Dear Editors and Referees:

Thank you very much for your review and comments concerning our manuscript entitled "Impact of stratospheric intrusion on near-surface ozone over the Sichuan Basin in China driven by terrain forcing of Tibetan Plateau" [MS No.: EGUSPHERE-2025-2628]. Those comments are all valuable and helpful for revising and improving the manuscript. We have studied the comments carefully and have accordingly made the revisions. Revised parts are highlighted with Track Changes in the updated manuscript. In the following, we quoted each review question in the square brackets and added our response after each paragraph.

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Response to Referee #1

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Stratospheric intrusion (SI) is a significant contributor to elevated tropospheric ozone levels. As a global hotspot for SI, the surface ozone concentration in the Tibetan Plateau region has garnered attention due to the influence of SI. However, it remains unclear whether ozone pollution in the surrounding low-altitude Sichuan Basin region is also regulated by this process. To address this issue, this study utilized the WRF-Chem model for investigation. The findings contribute to a comprehensive understanding of ozone pollution causes in the region, but I have some comments as below, and I hope this could help author to improve the paper for later submission.

Response: Many thanks for your encouraging comments. We have revised the manuscript accordingly. All the revisions have been highlighted with Track Changes in the revised manuscript. The point-by-point responses to the reviewer's comments are as follows.

1. Why were only four months selected as representatives for studying annual ozone pollution? Why not choose data from the entire year?

Response 1: This study selects four SI events respectively in January, April, July and October 2017 for the WRF-Chem simulation experiments, because January, April, July and October are climatologically regarded as the representative months for boreal winter, spring, summer and autumn. Choosing the SI events in the four months could be characterized by the typical seasonalities of the SI and regional O_3 pollution. In the revised manuscript, we have clarified the modeling study on four SI events respectively in January, April, July and October 2017 (not selected four entire months). In addition, the four representative case studies allow us to manage computational resources effectively with yielding meaningful insights into the SI impact on near-surface O_3 over the SCB driven by terrain forcing of the TP.

We acknowledge that the findings presented are based on these specific case studies and thus exist inevitable limitations in generalizability. As explicitly stated in the manuscript, these quantitative results of SI-induced near-surface O_3 increments are preliminary and require future work utilizing long-term climatological analyses to establish more robust and generalizable conclusions. We have added the related explanation in the revised manuscript as follows:

Lines 132-134: "The months of April, July, October and January in the year 2017 are chosen to characterize seasonal variations in SI and atmospheric circulation patterns in the study as a sequel to our previous studies (Shu et al., 2022; Shu et al., 2023)."

Lines 274-278: "We acknowledge that quantifying SI contributions based on four case studies imposes inherent limitations in generalizability. While these events reveal significant SI impacts on regional air quality changes, future multi-year analyses integrating climatological SI frequencies are needed in further study on the SI contributions derived from observations and simulations."

2. In Figure 1, there were several SI events in January. How were the specific cases selected?

Response 2: Thank you for raising this important point on our case selection. As shown in Fig. 1, multiple stratospheric O_3 intrusion events occurred in January 2017. The selection of four specific stratospheric intrusion (SI) events (one per season) as representative cases is primarily based on peak SI intensity within their respective months and significant impact on lower-tropospheric O_3 concentrations over the region, which is derived from our analysis of O_3 vertical structure over the eastern TP and SCB. These "strong-impact" cases are chosen to clearly elucidate the mechanisms and quantitative contributions of SI events to near-surface pollution under seasonal patterns of atmospheric circulations. This approach provides the clearest insight into processes most relevant to each season.

In the revised manuscript (Sect. 2.2), we have clarified the selection criterion as follows:

“In this study, four SI events were selected based on vertical O_3 structures over the eastern TP and SCB, prioritizing peak SI intensity and significant impacts on the lower-tropospheric O_3 concentrations. The strongest-impact cases within their respective months occurring during 12–17 April (EP1), 1–3 July (EP2), 23–28 October (EP3), and 26–30 January (EP4) (Fig. 1) serve as typical seasonal representatives. Their selection enables clear elucidation of seasonal atmospheric circulation mechanisms and quantitative O_3 contributions to near-surface pollution.”

3. Lines 242-244: Ozone concentration inherently exhibits diurnal variation. How can it be demonstrated that this is due to vertical mixing?

Response 3: We fully agree with the reviewer that near-surface O_3 concentration inherently exhibits diurnal variation, primarily driven by tropospheric photochemistry. In our study, to accurately quantify the contribution of SI to the near-surface ambient atmosphere, we designed the sensitivity experiments EXP_{stro3} to isolate the contribution of stratospheric O_3 sources $\triangle O_3$ with the simulation differences between control (Base) and sensitivity experiments, which filter out the tropospheric O_3 signals including the diurnal cycle of tropospheric O_3 photochemistry. Consequently, the diurnal variation pattern in near-surface $\triangle O_3$ is governed by the downward transport of stratospheric O_3 in the free troposphere and the vertical mixing within the atmospheric boundary layer.

4. How was the "relative contribution" calculated?

Response 4: We sincerely regret the lack of clarity in the study. We have added the explicit descriptions of O_3 differences and their relative contributions calculation to enhance understanding in section 2.3:

“To elaborately quantify the contribution of SI in the study, we calculate the relative contributions derived as $RC = (\Delta x / Base) \times 100\%$, where Δx is the simulation differences between Base and EXPstro3 experiments (Δx = Base – EXP_{stro3}), and Base is the Base experiment simulations for O_3 concentrations, horizontal transport (ADVH) and vertical transport (ADVZ).”

5. Lines 273-275: The tropopause over the Tibetan Plateau is almost the highest in the global during the Northern Hemisphere summer, making it difficult for deep tropospheric convection to penetrate the tropopause. Additionally, EP1 does not occur during the summer monsoon season.

Response 5: We sincerely appreciate the reviewer's comments on the tropopause height and event timing. The tropopause over the TP is almost the highest (above sea level) in the world during the Northern Hemisphere summer. Considering the averaged terrain elevation of approximately 4000 m in the TP, the height of the tropopause relative to the local surface is notably lower compared to lowland areas. Especially, the deep atmospheric boundary layer over the TP, intensified by strong topographic forcing, nearly extends to the height of the tropopause. This process contributes to a downward dragging effect on the tropopause, facilitating the intrusion of stratospheric O_3 into the free troposphere (Zhang et al., 2025).

EP1 actually occur in the transit month of April from winter to summer. We have corrected the description in the revised manuscript (Lines 300-304) as follows:

"During the SI periods of EP1 and EP2, intense sensible heating over the elevated topography of Iranian plateau and TP induces deep convection extending to the upper troposphere. A pronounced anticyclonic circulation is set up at 200 hPa over the Northern Hemisphere with the deepening of the westerly ridge and trough on the zonal airflow intersection."

References:

Zhang, Y., Zhao, T., Ning, G., Xu, X., Chen, Z., Jia, M., Sun, X., Shu, Z., Lu, Z., Liu, J. and Qie, X.: A unique mechanism of ozone surges jointly triggered by deep stratospheric intrusions and the Tibetan Plateau topographic forcing. Geophysical Research Letters, 52(10), p.e2024GL114207. https://doi.org/10.1029/2024GL114207, 2025.

6. Lines 276-278: How does the SAH trigger SI? Is there any evidence to support this conclusion?

Response 6: The South Asian High (SAH) triggers SI through two dynamical processes involving: 1. anticyclone-driven peripheral subsidence: The anticyclonic circulation of SAH generates strong divergent airflows along its eastern periphery, forcing large-scale subsidence that entrains stratospheric O_3 into the upper troposphere; 2. Rossby wave breaking (RWB) with tropopause folding: anticyclone-enhanced vertical wind shear initiates RWB, fragmenting the tropopause folds that inject stratospheric air into troposphere. In the revised manuscript, we have updated the corresponding sentence at lines 304-314 as follows:

"The SAH triggers SI through two dynamical processes involving: 1. anticyclone-driven peripheral subsidence: The anticyclonic circulation of SAH generates strong divergent airflows along its eastern periphery, forcing large-scale subsidence (Fig.7a) that entrains stratospheric O_3 into the upper troposphere (Yang et al., 2025); 2. Rossby wave breaking (RWB) with tropopause folding (Wang et al., 2025): anticyclone-enhanced vertical wind shear initiates RWB, fragmenting the tropopause folds that inject stratospheric air into the troposphere. Anticyclonic anomalies of SAH in the upper troposphere and lower stratosphere strengthen the northern branches of the westerly jet (Yang et al., 2025) on deepening the westerly trough for deep SI events and transporting high-latitude O_3-rich air intruding into the troposphere (Fig. 6), which affects lower-troposphere O_3 changes over the downstream East Asian region (Wang et al., 2020; Zhang et al., 2022)."

References:

Yang, Q., Zhao, T., Bai, Y., Meng, K., Luo, Y., Tian, Z., Sun, X., Fu, W., Yang, K., and Hu, J.: Distinct structures of interannual variations in stratosphere-to-troposphere ozone transport induced by the Tibetan Plateau thermal forcing, Atmos. Chem. Phys., 25, 8029–8042. https://doi.org/10.5194/acp-25-8029-2025, 2025.

Wang, Y., He, Y., Sheng, Z., Sun, J., Qin, Z. and Tao, Y. Vertical ozone transport by Rossby wave breaking in upper troposphere-lower stratosphere is weakening. Atmospheric Environment, 343, p.120999. https://doi.org/10.1016/j.atmosenv.2024.120999, 2025

Wang, H., Wang, W., Huang, X., and Ding, A.: Impacts of stratosphere-to-troposphere-transport on summertime surface ozone over eastern China. Science Bulletin, 65, 276–279. https://doi.org/10.1016/j.scib.2019.11.017, 2020.

Zhang, Y., Li, J., Yang, W., Du, H., Tang, X., Ye, Q., Wang, Z., Sun, Y., Pan, X., Zhu, L., and Wang, Z.: Influences of stratospheric intrusions to high summer surface ozone over a heavily industrialized region in northern China. Environmental Research Letters, 17, 094023. https://doi.org/10.1088/1748-9326/ac8b24, 2022.

7. Line 280: What is shown in Figure 1?

Response 7: Thank you for your careful reading and valuable feedback. We sincerely apologize for the print error in the manuscript. The correct reference should indeed be to Figure 2. The updated sentence (updated Lines 315-316) reads as:

"…while the summertime TP's dynamical pumping (Fig. 2) reinforces SAH evolution controlling TP region (with an intensity of 12,300 gpm)."

8. Lines 285-286: Previous studies only found that the location of tropopause folding is related to the subtropical westerly jet, but there is no evidence proving that the subtropical westerly jet is the driving factor for tropopause folding.

Response 8: We appreciate this insightful comment. The subtropical westerly jet (SWJ) is not a primary driver of tropopause folding over the Tibetan Plateau (TP), but acts as the atmospheric circulation background to form the tropopause folding. We have revised the manuscript as follows:

"The subtropical westerly jet provides the atmospheric circulation background for the tropopause folding to trigger the SI of O_3 over the TP. "

9. Lines 285-297: Are these results derived from Figures 5c and 5d?

Response 9: We have updated the description sentence in the revised manuscript as follows:

"Westerlies are seasonally strengthened from autumn to winter over the TP region with the southernward shift of the subtropical jet, which is reflected with the stronger westerlies in EP4 than those in EP3 forming a significant zonal structure of tropopause folding over the TP region (Fig. 6c and 6d), with a high-value region of potential vorticity at 200 hPa approximately with 4–7 PVU."

10. Figure 5: It is unlikely that the SAH is depicted in Figure 5a since it represents April. What do the red contours in Figures 5c and 5d indicate? It is suggested that the authors include the westerly jet in Figure 5.

Response 10: It is climatologically true that the SAH is unlikely depicted in Figure 5a since it represents April. However, the SAH actually existed as a synoptic process on 15 April, 2017 due to the transit month of April from winter to summer. Following the reviewer's suggestions, we have included the westerly jet (refers to Fig. S6 in Supplement) in the revised Fig. 6, where the red contours mark the SCB-region.

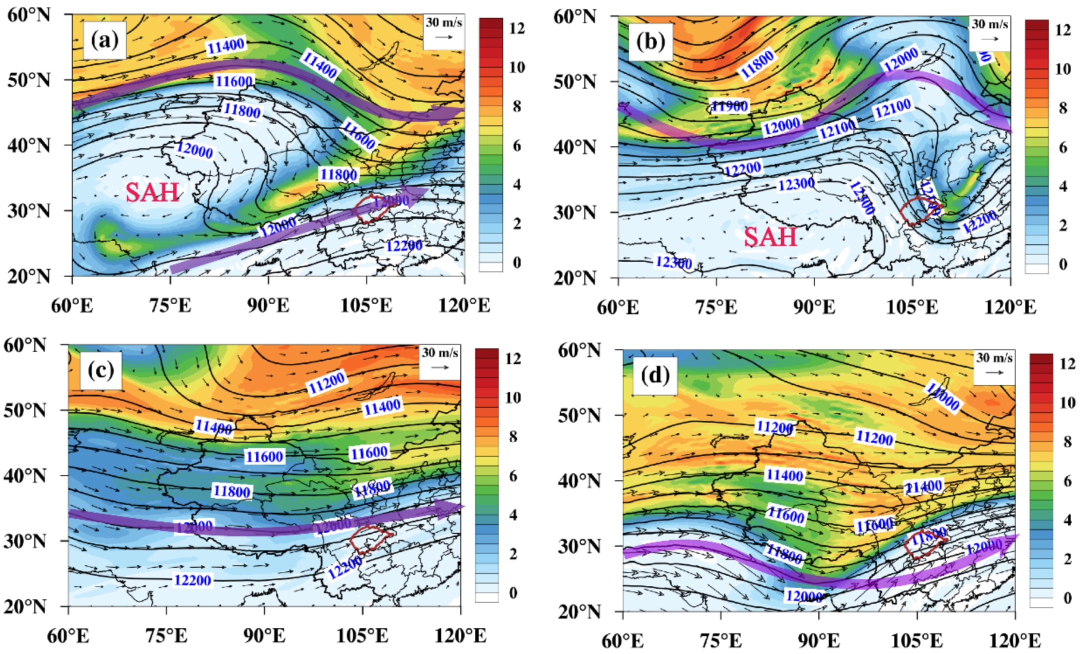

Fig 6. Spatial distribution of geopotential height (in gpm; black lines), horiziantal wind vectors and potential vorticity (units in PVU, 10^{-6} m^2 s^{-1} K kg^{-1}; color shaded) with subtropical westerly jet (purple lines with arrows) at 200 hPa during (a) 15 April, (b) 1 July, (c) 26 October and (d) 28 January in 2017. The SAH indicates the South Asian High in the upper troposphere, and the red contours mark the SCB-region.