
Reply to Referee #1 Report on “Sources and variability of surface ozone over the Tibetan Plateau revealed by in situ observations and EMAC model simulations” by Zou et al. (egusphere-2026-499)

The referee comments are written in this font style and color.

Our answers are written in this font style and color, with the page and line numbers referring to the track-changes version of the revised manuscript.

Changes in the revised version of the manuscript are written in red.

Zou et al. study the causes for the temporal variability of surface ozone over the Tibetan Plateau by combining in situ observations at two sites with the results from a global atmospheric chemistry climate model. The focus is on the time period between 2010 and 2012 for which observations are continuously available at both sites. The model output comes with source-tagged O_3 *tracers to allow for a quantification of contributions to the modeled* O_3 *at the two sites. The major results of this study according to the authors are the capability of the model to capture the observed* O_3 *variability. The* O_3 *variability is mainly attributed to long range transport from tropospheric and stratospheric source regions. The stratosphere is particularly important to explain a spring maximum and this source is related to the location of the subtropical jetstream. During summer tropospheric source regions at mid-to-high latitudes serve as sources for the* O_3 *variability. During the transition time period, i.e., pre-monsoon,* O_3 *abundance is strongly linked to* O_3 *sources in South and Southeast Asia.*

We sincerely thank the reviewer for the constructive comments and suggestions. We have fully considered all the comments and suggestions and made modifications in the revised manuscript.

The authors address an interesting question about which source regions and transport processes contribute most to explain ozone levels at a remote site with negligible local precursor emissions. Such analysis sheds new light in local air pollution. The combination of model and in situ data is a very good choice (i) to show the model capability to add information to a complex question on transport processes in a complex environment and (ii) to put the observations into a broader perspective. The source tagging method is a very good approach to identify potential contributions of various source regions. Consequently, the study addresses a question which is well placed into the scope of ACP. However, I think the authors do not fully use the capabilities of the model for their analysis. More so, I think several explanations lack the necessary depths to comprehensibly address the topic and the discussions are often too descriptive. I will lay out my major concerns in more detail below and recommend major revision at this stage before the manuscript is ready for publication.

We highly value your critical and constructive feedback, indicating that our previous explanations lacked the necessary depth and were overly descriptive. We fully agree with your assessment. To address your overarching concerns and fully utilize the model's capabilities, we have undertaken a major revision of the manuscript, providing deeper physical and chemical mechanistic insights. The most significant improvements include:

1. **Deepening the Stratospheric Mechanism:** We have moved beyond merely using the jet stream position as a proxy. We calculated the Tropopause Fold Frequency based on a 3D labeling algorithm.
2. **Integrating Chemistry and Transport for Tropospheric Sources:** To address the missing links in chemical effects and vertical transport, we added a new quantitative analysis of the net photochemical ozone production rates within the planetary boundary layer (new Figure 6). Furthermore, we explicitly detailed the complete transport pathway (vertical lifting of precursors in source regions followed by 500 hPa horizontal steering) using newly generated longitude-pressure cross-sections.
3. **Contextualizing Tagged Ozone:** We have provided comprehensive relative contribution maps (tagged O_3 / total modeled O_3) in the Supplement, along with the corresponding absolute distribution figures, to ensure readers can accurately assess the significance of each source.
4. **Validating Event Selection and Model Performance:** We clarified the rigorous statistical basis (the 95th percentile threshold) for our event selections. We also evaluated the high-resolution temporal evolution of the model to demonstrate its fidelity in capturing these fast transport processes.
5. **Addressing Interannual Variability:** We acknowledged the limitations of the 3-year study period and added discussions on how large-scale climate modes (e.g., ENSO, QBO) might modulate these transport patterns on longer timescales.

We believe that these substantial additions and structural revisions have fundamentally enhanced the scientific depth, logical rigor, and completeness of our study, thereby fully addressing your major concerns. Please find our detailed, point-by-point responses below.

Major comments :

1. Data analysis time period

The authors focus their analysis on a three year time frame, from 2010-2012. I guess this is based on the availability of the observational data. I think it is always good that -with model data at hand- the authors compare the model with the observational data. But I wonder why the authors limit themselves to this time period. I ask because transport processes which affect inter-annual variability of pollution may depend on large scale patterns such as ENSO or the phase of the QBO. I think it would be at least good to address this topic in the discussion to give *an outlook on whether and if how much such variability on longer time scales could affect the results. This also includes a brief discussion on whether the chosen time period of this study can be regarded as a good representative in terms of average conditions.*

We thank the reviewer for this insightful comment. We agree that large scale patterns such as ENSO and QBO can modulate ozone over the Tibetan Plateau and therefore should be acknowledged when interpreting a three-year study period. The period of 2010-2012 was chosen primarily due to the availability of continuous, simultaneous in-situ observations at both the NMC and PYR stations. Regarding whether this period represents average conditions, it is important to note that 2010-2012 was characterized by persistent La Niña conditions. According to the NOAA Oceanic Niño Index and previous diagnostic studies (Feng et al., 2015), 2010 transitioned from an El Niño into a strong La Niña; 2011 experienced a "second-year cooling" with La Niña re-emerging in the fall after a brief neutral summer; and 2012 transitioned from La Niña to ENSO-neutral conditions. Therefore, our study period largely represents a La Niña-dominated climate state rather than a long-term climatological average. Previous studies have reported that ozone over the Tibetan Plateau exhibits clear interannual signals associated with large-scale circulation variability, including ENSO- and QBO-related changes in the upper troposphere and lower stratosphere. These modes can alter ozone distribution by altering circulation, tropopause structure, and transport pathways, and thus may influence the magnitude of plateau ozone anomalies on multi-year timescales.

In the revised manuscript, we have added a short discussion to clarify that our analysis is based on the observationally available period 2010–2012 and therefore represents a physically meaningful case study, but not a climatological average over all ENSO/QBO phases. We also note that this period should be interpreted with caution because interannual variability may modulate the absolute ozone levels and source contributions to some extent. Nevertheless, the main source-attribution patterns identified in this study are robust because they are derived from the seasonal and synoptic-scale relationships between source tracers, transport, and surface ozone at the two stations. We further state that future work using longer simulations and multi-year observations would be needed to assess the sensitivity of Tibetan Plateau ozone to climate modes changes more comprehensively. We have clarified this point in the revised manuscript (Page 27, Line 29 - Page 28, Line 1 in the track-changes version of the revised manuscript)

It should be noted that the present analysis is limited to the observationally available period of 2010–2012. According to historical sea surface temperature data, this period was characterized by persistent La Niña conditions (Feng et al., 2015). Previous studies have shown that the El Niño-Southern Oscillation (ENSO) and the stratospheric quasi-biennial oscillation (QBO) can strongly influence cross-tropopause transport and tropospheric ozone anomalies (Han et al., 2001; Li et al., 2023; Li et al., 2024), while the 11-year solar cycle contributes to longer-term ozone variations (Xu et al., 2016; Xu et al., 2018a). Future studies employing long-term transient simulations are essential to quantify the impacts of these climate modes on the interannual variability of ozone sources over the TP.

2. Seasonal patterns of surface ozone from the stratospheric sources

First of all, the entire discussion is only centered around the position of the jet as cause for the seasonal differences. However, an important fact which is not mentioned at all is the background ozone in the lower stratosphere. This depends a lot on the stratospheric circulation and particularly on the downwelling in the stratosphere. Said differently, you could have a constant transport from the lower stratosphere into the troposphere, but would get different contributions from the stratosphere to the surface O_3 *due to a varying background* O_3 *in the lower stratosphere. So, an important quantity to look at here would be the ozone at the level of the tropopause or even in the lower stratosphere, both in absolute numbers and the NTST-*O_3 *fraction.*

We sincerely thank the reviewer for this highly insightful and constructive comment. To evaluate the impact of stratospheric background ozone, we extracted the ozone data exactly at the tropopause level in the EMAC model. As shown in Figures A1 and A2 below, we plotted the seasonal distributions of both the absolute NTST-O_3 mixing ratios and their relative contributions (defined as the ratio of NTST-O_3 to the total simulated ozone) at the tropopause. The results clearly demonstrate that both the absolute mixing ratios and the relative contributions of NTST-O_3 at the tropopause reach their annual maximums during spring over the Tibetan Plateau. This elevated background ozone at the tropopause level during spring acts as a source for downward transport, which fundamentally supports and is highly consistent with our conclusion regarding the spring maximum of surface NTST-O_3 over the TP.

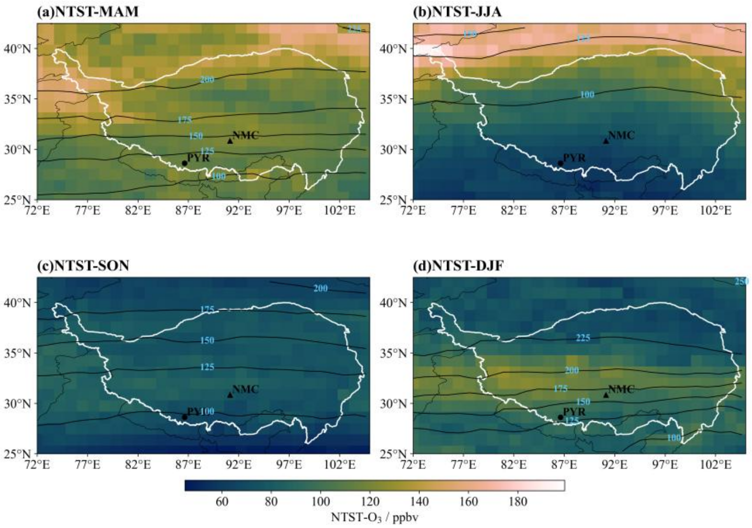

Figure A1. EMAC simulated regional distributions of tropopause NTST-O_3 absolute mixing ratios and tropopause pressure over the Tibetan Plateau in different seasons during 2010 – 2012: (a) Spring, (b) Summer, (c) Autumn, (d) Winter. Color shading denotes NTST-O_3 volume mixing ratio (units: ppbv), and black contour lines represent the tropopause pressure (units: hPa).

White lines refer to the 3 km terrain height contour. Black dots mark the locations of the PYR (circle) and NMC (triangle) stations.

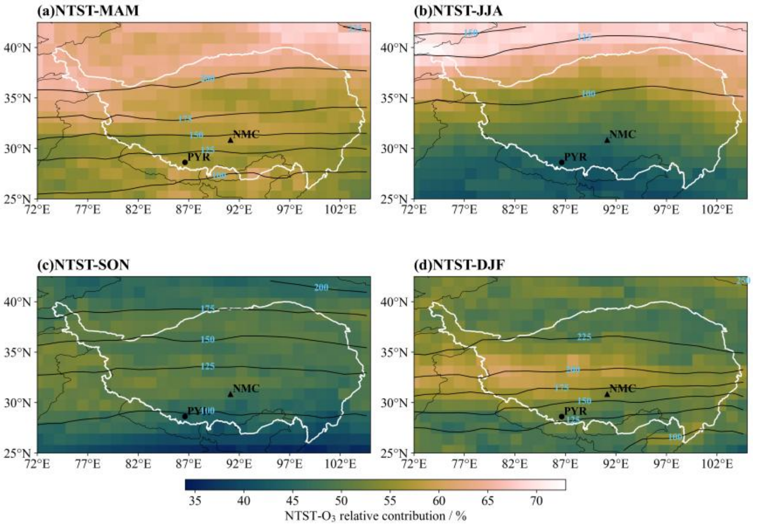

Figure A2. EMAC simulated regional distributions of the relative contribution of tropopause NTST-O_3 to total modelled O_3 and tropopause pressure over the Tibetan Plateau in different seasons during 2010 – 2012: (a) Spring, (b) Summer, (c) Autumn, (d) Winter. Color shading denotes NTST-O_3 relative contributions (units: %), and black contour lines represent the tropopause pressure (units: hPa). White lines refer to the 3 km terrain height contour. Black dots mark the locations of the PYR (circle) and NMC (triangle) stations.

Then the discussion on Rossby waves and downward transport. This discussion is in the current form also too brief. It is simply argued that the position of the jet is the proxyfor the surface NTST-O_3. As mentioned in the text, the wave breaking is the crucial factor and this topic is not addressed in much detail. So instead of the position of the jet, a seasonal distribution showing the location of wave breaking (position, frequency) would be more informative. Or a map of the occurrence of tropopause folding events. From the literature, it is well known that the tropopause folds occur over the Tibetan Plateau but how EMAC represents this is not clear at this point. So, the processes relevant for the stratospheric contribution could be discussed in more detail.

Tropopause Folding Events: To explicitly demonstrate downward transport processes rather than relying on the jet position as a proxy, we calculated the Tropopause Fold Frequency (TFF) using the 3D labeling algorithm refined by Škerlak et al. (2015). We have added the seasonal occurrence maps of tropopause folding events over the Tibetan Plateau to the Supplementary Material (Figure S5) and detailed the methodology in the revised text. In the revised manuscript, we have integrated the analysis of the tropopause fold frequency to comprehensively explain the seasonal variations of surface NTST-O_3.

Page 13, Lines 17-24 in the track-changes version of the revised manuscript.

To quantify dynamical transport processes related to the stratosphere, we calculated the tropopause fold frequency using the 3D labeling algorithm refined by Škerlak et al. (2015). The air masses were classified by detecting multiple crossings of the dynamical tropopause interface, defined by the 2 PVU isosurface and specific humidity threshold (0.1 g/kg). Folds are characterized by their vertical extent (ΔP). In this study, instances with a pressure difference ΔP ≥50 hPa within the interconnected fold grids were cataloged as tropopause folding events to compute the seasonal occurrence frequencies (Figure S5). In spring, the region of maximum tropopause fold frequency is concentrated within the 28°N–34°N latitudinal band, where the occurrence frequency exceeds 35% and reaches a peak of 48% (Figure S5a).

Page 13, Line 29-31 in the track-changes version of the revised manuscript.
In summer (Figure 4b), the subtropical westerly jet shifts northward (Schiemann et al., 2009), with the jet core located on the northern side of the Tibetan Plateau, and the frequent tropopause folding zone migrates to the northern edge of the plateau (Figure S5b).

Page 14, Line 3-5 in the track-changes version of the revised manuscript.
In autumn (Figure 4c), with the southward retreat of the jet stream and the significant decrease in tropopause fold frequency over the plateau (Figure S5c),

Page 14, Line 6-8 in the track-changes version of the revised manuscript.
For the winter 200 hPa wind field (Figure 4d), the jet stream exhibits the strongest intensity during this season, and its center has retreated to the southern Tibetan Plateau, leading to a resurgence of tropopause folding events along the southern edge (Figure S5d), and the NTST-O_3 mixing ratio shows a slight increase compared to that in autumn.

3. Tropospheric sources

The discussion around Fig. 6 and generally in Sect. 5.2.1 highlights seasonal differences of surface O_3 in relation to the seasonal mean 500 hPa wind. I have some issues in seeing the direct connection between the mid-tropospheric wind and surface ozone. I assume the 500 hPa wind represents some sort of "surface" wind over the Tibetan Plateau. However, this is not the case in most other source regions. So, the connection between surface precursor emissions at pressures usually much higher than 500 hPa and the wind at 500 hPa is missing. So how much of these emissions are lifted to the respective altitudes. I can imagine that the authors use the 500 hPa wind as sort of "steering" wind (which is true to some extend for the horizontal transport), but I am missing the vertical component in that discussion. A second point here is chemistry. Although the focus of the paper is on transport, ozone is difficult to interpret without the consideration of chemical effects. At least to the degree to provide some background information on precursor species and their distributions, e.g., through observations of or modeled CO, CH4, NMVOCs. This would help to understand and interpret the O_3 distribution over the Tibetan Plateau.

We completely agree that the 500 hPa wind acts primarily as a "steering" wind and requires a vertical mechanism to lift emissions from the surface to this mid-tropospheric level in the source regions. To verify the transport pathway, we plotted longitude-pressure cross-sections of absolute NHTS-O_3 concentrations alongside vertical-zonal wind vectors across key latitudes (e.g., 27°N, 32.5°N, and 38°N). These cross-sections (Figures A2-A4) clearly illustrate the missing "vertical component": intense convection and updrafts over the highly populated/industrialized source regions lift boundary-layer O_3 and its precursors to the mid-troposphere (e.g., 500 hPa). Once aloft, the 500 hPa winds efficiently steer and transport these air masses horizontally toward the TP. Upon encountering the massive topography of the plateau, large-scale subsidence and terrain-following flows transport O_3 downward to the TP surface.

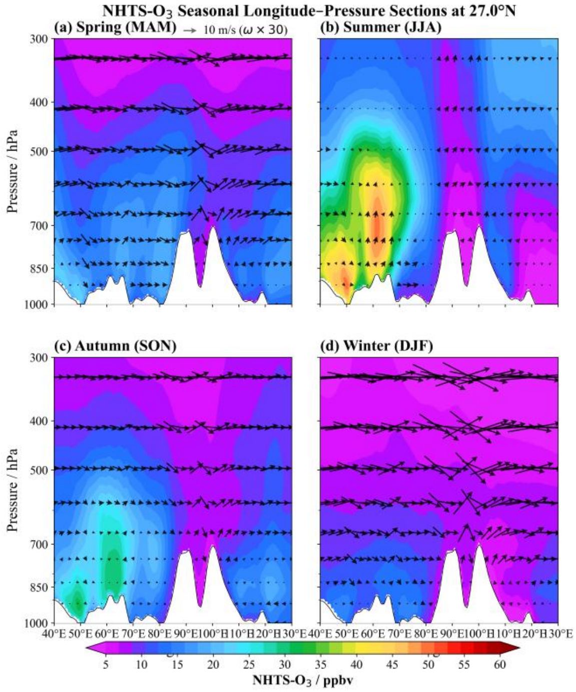

Figure A3 Longitude-pressure cross-sections of NHTS-O_3 absolute values (shading) and vertical-zonal wind vectors along latitudes 27 ° N. The wind vectors are composed of zonal and vertical winds (the vertical wind speeds are scaled for visualization to show flow directions).

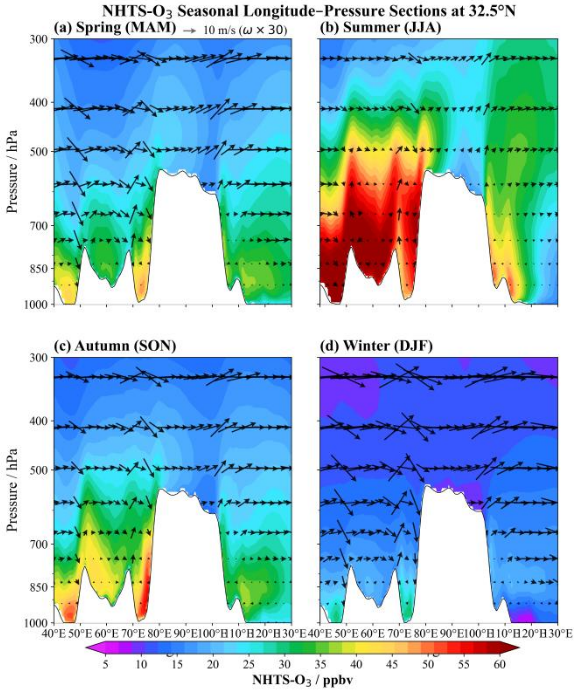

Figure A4 Longitude-pressure cross-sections of NHTS-O_3 absolute values (shading) and vertical-zonal wind vectors along latitudes 32.5°N. The wind vectors are composed of zonal and vertical winds (the vertical wind speeds are scaled for visualization to show flow directions).

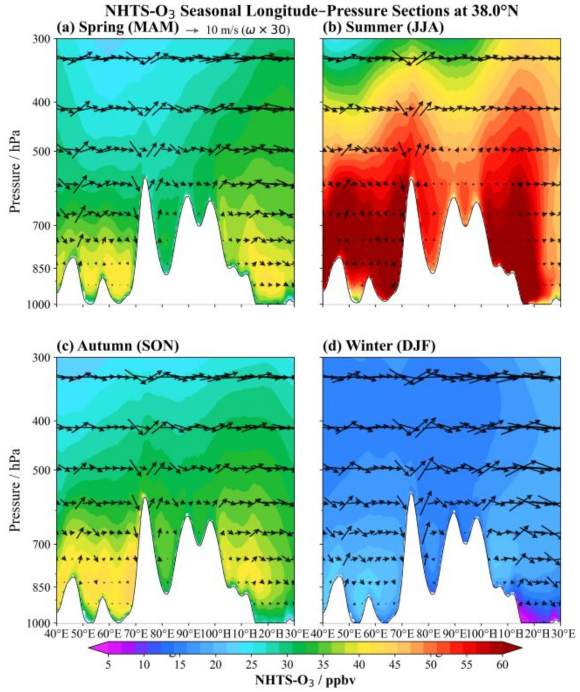

Figure A5 Longitude-pressure cross-sections of NHTS-O$_3$ absolute values (shading) and vertical-zonal wind vectors along latitudes 38°N. The wind vectors are composed of zonal and vertical winds (the vertical wind speeds are scaled for visualization to show flow directions).

To provide the necessary chemical background, we plotted the seasonal spatial distributions of key surface ozone precursors, including CO, NOx, and HCHO (as a proxy for NMVOCs). The distributions clearly demonstrate that while the surrounding regions (East Asia, South Asia, Southeast Asia) are characterized by high precursor concentrations, the Tibetan Plateau remains an extremely pristine environment with low precursor concentrations (Figures A5-A7).

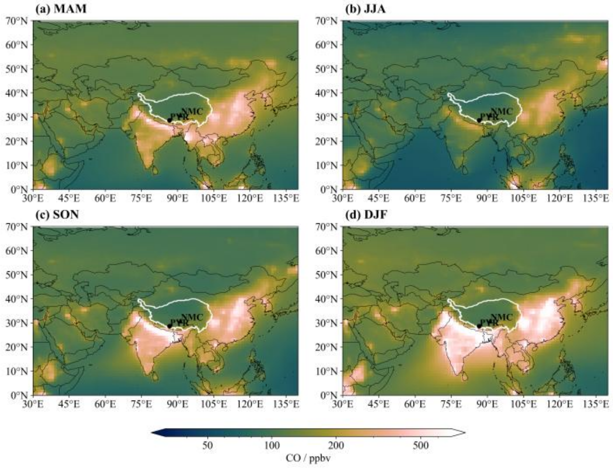

Figure A6 Seasonal spatial distributions of surface carbon monoxide (CO) mixing ratios.

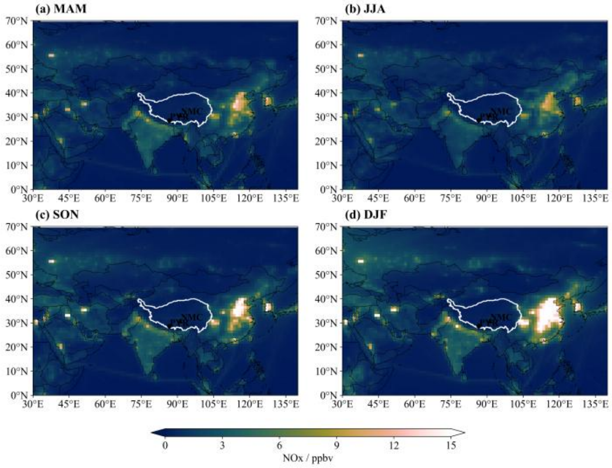

Figure A7 Seasonal spatial distributions of surface nitrogen oxides (NOx) mixing ratios.

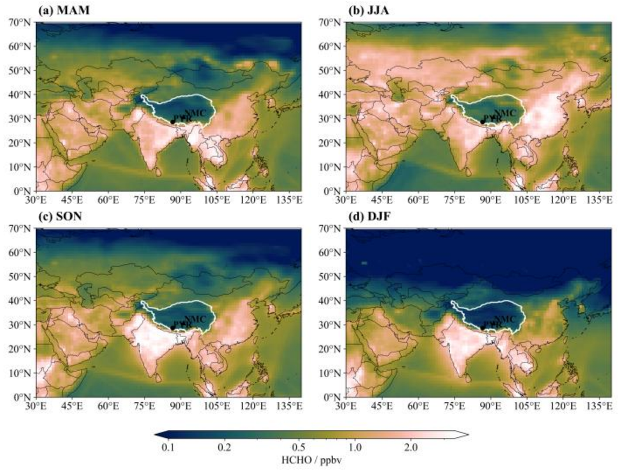

Figure A8 Seasonal spatial distributions of surface formaldehyde (HCHO, a proxy for NMVOCs) mixing ratios.

To further clarify how this chemical environment affects O_3, we calculated the seasonal mean net photochemical ozone production rates (ppbv/day) within the planetary boundary layer and added this as a new figure to the main text (Figure 6 in the revised manuscript). The results reveal intense photochemical O_3 production in the surrounding source regions, whereas the net production over the TP is nearly zero or even acts as a weak sink. This firmly establishes the scientific premise that surface O_3 over the TP is overwhelmingly dominated by long-range transport from external source regions rather than local photochemical generation.

We have carefully integrated these findings into Section 5.2 of the revised manuscript (Page 17, Line 15-30 in the track-changes version of the revised manuscript.)

Figure 6 presents the regional distributions of seasonal mean net photochemical ozone production rates within the planetary boundary layer of Eurasia 30°E-140°E, 0°N-70°N) in different seasons, averaged over the period 2010-2012. A stark spatial contrast is evident across all seasons: the Tibetan Plateau primarily acts as a pristine ozone receptor region, whereas its surrounding densely populated and industrialized areas serve as massive regional ozone sources. In spring (Figure 6a), intense net photochemical ozone production is concentrated in South Asia and Southeast Asia with rates commonly exceeding 20 ppbv/day. In contrast, the net production rate over the entire Tibetan Plateau, including the central and southern plateau where NMC and PYR are located, hovers near zero. In summer (Figure 6b), the photochemical ozone production over Eurasia reaches its annual peak, driven by strong solar radiation and abundant precursor emissions. Extensive areas in southern Central Asia, further West Asia and Europe, East Asia, and South Asia exhibit prominent production rates exceeding 15 ppbv/day. Strikingly, while the surrounding external sources peak, the Tibetan Plateau acts as a weak chemical sink with negative net production rates (ranging from -1 to 0 ppbv/day), though its eastern and northern peripheries show slightly positive values (1-2 ppbv/day). In autumn (Figure 6c), the net photochemical production in the external source regions begins to decline, but South Asia and southern China remain active sources. In winter (Figure 6d), the high net production belt retreats to lower latitudes (South and Southeast Asia), and the boundary layer over the plateau acts predominantly as a weak sink. This persistent absence of local net photochemical generation confirms that surface ozone over the plateau is overwhelmingly transported from external source regions.

Page 18, Line 8-13 in the track-changes version of the revised manuscript.

Strong convective activity and updrafts can lift boundary-layer ozone and its precursors into the mid-troposphere over the source and pollution-plume areas. Once lofted to the mid-troposphere, these ozone-rich air masses are captured by large-scale circulation systems at mid-to-high latitudes and then horizontally advected toward the Tibetan Plateau by broad "steering winds", as shown in the 500 hPa wind fields in Figure 7. Upon encountering the massive topography of the plateau, large-scale subsidence and terrain-following downdrafts ultimately transport ozone generated from external source regions down to the surface layer of the Tibetan Plateau.

4. Tagged and total O_3

The discussions in the analysis sections 4 and 5 mainly focus on the tagged O_3. Although this is more a technical comment I put this under major because it affects large parts of the manuscripts and several figures. A lot of the discussions are made based on the tagged O_3 and in particular the figures show only this tagged O_3. I would like to have a reference on how much the tagged O_3 is compared to the total O_3 in these figures (essentially Figures 4 and following). So, the discussion and interpretation would generally benefit from absolute references to total modeled O_3 or relative contributions (tagged/total). I am aware that this is presented in Figure 3 and in some places discussed in the text, but I think the readers would value if this is put in more context in the other figures as well.

We agree with the reviewer in that providing the relative contributions would enhance the reader's understanding of the significance of each source. To address this without overly lengthening the main manuscript, we have generated a series of new figures showing the spatial and temporal distributions of the relative contributions (ratio of tagged O_3 to total modeled O_3) corresponding to all absolute distribution maps and cases shown in Figure 4 and afterward. These new figures have been added to the Supplement as Figures S4 and Figures S6-S10. Furthermore, we have added explicit reference sentences in the main text (Sections 4 and 5) to guide readers to these supplementary figures. This approach provides the necessary context for total ozone levels while maintaining a focused discussion on the transport mechanisms of the tagged tracers.

We have added references to figures showing the relative contributions in the Supplement throughout Sections 4 and 5.

Page 13, Line 5-6 in the track-changes version of the revised manuscript. The corresponding distributions of the relative contribution of surface NTST-O_3 to total modelled O_3 are provided in Figure S4 in the Supplement.

Page 15, Line 12-15 in the track-changes version of the revised manuscript. The temporal variations in the relative contribution of NTST-O_3 to total modelled O_3 during this event are illustrated in Figure S6 in the Supplement.

Page 18, Line 15-16 in the track-changes version of the revised manuscript. The relative contributions of NHTS-O_3 to total surface ozone are shown correspondingly in Figure S7 in the Supplement.

Page 20, Line 2-3 in the track-changes version of the revised manuscript. For reference, the corresponding relative contributions of TRTS-O_3 to total modelled O_3 are presented in Figure S8 in the Supplement.

Page 21, Line 12-13 in the track-changes version of the revised manuscript. The relative contributions of tagged O_3 from these two sources to total modeled ozone along the same cross-section are detailed in Figure S9 in the Supplement.

Page 24, Line 1-2 in the track-changes version of the revised manuscript. The spatial patterns of the relative contribution of NHTS-O_3 to total modelled O_3 during this episode are provided in Figure S10 in the Supplement.

Page 24, Line 20-21 in the track-changes version of the revised manuscript. The relative contribution of TRTS-O_3 to total modelled O_3 during this transport event is presented in Figure S11 in the Supplement to contextualize its impact.

5. Presentation of the events

Sect. 5.1.2 and Sect. 5.2.3 focus on the presentation of so called events, that is time periods of enhanced O_3 *and its variability at the two observational sites. I like the general idea of including these discussions because they provide more insight on the process level. However, I would like to have more information on these events and why they have been picked. Are these common events? How frequent do such events occur? Do the ones shown differ significantly from other, similar events? And also I would like to have more visual context here: a time series at the observational sites for the respective event as well as comparison with the model, at least to see how good the model performs here? In total, the events are a little bit too descriptive with too little background information and the analysis could go further in terms of temporal evolution and model performance analysis. For the troposphere, I also would like to have some more information on precursor emissions and chemical evolution during the transport.*

We sincerely thank the reviewer for appreciating the process-level discussion and for these insightful suggestions. We agree that providing clear justification for the event selection and demonstrating the model's performance during these specific periods is essential.

(1) Event Selection Criteria and Frequency:

To address your concern regarding why these events were picked and their frequency, we have clarified the selection criteria in the revised manuscript. These events are not isolated anomalies but represent the most robust transport episodes. Specifically, they were selected because both the absolute mass contribution and the relative percentage contribution of the respective tagged source (NTST-O_3, NHTS-O_3, or TRTS-O_3) exceeded the 95th percentile for the entire 2010-2012 period. Events of this magnitude represent the upper extreme of typical transport pathways that occur regularly during their respective peak seasons. The criteria for event selection have been explicitly specified in the revised manuscript.

Page 15, Line 13-15 in the track-changes version of the revised manuscript. This event was specifically chosen because both the absolute and relative contributions of NTST-O_3 at the sites exceeded the 95th percentile for the 2010 – 2012 period, representing a robust stratospheric intrusion.

Page 24, Line 2-3 in the track-changes version of the revised manuscript. This episode corresponds to a predominant-contribution period (above the 95th percentile) for NHTS-O_3 on the southern plateau.

Page 24, Line 21 in the track-changes version of the revised manuscript. This episode corresponds to a predominant-contribution period (above the 95th percentile) for TRTS-O_3 at the southern plateau.

(2) Visual Context and Model Performance (Time Series):

We completely agree that evaluating the model's temporal evolution during these events is important. Since a comprehensive evaluation of the modeled vs. observed O_3time series over the entire study period is already presented in Section 3, we opted to provide the high-resolution event time series here in this response letter to avoid redundancy in the main text. Figures A8-A10 below show the daily O_3 time series for the NTST, NHTS, and TRTS events, respectively. In these figures, modeled total surface O_3 closely tracks the observed variations. The EMAC model accurately simulates the physical transport processes and temporal evolution of these events.

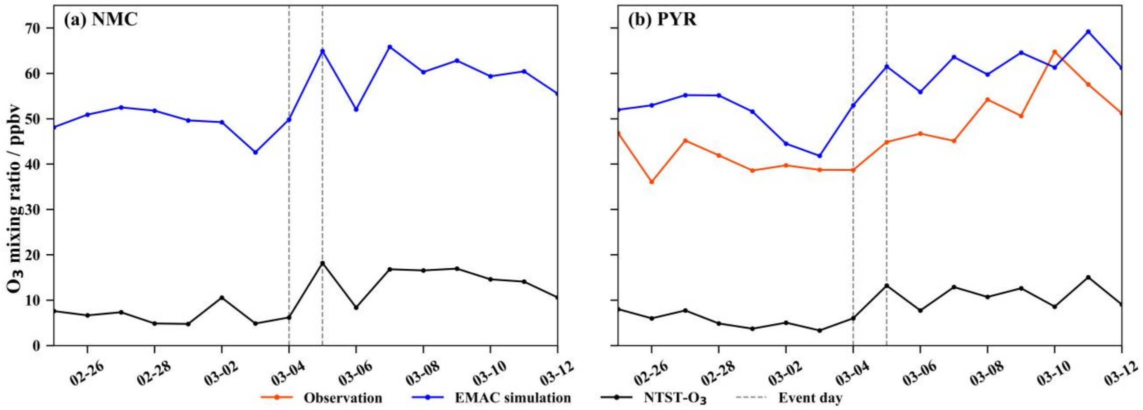

Figure A9 Time series of observed surface O_3, modeled total surface O_3, and surface NTST-O_3 at NMC and PYR stations during the stratospheric intrusion event of 4-5 March 2010.

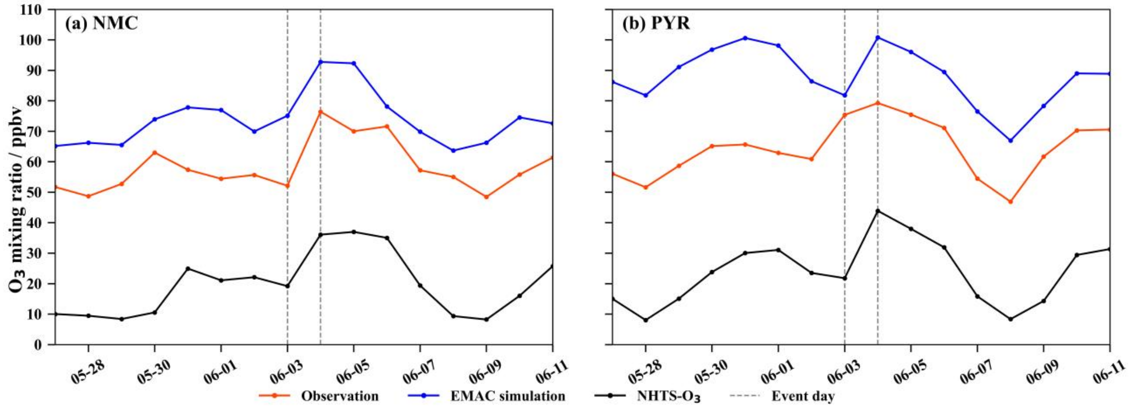

Figure A10 Time series of observed surface O_3, modeled total surface O_3, and surface NHTS-O_3 at NMC and PYR stations during the transport event of 3-4 June 2012.

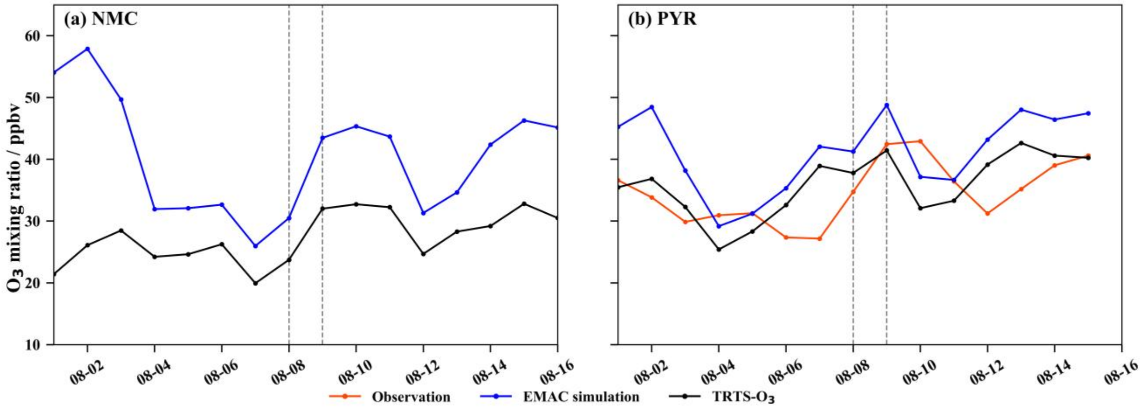

Figure A11 Time series of observed surface O_3, modeled total surface O_3, and surface TRTS-O_3 at NMC and PYR stations during the transport event of 8-9 August 2012.

(3) Precursor Emissions and Chemical Evolution:

Regarding the tropospheric precursor emissions and chemical evolution, we appreciate your perspective. However, as discussed in our response to Comment #3, the local photochemical production of O_3 over the Tibetan Plateau is extremely weak. Furthermore, the primary scope of this study is to quantify the contributions from different stratospheric and tropospheric origins using the EMAC model-coupled ozone source-tracing technique. Detailed analysis of precursor transport and intermediate chemical evolution would significantly expand the scope and dilute the main focus of the current paper. Therefore, we prefer to keep the focus strictly on the source apportionment, and we hope the reviewer supports this structural decision.

Minor comments and technical recommendations (in order of appearance)

General remark: *The manuscript is quite heavy on acronyms. This disturbed my flow of reading at several points and I wonder whether the authors may introduce a table which summarizes the commonly used acronyms.*

We appreciate this constructive suggestion. We agree that the extensive use of acronyms can sometimes hinder the flow of reading. To address this, we have added a new table (Table S1) in the Supplement that summarizes all commonly used acronyms, their full names, and their definitions within the context of this study.

- ***P6, L5:*** *Why has RCP8.5 been chosen? Does this affect the O_3 concentrations substantially?*

The RCP8.5 global emission inventory was selected because it provides a reasonable and widely used representation of anthropogenic emissions for the historical period of 2000-2010. We have added additional information about the selected emission inventory in the revised manuscript (see Page 6, Line 4-11). More detailed information about RCP emission inventories and EMAC model evaluation can be found in the references therein. It should be noted that previous work (e.g., Jöckel et al., 2016) evaluated model's performance in simulating stratospheric and tropospheric ozone focusing on the global and climatological scale. In this study, we investigate ozone variations over the Tibetan Plateau at a synoptic scale.

Emission sources from fossil fuel combustion and biomass burning were simulated based on the Representative Concentration Pathways scenario 8.5 (RCP8.5) inventory (Jöckel et al., 2016). The RCP emission inventories have been used within the global atmospheric chemistry–climate model simulations in support of World Meteorological Organization (WMO)/United Nations Environment Programme (UNEP) ozone and International Global Atmospheric Chemistry (IGAC) climate assessments (Jöckel et al., 2016). The RCP8.5 global emission inventory has a horizontal grid resolution of 0.5° by 0.5° at monthly intervals and vertical distributions as described in Pozzer et al. (2009), and it is a reasonable choice for anthropogenic emissions over the period from 2000 to 2010 (Granier et al., 2011; Pozzer et al., 2015). The monthly RCP8.5 emissions in 2010 are used in this study.

- ***P6, L9:*** *Which reanalysis? ERA5?*

The data used for nudging is the ECMWF operational data, giving high level of accuracy to observational data.

- **P6, L12:** *What is the temporal sampling of the model data at the two sites? 6 minutes? This is important for the interdaily variability comparison discussion.*

The simulation results were output at one-hour intervals for analysis. We have added this information to the revised manuscript (Page 6, Line 18).

- **P6, L20:** *Why are 14 source regions defined (all with an individual acronym) and then only 3 used? Maybe for the sake of claritify, just say that there are originially 14 which have been lumped into three source regions for the analysis.*

As suggested, we have moved the parts that describe detailed ways of lumping these 14 source regions in the main text to the Supplement.

- **P6, L 30 ff:** *Why do you start your discussion with the interdaily variability? Maybe start with a more general description of the observations. So, it is more difficult to put the variability into context to the absolute values.*

We have carefully considered the reviewer's suggestion regarding the discussion order. We chose to start with interdaily variability because it represents a more rigorous test of the model's process-level capability. Capturing the high-frequency "pulses" and daily fluctuations is a prerequisite for ensuring that the simulated seasonal cycles and absolute values are robust and physically grounded.

- **P 7, L 3-5:** *A correlation coefficient (why coefficient is used here?) of 0.72 leads to a coefficient of determination of smaller about 0.5 which is in my opinion not very large and I would even argue that the model should be able to simulate the O3 at the sites with this "precision" to make any valid comparisons.*

We thank the reviewer for this critical comment regarding the statistical robustness of our model evaluation. Regarding the magnitude of $R = 0.72$ ($R^2 \approx 0.52$), we agree that in an idealized setting, a higher R^2 is always preferred. However, in the context of global atmospheric chemistry modeling over the Tibetan Plateau (TP), an R value of 0.72 is generally considered to represent a high level of agreement. The TP presents unique challenges due to its complex topography, which leads to significant subgrid-scale variability in meteorology and transport processes that 1.125° × 1.125° global models cannot fully capture. Our model (EMAC) successfully captures the dominant seasonal cycle and the day-to-day variability driven by large-scale circulation, which is the primary focus of our source attribution analysis. Given that the model reproduces the observed O_3 phases and seasonal transitions accurately at NMC, we believe the simulation provides a sufficiently valid basis for investigating the broad source-receptor relationships.

- **P8, L1-3:** *Do you have an explanation why the model has a bias to the observations? Or more precisely, what are the major causes of the deviations which you report? Is it an interpolation artifact or does this point to a more general issue?*

We have added a paragraph discussing about the causes of the deviations in the revised manuscript (Page 8, Line 19-25)

The persistent positive bias at PYR indicates that the model tends to overestimate surface O_3 over the southern Tibetan Plateau, particularly during late spring and early summer when stratospheric influence and photochemical O_3 formation are strongest. Because the model performance at NMC is much better, the PYR bias is unlikely to arise from a uniform overestimation across the entire Tibetan Plateau. Instead, it likely reflects the difficulty of representing the complex topography, local wind systems, precipitation, and boundary-layer exchange at PYR, as well as potentially underestimated dry deposition (e.g., due to underestimated vegetated surfaces, also because the bias is largest in the growing season). While the bias affects the absolute magnitudes, the simulated seasonal cycles and relative source contributions remain robust. Consequently, we interpret the PYR source contributions as physically meaningful within the current model configuration, while noting that their absolute magnitudes are subject to local terrain uncertainty.

• ***P12, L10:*** *"of the" → "of the"*

Done.

• ***Figures 7, 9, 10:*** *PBL wind: Is this a model based PBL? How deep is the PBL here and well does the model represent the PBL over this complex terrain?*

The PBL wind shown in these figures represents the modeled average wind within the planetary boundary layer. In our EMAC configuration (90 vertical layers from surface to 0.01 hPa), the PBL is typically represented by the bottom ~6 layers. We acknowledge that the PBL depth varies seasonally and diurnally; the model dynamically calculates this depth to reflect the local meteorology. While evaluating the sub-grid scale PBL exchange over such complex terrain is challenging due to the lack of high-resolution vertical profile observations, the model's ability to reproduce surface concentrations and variations (as shown in Sect. 3) suggests that the simulated boundary layer dynamics are reasonably represented for the purposes of this study.

• ***P24, L13:*** *remove "that" at the beginning of the line*

Done.

• ***P25, L14:*** *What is meant with "multi-scale" ?*

The term "multi-scale" was intended to encompass both the spatial and temporal dimensions of our analysis. Spatially, our study covers processes from the large-scale (hemispheric source regions, stratospheric intrusions, and the subtropical westerly jet) to the regional-scale (Asian summer monsoon), and down to the local-scale (mountain-valley circulations and boundary layer dynamics at specific sites like PYR and NMC). Temporally, our analysis spans both seasonal and diurnal (daily) variations. To avoid ambiguity and make our conclusion clearer, we have removed the vague term "multi-scale analysis" and explicitly stated the dimensions we investigated. We have revised the sentence in the manuscript as follows (Page 27, Line 22).

By analyzing ozone variations across multiple spatial and temporal scales,

- ***P25, L14-15:*** *What is the difference between westerly circulation and subptropical westerly jet?*

We have corrected "westerly circulation" to "zonal circulation" in the revised manuscript.

Many thanks!