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 ($\Delta x = Base - EXP_{stro3}$), 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.

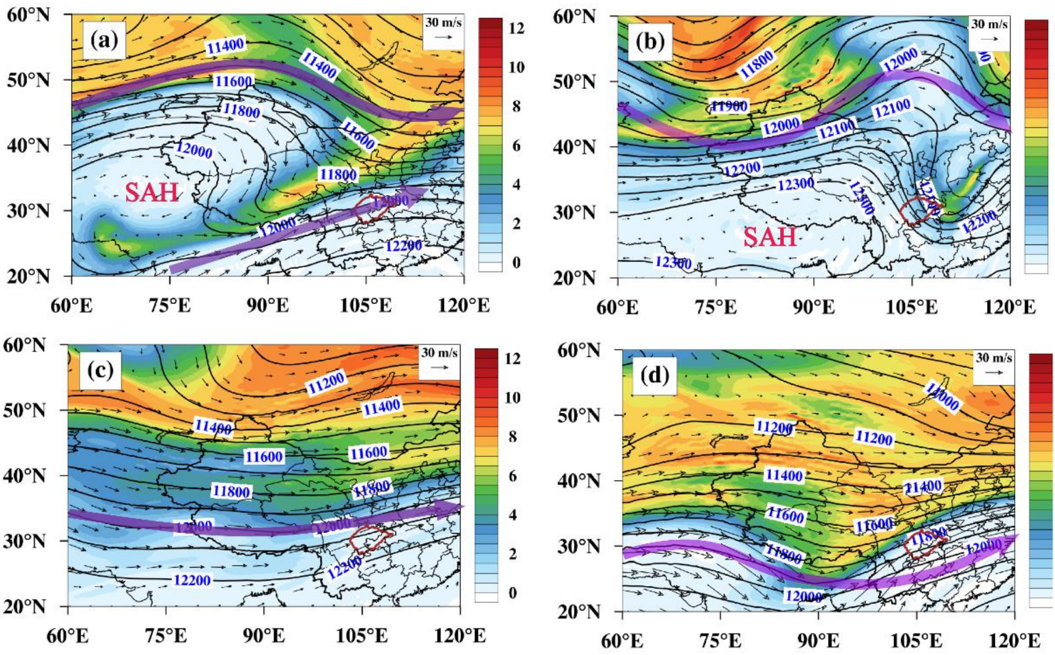

Fig 6. Spatial distribution of geopotential height (in gpm; black lines), horiziantal wind vectors and potential vorticity (units in PVU, 10^{-6} m^2 s^{-1} K kg^{-1}; color shaded) with subtropical westerly jet (purple lines with arrows) at 200 hPa during (a) 15 April, (b) 1 July, (c) 26 October and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

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Response to Referee #2

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1. Sensitivity of the results

Since this study aims to quantify the SI contribution to regional O3 pollution, it is important to more thoroughly discuss the representativeness of the four selected cases and the sensitivity of the results to the choice of SI events and background conditions (i.e., other contributing factors to O3 concentration).

1a) Representativeness of the four selected cases

While I understand that this study builds on previous works (Shu et al., 2022; Shu et al., 2023), the extent to which the four selected cases differ from other SI events and the reason for selecting them as representative cases for each season requires further clarification. Do these cases significantly differ from other SI events, or do they reflect typical conditions within their respective seasons? What criteria were used to select these four cases?

Response 1a: Thank you for raising this important point regarding 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 were 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 are 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.”

1b) Sensitivity of the results on the definition of domain of interests

Lines 235-236: its relative contribution rate to near-surface O3 levels averaged over the SCB region.

How is the SCB region defined in this calculation? Is it the same area described in Section 2.2 as SCB (103 – 110° E, 28 – 33° N)? If so, I believe this definition may require some changes, especially given that the analysis focuses on the downstream impacts of the TP. This domain appears to include part of the edge of the TP. For instance, the high O3 concentrations in the northwestern portion of Figure 3 seem to originate from higher altitudes on the Eastern TP. While I assume this area is relatively small and may not significantly affect the overall results, for consistency, it would be better to exclude the TP edge from the SCB domain definition (one possible option could be the area inside the white lines shown in Fig. S3).

Response 1b: Thanks for the referee’s suggestion. The rectangular domain (103–110°E, 28–33°N) in Section 2.2 is only a rough region for illustrating the vertical structure of O_3 between eastern TP and SCB. However, all quantitative analyses of SI impacts on near-surface air quality over the SCB are calculated over the area within the white line (the altitude at 750 m above sea level) shown in revised Fig. 4. The corresponding sentences have been revised in the revised manuscript (Lines 248-251) as follows:

“To assess the impacts of SI transport on atmospheric environmental changes over the SCB, we calculate the hourly concentrations of $\triangle O_3$ and its relative contribution rate (RC) to near-surface O_3 levels averaged in the region with the altitudes below 750 m (white line in Fig. 4).”

1c) Generalization of the results

Lines 19-21: Results show that SI over the TP penetrates deep to the near-surface atmosphere in SCB with a maximum increment of 38.7% in the O3 level, providing an extra contribution of 11.1–16.0% to regional O3 pollution.

The numbers presented in this study reflect only a few selected cases based on WRF-Chem simulations and are not generalizable. Therefore, I think the language used to describe the findings should be more cautious and explicit about the limits. As currently written, the results may imply that they represent a general SI contribution to O3 pollution across all seasons, rather than case-specific results.

I suggest that the authors explicitly state that the results are based on four selected cases from specific time periods and clearly specify the reference state used to calculate the relative contribution of the SI events.

It would also be helpful to clarify whether these estimates are derived from WRF-Chem simulations, observations, and if possible, to discuss any differences between the models and observations.

Response 1c: Thanks for your valuable feedback. We have clarified the corresponding statements and updated the Abstract in the revised manuscript as follows:

"Based on the simulations on four selected SI events in 2017, it is estimated that SI over the TP can penetrate deeply into the near-surface atmosphere in SCB, with event-specific maxima of up to 38.7% in O_3 increments, providing an extra contribution of 11.1–16.0% to regional O_3 pollution. The evolution of South Asian High in the upper troposphere with the peripheral subsidence in the warm seasons and the subtropical westerly jet over the TP in the cold seasons facilitates tropopause folding, driving stratospheric O_3 into the free troposphere. We further identified the dominant processes for SI-derived O_3 entering the near-surface layer over the basin with 1) a direct intrusion pathway of downward transport over the central and eastern SCB regions in the warm seasons, and 2) an indirect pathway of downslope transport along the TP-SCB slope into the western SCB region in the cold season, revealing the distinct seasonal effects of TP thermal and mechanical forcing on stratospheric O_3 transport into the SCB region. These findings highlight the critical role of the TP in modulating stratosphere-to-troposphere O_3 transport and its implications for regional air quality changes."

We have also added the sentences in the revised Sect. 3.1 (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 contribution derived from observations and simulations.”

1d) Other factors contributing to the changes in ozone concentration

While the focus is on downstream impacts of the SI events, the role of non-stratospheric influences on near-surface ozone should also be further discussed (e.g., regional pollution sources, role of temperature, regional atmospheric chemistry, deposition, and other factors contributing to the near surface high ozone events). How does the amplitude of SI-driven ozone anomalies compare to the variability of ozone from other processes?

I assume the role of ozone chemistry in the WRF-Chem runs is limited, since the key chemical species are fixed to climatological values. But do they still contribute, or are their effects negligible?

There was a short discussion about the regional pollution events for EP2/EP3, but not explained enough to help readers understanding the regional pollution and how Fig. S4 explains that (L245-256). I think it needs more detailed discussions.

The seasonal differences in background dynamics and their relative roles in the different cases, have been discussed briefly. However, seasonality can also influence the climatological O3 burden. How does the climatological O3 burden vary by season?

Response 1d: Following the referee’s comments, we have added the comparisons on the amplitude of SI-driven O_3 anomalies with the variations of O_3 from the tropospheric processes at Line 267-273 in the revised manuscript:

“Previous studies indicate that the unique topography of SCB amplifies the synergy effects of meteorology and emission on photochemical O_3 formation, dominating regional near-surface O_3 pollution (Yang et al., 2020; Xu et al., 2025; Wei et al., 2025). In this case study, we find the contribution of SI to near-surface O_3 levels is comparable to that from transboundary transport of tropospheric O_3 (Shen et al., 2022), highlighting the non-negligible impact of SI on SCB’s atmospheric environment and thereby deserve more concern on the control of air pollution in the region."

References:

Yang, X., Wu, K., Wang, H., Liu, Y., Gu, S., Lu, Y., Zhang, X., Hu, Y., Ou, Y., Wang, S. and Wang, Z.: Summertime ozone pollution in Sichuan Basin, China: Meteorological conditions, sources and process analysis. Atmospheric Environment, 226, p.117392. https://doi.org/10.1016/j.atmosenv.2020.117392, 2020.

Xu, T., Gao, X., Jiang, S., Hu, K., Peng, Z., Zhao, X. and Tang, X.: Nonlinear ozone response to extreme high temperature in a subtropical megacity basin: Integrated observation and modeling analysis. Environmental Research, p.122274. https://doi.org/10.1016/j.envres.2025.122274, 2025.

Wei, J., Ren, J., Li, J. and Xie, S.: Characteristics and drivers of springtime ozone pollution in the Sichuan Basin, China, in May 2020 and 2024. Atmospheric Environment, 361, p.121476. https://doi.org/10.1016/j.atmosenv.2025.121476, 2025.

Shen, L., Liu, J., Zhao, T., Xu, X., Han, H., Wang, H. and Shu, Z.: Atmospheric transport drives regional interactions of ozone pollution in China. Science of the Total Environment, 830, p.154634. https://doi.org/10.1016/j.scitotenv.2022.154634, 2022.

We acknowledge that the stratospheric O_3 chemistry is not considered in the WRF-Chem, with fixing key species concentrations including O_3 in the stratosphere to climatological ozone values for the upper stratospheric layers. Because of the monthly-scale lifetime of stratospheric O_3, the WRF-Chem simulation on the air pollution in a few days can use the climatological ozone values above tropopause. Based on the differences between Base and EXP_{stro3} experiments, our simulation study can quantify the contribution of SI to the troposphere including the near-surface atmosphere, indicating the effective contribution of stratospheric O_3 intrusion to the tropospheric O_3 in diurnal variations driven by atmospheric circulation over the TP-SCB region.

The detailed discussions on regional pollution events from Fig.S4 have been revised at line 262 as follows:

“It is noteworthy that the SCB experienced O_3 pollution during the EP1 and EP2 episodes. As shown in Fig. S4, the site-observed near-surface O_3 concentrations averaged over SCB are respectively 152.8 $\mu m\ m^{-3}$ for EP1 episode and 157.8 $\mu m\ m^{-3}$ for EP2 episode with peaks of daily maximum 8-h average O_3 concentrations of 219.0 $\mu m\ m^{-3}$ and 233.6 $\mu m\ m^{-3}$. The O_3 of SI induces O_3 pollution aggravation in the SCB with an extra contribution of approximately 11.1–16.0%."

We agree that seasonality of meteorology can also influence the climatological O_3 burden. The climatological O_3 burden over the TP and surrounding regions exhibits a seasonal cycle with springtime peak values but persistent total column ozone low in summer (Li et al., 2020), which refers to the multiple processes involving photochemical production, thermodynamic forcing of the TP on the downstream regions and Asian monsoon circulations (Bian et al., 2011; Guo et al., 2015).

References:

Bian, J., Yan, R., Chen, H., Lü, D. and Massie, S.T.: Formation of the summertime ozone valley over the Tibetan Plateau: The Asian summer monsoon and air column variations. Advances in Atmospheric Sciences, 28(6), pp.1318-1325, https://doi.org/10.1007/s00376-011-0174-9, 2011.

Guo, D., Su, Y. C., Shi, C. H., Xu, J. J., and Powell, A. M.: Double core of ozone valley over the Tibetan Plateau and its possible mechanisms, J. Atmos. Sol.-Terr. Phys., 130, 127–131, https://doi.org/10.1016/j.jastp.2015.05.018, 2015.

Li, Y., Chipperfield, M. P., Feng, W., Dhomse, S. S., Pope, R. J., Li, F., and Guo, D.: Analysis and attribution of total column ozone changes over the Tibetan Plateau during 1979–2017, Atmos. Chem. Phys., 20, 8627–8639, https://doi.org/10.5194/acp-20-8627-2020, 2020.

2. The EXPstro3 case as a reference case with non-SI events

The EXPstro3 experiment was used as a reference case, without the UBC scheme and thus without non-SI events. However, I'm concerned that a better reference case would be simulations run with the UBC scheme, focusing on periods without SI events, rather than simulations run without the UBC scheme.

Is there any difference in cross-tropopause ozone transport and background ozone concentration between 1) the Base experiment during periods without SI events, and 2) the EXPstro3 experiment in general?

Response 2: We appreciate the reviewer's thoughtful consideration of our experimental design. Regarding the choice of the EXP_{stro3} simulation as the reference case, we need to clarify the methodology as follows:

As explicitly stated in our manuscript (Section 2.3), the WRF-Chem framework lacks stratospheric chemistry. Alternatively, the UBC scheme was employed to overwrite the model's default stratospheric O_3 with climatological values, which is a currently common status in the simulation investigation for stratosphere-troposphere transport.

The EXP_{stro3} experiment was designed specifically to isolate the contribution of stratospheric sources by disabling the UBC scheme and setting default O_3 concentrations to zero above the tropopause. By maintaining the identical dynamical and chemical conditions in the troposphere, the EXP_{stro3} provides a scenario control baseline to isolate the contribution of SIs, based on the simulated differences between the Base and EXP_{stro3} experiments, identifying the contribution of the cross-tropopause transport of stratospheric O_3 to the troposphere and further downwards to the near-surface layer.

3. Comparison with the observations

1) Fig. S3 provides important implications by demonstrating the verification of WRF-Chem using ESAC4 data. I recommend including it in the main figure set.

2) I think it' s somewhat unclear how the relative ozone concentration was calculated (Lines 234-239). I assume that the most of the Delta O3 values (and relative contributions) are inferred from the WRF-Chem simulations (as difference between the Base and EXP_stro3). What period was used to calculate each number in Line 238?

3) How do the WRF-Chem results compare with observed values? For example, have you derived observational anomalies as near-surface ozone during SI-affected periods minus those during reference periods? EP4 in the observations appears to show higher ozone levels over the SCB region than the WRF-Chem results, despite having relatively lower O3 concentrations in the eastern TP (Figs. S3d and 3h). Maybe lines 229 – 231 apply only to the WRF-Chem results, and not to the observations?

I think it would be helpful to include a figure like Fig. 4, but based on the observations. While the observational data may not have a zero reference value like in the model, it should still capture the relative increases in O3 associated with the SI events.

4) Also, what are the background ozone levels in observations for non-SI periods across each season? The seasonality of background ozone concentrations in observations requires further discussion.

Response 3: 1) Thank you for your valuable feedback. Following your comments, we have moved supplementary Fig. S3 into the revised manuscript as Fig. 3.

2) We sincerely regret the lack of clarity in this section and have revised the manuscript accordingly as follows:

In section 2.3: We have clarified explicit descriptions of the simulated O_3 differences and their relative contributions to enhance understanding:

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

At Lines 251-254: We have now specified the exact calculation time period corresponding to each numerical value presented.

"As shown in Fig. 5, stratospheric O_3 transport affects the SCB region during the periods of 13–17 April, 1–3 July, 26–28 October and 29–30 January, with the averaged near-surface O_3 enhancements of 6.3 ppb, 5.5 ppb, 4.3 ppb and 3.1 ppb, contributing 18.2%, 15.4%, 12.7% and 17.0% to regional near-surface O_3 concentrations."

3) Following your suggestion, we have added Fig. S3 in the revised Supplement:

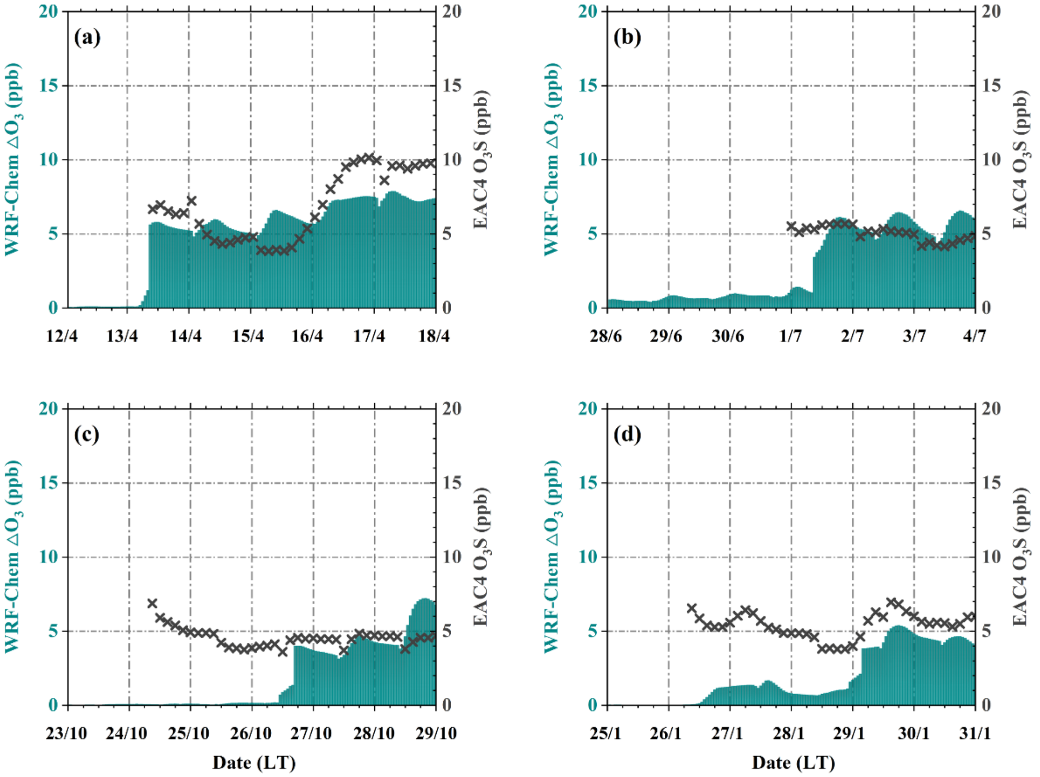

Fig S3. Comparison between hourly WRF-Chem $\triangle O_3$ (ppb) and 3-hourly EAC4 O_3S (ppb) during the period of SI events (a) EP1, (b) EP2, (c) EP3 and (d) EP4 averaged over the SCB.

Our investigation is primarily based on the analysis of WRF-Chem simulation results of SIs events. In the modeling evaluation (Section 2.4; Figs. 3 and S3), we have compared WRF-Chem with EAC4 to assess the simulation performance. Results showed that the Base experiment reasonably demonstrates the contribution of SI to near-surface O_3 levels. Therefore, the WRF-Chem simulation results are representative of the O_3 variations during the SI periods for further study.

4) The shift of East Asian monsoons shapes the significant seasonality of O_3 over the monsoon regions including SCB. It is found that the near-surface O_3 concentrations over the SCB region present a distinct pattern from high levels during the summer monsoon period (April-July) to low levels over the winter monsoon period (October-January). The seasonality of background O_3 concentrations in observations has been further discussed:

“The East Asian monsoons significantly modulate the seasonality of near-surface O_3 over the SCB region, leading to high levels and frequent O_3 pollution during the summer monsoon period (April-July) to low levels over the winter monsoon period (October-January) (Gao et al., 2020; Wang et al., 2022).”

References:

Gao, M., Gao, J., Zhu, B., Kumar, R., Lu, X., Song, S., Zhang, Y., Jia, B., Wang, P., Beig, G., Hu, J., Ying, Q., Zhang, H., Sherman, P., McElroy, M.B.: Ozone pollution over China and India: seasonality and sources. Atmos. Chem. Phys. 20 (7), 4399–4414. https://doi.org/10.5194/acp-20-4399-2020, 2020.

Wang, W., Parrish, D.D., Wang, S., Bao, F., Ni, R., Li, X., Yang, S., Wang, H., Cheng, Y., Su, H.: Long-term trend of ozone pollution in China during 2014–2020: distinct seasonal and spatial characteristics and ozone sensitivity. Atmos. Chem. Phys. 22 (13), 8935–8949. https://doi.org/10.5194/acp-22-8935-2022, 2022.

4. Interpretations of Figure 7

The implications of Fig. 7 are quite difficult to understand. For example, point C in panel (a) appears to suggest that low-level transport near the surface is dominated by horizontal circulation anomalies. However, the budget at point C shows that ADVZ is the key component driving the positive ozone anomaly at low levels, while ADHZ provides a smaller negative contribution. Is the main purpose of Figure 7 to highlight the dominant component between ADVZ and ADHZ in driving the ozone anomalies? Also, is it possible to remove the background climatological values from both ADVZ and ADHZ to better isolate the anomaly-driven contributions only? (currently I see large portion of ADVZ and ADHZ cancels each other)

Response 4: The IPR analysis at points A/B/C in Figure 7 aims to identify the dominant processes (particularly ADVH vs. ADVZ) driving ΔO_3 anomalies during the SI periods, based on the simulation differences between Base and EXPstro3 experiments. ADVZ (vertical advection) provides the primary positive contribution to near-surface O_3 variations rather than ADVH (horizontal advection) with a smaller negative contribution at point C. This confirms that vertical transport dominates in driving the O_3 variations in the ambient atmosphere, despite the apparent prominence of horizontal wind vectors (Fig. 7a).

We would like to emphasize that the comparative approach between our baseline and sensitivity experiments inherently removes the common background signal, thus isolating the anomaly-driven contributions from ADVZ and ADVH, although our WRF-Chem simulation specifically focuses on four SI events, and does not include a multi-decadal baseline simulation for climatological tropospheric O_3. We fully agree that future multi-year analyses are needed to remove the background climatological values to better isolate the anomaly-driven contributions.

5. The term “environmental atmosphere” has been used multiple times, but I am not sure whether it is commonly accepted terminology in atmospheric science. Do you mean “atmospheric composition”? I suggest that the authors double-check the usage of this term.

Response 5: All the "environmental atmosphere" has been replaced with "ambient atmosphere" in the revised manuscript.

6. Lines 75-76: “residual-rich O3” -> residual O3-rich air? I think it would be helpful if this sentence could be clarified (lines 74-77).

Response 6: Following the suggestion of referee, we have revised the sentence as follows:

“However, with the distinct topography of TP and frequent SI occurrence, few studies consider the impacts of residual O_3-rich from SI on atmospheric environmental changes over downstream regions of westerlies, particularly in the typical pollution regions.”

7. Line 136: rich o3 of SI -> the O3-rich air from SI

Response 7: Revised as suggested.

8. Line 144: I suggest rewriting the sentence to something like, “The intensity and location of SIs are influenced by the distinct seasonality of vertical motion.”

Response 8: Following your suggestion, we have rewritten the sentence at Lines 152-153 in the revised manuscript as follows.

“The intensity and location of SIs are influenced by the distinct seasonality of vertical motion in the atmosphere.”

9. Lines 145-147: While alternating rising and sinking momentum leads to a deep SI event over the central TP during EP1. Why is there any contrast between the updraft and downdraft regions in EP1 in Figure 2a? The vertical gradient of ozone appears to be fairly

symmetrical.

Response 9: The phenomenon can be attributed to the convergence between the periphery of anticyclonic system and the Southwest Monsoon, facilitating the formation of an upper-level frontal system. The structure deepens the westerly ridge and trough with strong vertical momentum contrasts, leading to a deep SI event over the central TP during EP1. The symmetrical O_3 gradient pattern might result from temporal and spatial averages over the study region.

10. Line 180: Does the simulated tropopause in WACCM exhibit a similar structure to observations, including features such as tropopause folding? It would be helpful if the authors could comment on how well the model captures these structures.

Response 10: We appreciate your insightful comments on WACCM verification of tropopause folding structure. The WACCM data provide the tropopause height with the longitude, and latitude in a horizontal resolution of 2.5°×2.5° in the monthly variations, while the high temporal resolution (e.g., daily or hourly), fine-scale spatial distribution of tropopause is produced by the WRF-Chem simulation. Therefore, the modeled dynamic structures at the synoptic scale can not be assessed with the WACCM dataset.

11. Lines 197-198: Delta O3basin=EXPterr - EXPstro3+terr

I’m confused that the difference between EXPterr minus EXPstro3+terr is used to investigate the deep-basin terrain forcing. Aren’t both simulations include the basin-filling terrain instead of the deep-basin terrain? Did you mean the comparison between delta O3basin and delta O3 (Base minus EXPstro3) can show the role of deep-basin forcing?

Response 11: Both EXP_{terr} and $EXP_{stro3+terr}$ experiments in the study utilize filled-basin topography (rather than deep-basin topography). The comparison between △O_3basin (EXP_{terr} – $EXP_{stro3+terr}$) and △O_3 (Base minus EXP_{stro3}) quantifies the role of deep-basin forcing on SI-induced ambient atmosphere changes. The description of WRF-Chem simulation is shown in the following table.

Table Senario setting of WRF-Chem simulation experiments.

Experiments	Basin-filling terrain	UBC	Default stratospheric O_3 values set as zero
BASE		○	
EXPstro3			○

EXPterr	○	○	
EXPstro3+terr	○		○

12. Line 219: It might be helpful to remind readers that Delta O3 refers to the difference in O3 between the Base and EXPstro3 runs.

Response 12: We have added the definition of Delta O_3 at Lines 232-235:

“To illustrate the impacts of SIs on ambient environment, the temporospatial variations of $\triangle O_3$ (the difference in O_3 between the Base and EXP$_{stro3}$ experiments) at the near-surface layer are analyzed based on the WRF-Chem simulation results of the innest domain.”

13. Line 225: lower levels (approximately ~10 ppb) -> It appears that the SCB region is mostly green rather than yellow, suggesting O3 levels lower than ~10 ppb, maybe around ~6 ppb. What is the actual area-averaged value over the SCB?

Response 13: We sincerely regret the misleading description in the original text. To clarify, the maximum contribution of $\triangle O_3$ almost reaches 10 ppb, not the average value as previously stated. Throughout the study period, the mean contribution was approximately 6 ppb (please see Fig. S3 in Response 3). We have corrected the relevant sentence.

14. Lines 244-247: It should be noteworthy that the SCB is experiencing regional O3 pollution on both 14－15 April and 1－2 July in 2017 during the SI episode periods (Fig. S4), in which daily maximum 8-hour average O3 concentrations exceed 160 μg m-3.
->How large is the relative contribution of this regional O_3 pollution to the near surface delta O3?

Response 14: During air pollution over the SCB, the relative contribution of SI-induced O_3 changes is approximately of 11.1–16.0%. The detailed related content on regional pollution has been added in the revised manuscript as follows:

“It is noteworthy that the SCB experienced O_3 pollution during the EP1 and EP2 episodes. As shown in Fig. S4, the site-observed near-surface O_3 concentrations averaged over SCB are respectively 152.8 μm m^{-3} for EP1 episode and 157.8 μm m^{-3} for EP2 episode with peaks of daily maximum 8-h average O_3 concentrations of 219.0 μm m^{-3} and 233.6 μm m^{-3}. The O_3 of SI induces O_3 pollution aggravation in the SCB with an extra contribution of approximately 11.1–16.0%.”

15. Lines 247-248: O3 pollution aggravation in the SCB with an extra contribution approximately of 11.1 – 16.0%.

Maybe worth so clarify that these numbers are estimated based on the WRF-Chem simulations, not based on the observations.

Response 15: Thank you for raising this point. We have clarified that all quantitative estimations of SI on the ambient atmosphere in our manuscript are derived from our WRF-Chem simulations. As noted at the outset of Section 3.1, we have clearly stated these specific quantitative results:

"To illustrate the impacts of SIs on the ambient environment, the temporospatial variations of △O_3 (referring to the difference in O_3 between the Base and EXP_{stro3} experiments) in the near-surface layer are analyzed for SCB and the surrounding regions based on the WRF-Chem simulation results of the innest domain."

16. Line 275: anticyclone -> anticyclonic

Response 16: Revised as suggested.

17. Line 289-290: Westerlies are gradually strengthened over the TP region controlled by subtropical jet from EP3 to EP4.

I find this sentence unclear. Does it mean that the westerlies are stronger in EP4 than in EP3, and that EP4 (January 2017) occurs after EP3 (October 2017)?

Response 17: We have clarified the description in the original 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."

18. Line 293: seasonal typical atmospheric circulation patterns -> seasonal patterns of atmospheric circulation.

I think this sentence (lines 293-294) also need further clarification.

Response 18: Revised as suggested. The sentence has been further clarified in the revised manuscript.

"These results reveal the seasonal patterns of atmospheric circulation triggering the SI over the TP hotspot region from large-scale anticyclonic circulation in the warm season to the subtropical jet in the cold season."

19. Figure 7: Could you also mark the TP boundary like for the SCB region?
Response 19: The TP is usually the area with the latitudes exceeding 3000 m above sea level. Therefore, we have added the rough TP boundary (blue lines) in revised Fig.8 as suggested.

In addition, we have updated the description of Fig. 8 (original Fig. 7) in the revised manuscript (Lines 373-397) as follows:

"There are two primary intrusion pathways directly and indirectly affecting air quality in the SCB for SI O_3-rich airflows (Fig. 8). The direct SI pathway is vertically downwind injection of $\triangle O_3$ from the free troposphere into atmospheric boundary layer, which is related to entrainment at the top of boundary layer (Škerlak et al., 2019), mainly over the central and eastern regions of SCB. In comparison, the indirect strtopsheric O_3 intrusion over the TP occurs with the slant transport pathway in the troposphere from the TP along the plateau-basin downslope into the western SCB. It is a quasi-horizontal transport process within the atmospheric boundary layer from the high-altitude eastern TP to western SCB, which results in a discernible horizontal gradient of $\triangle O_3$ expansion to the west of SCB (Fig. 4). Consistent with these patterns, IPR analysis further confirms that horizontal transport dominates ΔO_3 changes over the plateau-basin transition zone in western SCB, whereas vertical transport drives near-surface O_3 increases over the flat central and eastern regions during SI episodes. Notably, the dominant transport pathway exhibits significant seasonal variability: the direct intrusion pathway prevails during the warm-season episodes EP2 and EP3, while the indirect pathway dominates during the cold-season episodes EP1 and EP4. This seasonal shift underscores the modulation of TP's topography on SI-induced O_3 pollution over the SCB with atmospheric circulation variations.

Another notable feature is Asian Monsoon circulation with intensified easterly wind vectors over the SCB in both EP2 and EP4, facilitating cross-layer transport of SI O_3 by vertical vortex in EP2 and EP4 below the heights of 3 km and 2 km (a.s.l.). These mechanisms highlight the pivotal role of the plateau-basin topography in regulating the O_3 transport from free troposphere to the boundary layer during SI events. The thermodynamic forcing of this topography enhances both vertical and horizontal exchange between the free troposphere and atmospheric boundary layer, critically affecting the seasonal variations of stratospheric O_3 intrusion.”

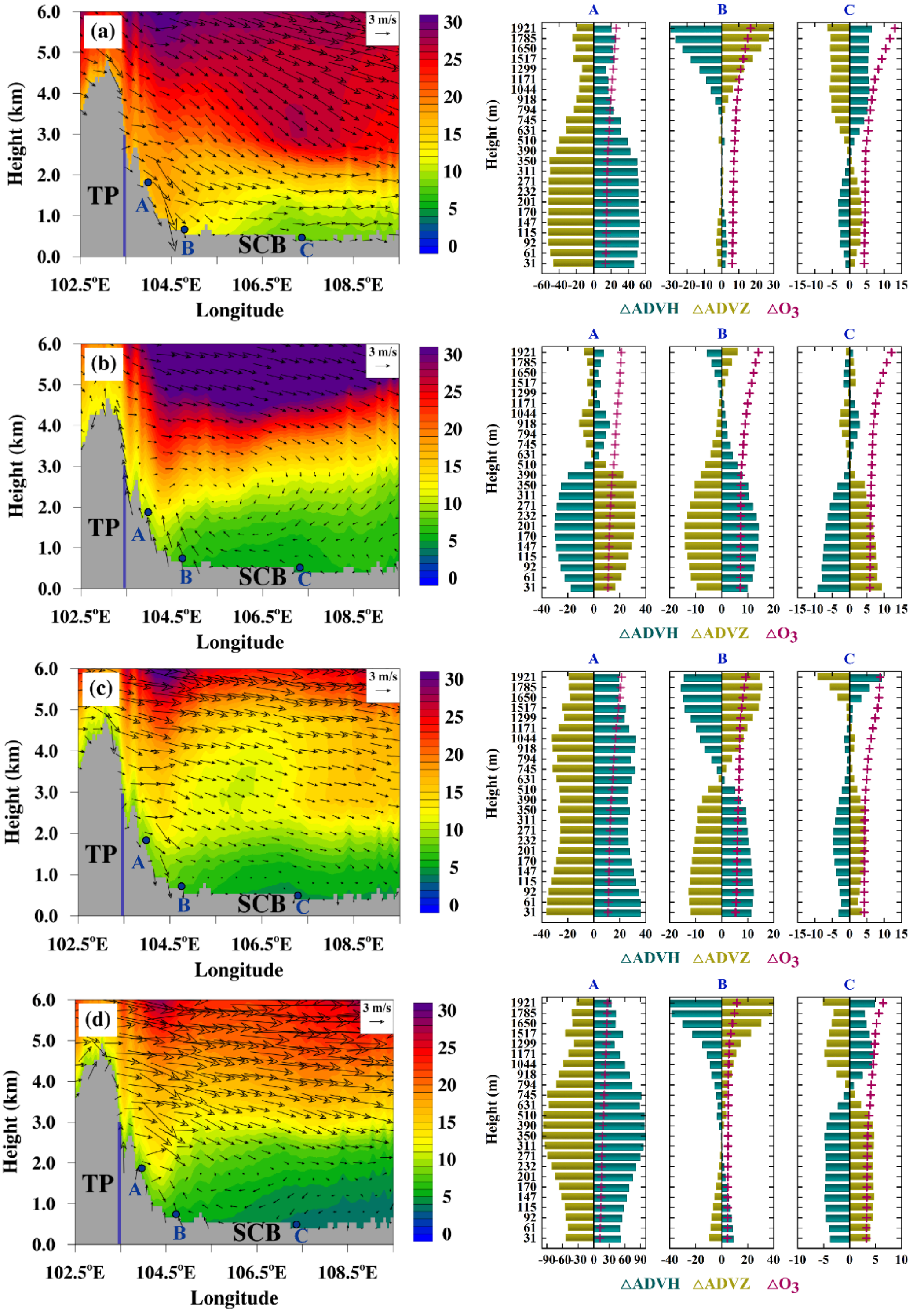

Fig. 8. Height-longitude cross-sections of △O₃ (ppb, color contours) and wind vectors averaged between 28–33°N on (a) 16 April, (b) 1 July, (c) 26 October and (d) 29 January 2017 (left panel) with correspondingly IPR on horizontal transport (△ADVH) and vertical transport (△ADVZ) respectively at points A (plateau region), B (western edge of SCB) and C (central SCB). The blue lines roughly outline TP's boundary.

20. Lines 318-319: Maybe remind the readers that the vertical velocity is defined positive downward?

Response 20: We have revised the Fig. 7 (original Fig.6) caption as suggested:

"Geopotential height (gpm; blue contours), wind vectors and vertical velocity (Pa s^{-1}; shaded contours) at 500 hPa for (a) 16 April, (b) 1 July, (c) 26 October and (d) 29 January 2017. Positive values of vertical velocity denote subsidence."

21. Line 330: vertical gradient of ozone (dO3/dp) is mentioned but the unit is for delta O3.

Response 21: We appreciate the careful review. The term "vertical gradient of O_3" has been replaced with "vertical O_3 differences" here. This revision explicitly refers to the O_3 concentration difference at 20 ppb from the height of 5 km to the near-surface layers.

22. Line 355: I think the subtitle should be changed to include something about "the role of deep-basin structure" not general SI.

Response 22: We appreciate the valuable comment on the subtitle of Sect. 3.2.3. It has been modified as "The role of deep-basin in SI into ambient atmosphere."

23. Line 356: It might be helpful for readers, if there is a short summarizing sentence explaining what is the delta O3basin experiment.

Response 23: We have revised the sentence in Sect. 3.2.3 for explaining $\triangle O_3$basin experiment as suggested.

"Based on the terrain sensitivity experiments ($\triangle O_3$basin = EXPterr – $EXP_{stro3+terr}$), we have further investigated the effect of deep-basin terrain on SI-induced near-surface O_3 increments. The results of $\triangle O_3$basin are mainly analyzed on cross-layer O_3 transport from the free troposphere to the near-surface atmosphere during SI episodes."

24. Lines 358 – 360: I'm not entirely convinced that the smoothed-terrain experiment is the most ideal case to represent a reference state in contrast to the realistic deep-basin structure. As the current basin-filling terrain doesn't necessarily represent the opposite of the realistic topography. But it's just one of many possible comparative configurations. Therefore, I recommend rephrasing to something like: "… mitigates regional O_3 pollution compared to the idealized experiments with basin-filling terrain" to clarify this point.

Response 24: Many thanks for your comments. Following your suggestion, the sentence has been revised as:

“We found that the low-lying basin of SCB can mitigate O_3 pollution derived from SIs compared to the idealized experiments with basin-filling terrain.”