and be locally modulated by, inertia-gravity waves and associated tropopause oscillations. Thus, the presence of an oscillating tropopause or wave activity does not, by itself, exclude the existence of a regional tropopause fold.
Our identification of the fold is based primarily on the regional potential-vorticity (PV) structure rather than on the short-period oscillations observed near the lidar site. Over approximately 25-28°N and 95-99°E, the regional PV field exhibits pronounced deformation of the dynamical tropopause and a downward intrusion of high-PV stratospheric air toward the troposphere. The corresponding high-PV intrusion can also be identified in the zonal PV cross-section near 26°N in Fig. 7. Moreover, the spatial extent of this structure is consistent with the region of enhanced cross-tropopause mass flux diagnosed in Figs. 9 and 10. Therefore, the basis for identifying a regional tropopause-folding system is the combination of the downward-reaching high-PV structure and the dynamically consistent cross-tropopause flux, rather than the short-period oscillations of a single tropopause contour.
To strengthen the robustness of the flux diagnosis, we also revised the numerical implementation of Wei's formulation. Eulerian diagnostics applied directly in pressure coordinates can be affected by numerical cancellation among individually large terms, potentially introducing substantial uncertainty into cross-tropopause flux estimates (Wirth, 1995; Wirth and Egger, 1999). Lagrangian trajectory-based approaches provide an alternative that is generally less susceptible to this cancellation problem and has been widely applied in global and large-domain studies of cross-tropopause transport (e.g., Wernli and Bourqui, 2002; Škerlak et al., 2014). For the present event-based regional analysis, however, we retained Wei's diagnostic framework because it allows the flux to be explicitly decomposed into contributions from tropopause motion, horizontal advection, and vertical motion. Rather than applying the formulation directly in pressure coordinates, we transformed it into potential-vorticity coordinates and performed the calculation within the PV-coordinate framework. The revised results are presented in Fig. 10. Although this transformation does not eliminate all sources of uncertainty, it reduces the numerical sensitivity and part of the noise associated with cancellation among large terms. The corresponding methodological clarification is provided in Lines 392-400 of the revised manuscript.
We agree with the reviewer that pronounced tropopause oscillations are also present. These oscillations occur on shorter spatial and temporal scales and can be superimposed on the larger-

scale folding structure. This interpretation is supported by previous observational studies showing that tropopause folds in strongly sheared jet-front environments can be accompanied by inertia-gravity waves, wave breaking, turbulence, and related dynamical instabilities. Cho et al. (1999), for example, directly observed gravity-wave breaking and dynamical instabilities within tropopause folds and showed that these processes can contribute to irreversible stratosphere-troposphere exchange. Similarly, Bertin et al. (2001), using a combined network of ST radars, temperature lidar, and ozone lidar, observed turbulent and stability structures during a tropopause-folding event that were consistent with unstable inertia-gravity waves generated in the jet-stream environment. The broader STE literature also recognizes tropopause folding and wave breaking as dynamically related processes that can jointly contribute to cross-tropopause exchange (Stohl et al., 2003).

Accordingly, the wave activity discussed later in the manuscript is not intended as an alternative explanation that rules out tropopause folding. Our interpretation is that the regional tropopause-folding system provides the larger-scale dynamical background, whereas gravity-wave activity produces shorter-timescale oscillations and local deformation of the tropopause and may further promote mixing and exchange. In other words, the regional high-PV intrusion is interpreted as the folding structure, while the oscillating tropopause noted by the reviewer represents shorter-scale wave-related modulation superimposed on that structure.

We have revised the manuscript to make this scale distinction and the diagnostic basis of the fold interpretation more explicit. The regional PV signature used to identify the fold and its relationship to the diagnosed mass flux are now described more clearly, while the shorter-timescale variations near the lidar site are characterized as wave-related tropopause oscillations superimposed on the evolving regional folding system. Relevant references have also been added to support this interpretation (Cho et al., 1999; Bertin et al., 2001; Stohl et al., 2003).

Changes in manuscript:

The corresponding revisions can be found in Lines 378-385 and 392-400 of the revised manuscript. The updated Fig. 10, recalculated using Wei's diagnostic reformulated in potential-vorticity (PV) coordinates, is presented below for reference.

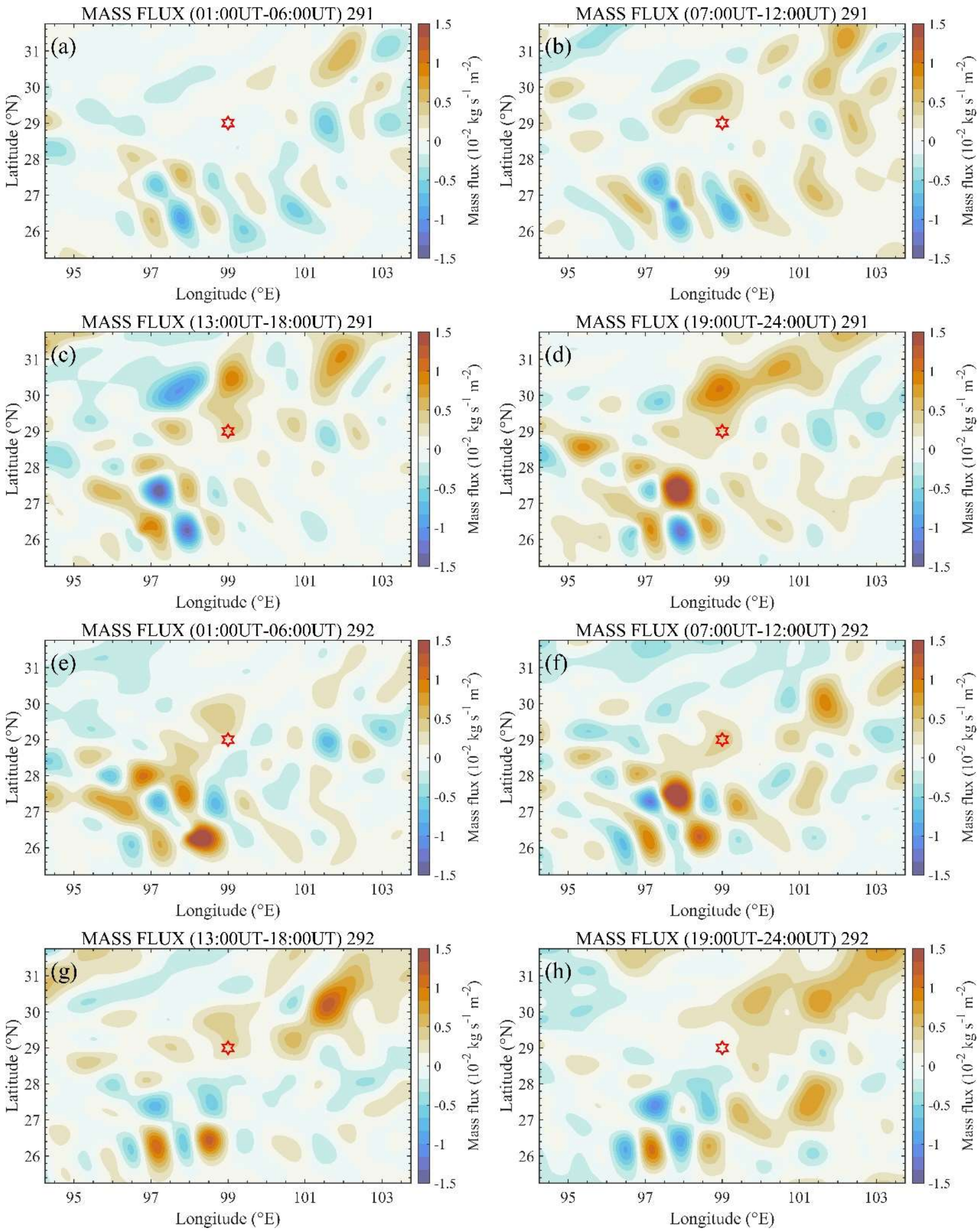

Figure 10: Spatiotemporal evolution of the cross-tropopause mass flux during 18-19 October 2017, diagnosed using Wei's formulation and ERA5 meteorological fields. Each panel shows the 6-h mean of the instantaneous cross-tropopause mass flux for the corresponding time interval. The red asterisk marks the location of the USTC Ozone Lidar at Yangbajing (29°N, 99°E).

Comments and Suggestions #24

Lines 328-331: Does this include the non-zero ozone-density gradients in the measured profiles?

Our Response:

Thank you for this question. We recognize that the term "uniform mixing ratio" used in the original description of Eq. (3) was misleading and could incorrectly suggest that ozone was assumed to be vertically constant within each layer.

In the actual calculation, $q(p)$ represents the pressure-dependent ozone mixing ratio derived from the lidar-measured ozone number-density profile, rather than a vertically uniform value. The complete $q(p)$ profiles within the 3-km layers immediately below and above the tropopause are integrated separately and normalized by their respective pressure intervals to obtain representative layer-mean ozone mixing ratios. Consequently, the observed vertical variability of ozone within each layer, including the effects of non-zero ozone gradients, is retained in the calculated layer means and therefore influences the resulting ozone-flux estimates.

To be precise, Eq. (3) does not contain a separate ozone-gradient term; instead, the effect of the measured vertical gradient is incorporated through the integration of the full pressure-dependent ozone profile. We have revised the explanation of Eq. (3) accordingly and removed the misleading expression "uniform mixing ratio."

Changes in manuscript:

The corresponding revisions can be found in Lines 438-453 of the revised manuscript.

Style

Comments and Suggestions #25

Line 20: what does the tilde mean? Consider revising. See also Figs. 7, 9 and 10.

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions. The tilde symbol (~) was intended to indicate a numerical range rather than an approximation. We agree that this notation is ambiguous and have therefore replaced it with an en dash throughout the manuscript. For example, the ozone-flux value previously written as "3~4 × 10^{-10} kg s^{-1} m^{-2}" is now expressed as "(3-4) × 10^{-10} kg s^{-1} m^{-2}."

Changes in manuscript:

We have also checked and revised the corresponding notation in Figs. 7, 9, and 10 to ensure consistency.

Comments and Suggestions #26

Line 75: Again: what does the tilde mean? It is the mathematical symbol for "proportional to" and should not used here.

Our Response:

Thank you for pointing this out. Thank you for pointing this out. The tilde symbol (~) was used in the original manuscript to indicate "approximately" or, in some cases, a numerical range. We agree that this notation is potentially ambiguous and is not appropriate in this context. We have therefore removed the tilde notation throughout the manuscript.

Changes in manuscript:

Where an approximate value is intended, the symbol has been replaced by the word "approximately" (e.g., "approximately 4,300 m above sea level"). Where a numerical range is intended, the tilde has been replaced. We have also checked the corresponding notation in the figures and captions and revised it consistently.

Comments and Suggestions #27

Line 200: "Jacobian" is not precise. Please, extend.

Our Response:

We thank you for the careful evaluation of our work and for the valuable suggestions. We agree that referring to J_η simply as the "Jacobian" was not sufficiently precise. We have revised the corresponding definition to clarify that $J_\eta = \partial z/\partial \eta$ represents the vertical coordinate-transformation factor relating the generalized vertical coordinate η to geometric height z. This revision makes both the mathematical meaning and the role of J_η in the flux formulation more explicit.

Changes in manuscript:

The corresponding clarification can be found in Lines 272-273 of the revised manuscript.

Comments and Suggestions #28

Line 330: , thereby, Lines 274, 298. 383: , therefore, Line 393: ,but

Our Response:

Thank you for pointing out these punctuation and sentence-structure issues. We have revised the indicated sentences to remove or rephrase the constructions involving "thereby," "therefore," and "but," and have adjusted the punctuation and sentence structure where appropriate to improve grammatical accuracy, clarity, and readability.

Changes in manuscript:

The corresponding revisions can be found in Lines 365-366, 404-405, 438-440, 494-496, and 504-506 of the revised manuscript.

After the modification, we found the reviewer's comments are quite helpful. Once again, we appreciate for your warm work earnestly, and hope that the correction will meet your standards.

Best Regards.

Yours Sincerely,

All authors