

Response to Reviewer #1

We sincerely thank Reviewer #1 for the positive evaluation of the manuscript and helpful suggestions. Our point-to-point response to the comments is provided below.

Q1.1: Minor correction: Please consider a small language edit for consistency. In the manuscript, the terms “stratospheric intrusion” and “stratosphere-to-troposphere transport (STT)” are sometimes used interchangeably. Adding a brief clarification early in the introduction to distinguish these terms would help readers.

A1.1: We thank the reviewer for this suggestion. Stratosphere-to-Troposphere Transport (STT) denotes the general process of air mass transport from the stratosphere to the troposphere, while Stratospheric Intrusion (SI) refers to specific, transient events in which stratospheric air penetrates into the troposphere, representing an episodic manifestation of STT. Following the reviewer’s suggestion, we have clarified these distinctions in [L25-29](#) in the Introduction section and revised the corresponding sentence as follows:

“STT is the general process of air mass transport from the stratosphere to the troposphere, playing a critical role in introducing ozone-rich stratospheric air into the troposphere (Hong et al., 2024; Stohl et al., 2003; Langford et al., 2015). When the folds occur, STT manifests as stratospheric intrusions (SIs), characterized by their episodic nature and rapid descent, significantly altering the total tropospheric ozone burden (Williams et al., 2019; Neu et al., 2014).”

Response to Reviewer #2

We sincerely thank Reviewer #2 for the positive and constructive comments, which remarkably improved our manuscript. Our point-to-point response is provided below.

Q2.1: L15–16. As shown by the author’s analysis, shallower intrusions account for a larger proportion. So, besides near-surface atmospheric composition and extreme weather events, I think this tropopause folding dataset might be more important for climate research on stratosphere-to-troposphere exchange (STE).”

A2.1: We thank the reviewer for this insightful comment. We fully agree that the tropopause folding dataset we developed is valuable not only for investigating impacts on near-surface air constituents and extreme weather events, but also for climate research on stratosphere-to-troposphere transport (STT). Thus, we have revised the abstract and relevant sections to include more implications of this study as follows:

“This dataset provides a solid foundation for in-depth investigations into the mechanisms and climatological characteristics of STT, as well as the subsequent impacts of tropopause folds on near- surface atmospheric composition and extreme weather events, thereby serving as a valuable resource for the atmospheric science community.”

“Moreover, it establishes a foundation for investigating STT processes and the subsequent impacts on near-surface ozone concentrations and regional extreme weather events. Additionally, this dataset serves as a critical resource for climate research on STT.”

Please also see **L15-16** and **L82-83** in the revised manuscript.

Q2.2: *L18–24. STE in the vicinity of the tropopause fold occurs in regions of turbulence and diabatic processes. Specifically, stratospheric air near the tropopause fold, characterized by high ozone, low water vapor, and high potential vorticity (PV), descends into the troposphere; meanwhile, tropospheric air with abundant water vapor, carbon monoxide, aerosols, and low PV is also transported into the stratosphere.*

A2.2: We thank the reviewer for this detailed and insightful comment. We fully acknowledge that STE is a bidirectional process, encompassing both stratosphere-to-troposphere transport (STT) and troposphere-to-stratosphere transport (TST). In this study, however, we focus on the tropopause fold, which represents a key mechanism of STT. Consequently, TST is outside the scope of the current dataset. To clearly convey the focus of our work, we have emphasized STT in the manuscript without extensive discussion of TST. Please see [L24-27](#) in the revised manuscript. We hope this explanation clarifies the scope of our study.

Q2.3: *L29. What do you mean by ‘downward advection’? Convection?’*

A2.3: We thank the reviewer for pointing it out. We agree that the term may cause some confusion. In this study, “downward advection” refers to the large-scale downward transport of air from the stratosphere into the troposphere, which is different from convection. To clarify it, we modified the term to “downward transport” in the revised manuscript as follows:

“... can strongly affect local weather conditions through a downward advection transport of air with high potential vorticity (Akritidis et al., 2021).”

Q2.4: *L69-70. The phrase ‘the folding data provided by this dataset ... alongside 37 vertical pressure levels’ sounds strange. How can tropopause folding be divided into 37 levels? This is not clear in this study, please rephrase it.*

A2.4: We thank the reviewer for pointing it out. We fully agree that this sentence causes some confusion. In this study, the identification of tropopause folding events is based on ERA5 meteorological data with 37 vertical pressure levels, but the folding data have only a single level, rather than 37 layers. We revised this sentence as follows:

“Regarding the resolutions, the folding data provided by this dataset possess an hourly temporal resolution and a horizontal resolution of $0.25^{\circ} \times 0.25^{\circ}$ (~28 km) alongside 37 vertical pressure levels, ranging from 1000 hPa to 1 hPa.”

Q2.5: *L91-93. Please describe in detail how you assign the five labels.*

A2.5: We thank the reviewer for this comment. We now provide a more detailed description in Section 2.2 of the manuscript about how these five labels are assigned. The revised part is as follows:

“Next, the method assigns various types of the air with five labels (see Fig. 1): 1 = troposphere, 2 = stratosphere, 3 = stratospheric cutoff or diabatically produced cyclonic PV anomaly, 4 = tropospheric cutoff, and 5 = surface-bound cyclonic PV anomaly. Label 1 denotes typical tropospheric air, characterized by low PV values (< 2 PVU). Label 2 represents stratospheric air, defined by high PV (> 2 PVU), low specific humidity (< 0.1 g/kg), and three-dimensional connectivity with the stratospheric reservoir. Label 3 corresponds to stratospheric cutoffs, which are isolated stratospheric air masses suspended in the troposphere, or high-PV tropospheric anomalies resulting from dissipative processes, characterized by high specific humidity (> 0.1 g/kg). Label 4 indicates tropospheric cutoffs, defined as isolated tropospheric air masses with low PV surrounded by stratospheric air. Label 5 identifies surface-bound PV anomalies, distinguished by high PV values extending down to the surface.”

Q2.6: Sect. 3.2.2. As seen in Figs. 7 and 8, fewer deep intrusions occurred on the rear (west) side of the cut-off low, while more occurred ahead of the low. Typically, there are strong downdrafts on the west side and updrafts on the east side of a cut-off low, so the results seem inconsistent with known dynamics. Could the cyclonic PV near the tropopause fold in the upper troposphere ahead of the cut-off low have been misidentified as stratospheric signals?

A2.6: We thank the reviewer for raising this question. In our original analysis, the 200 hPa trough was identified solely based on the wind speed, which led to a deviation in position of the trough. To address this issue, we have refined the method by incorporating 200 hPa geopotential height contours to define the trough location (see Fig. 1 in this rebuttal).

The improved results now show that the vast majority of medium and deep folds occur on the western (rear) side of the low, which is consistent with the comment of the reviewer and the related references. Regarding the small portion of deep folds remaining on the eastern side (see Fig. 1d in this rebuttal), we attribute this to the eastward advection of folds after their formation under the influence of strong upper-level westerly winds. These results further confirm that our dataset is capable of accurately capturing the spatial characteristics of regional SI cases.

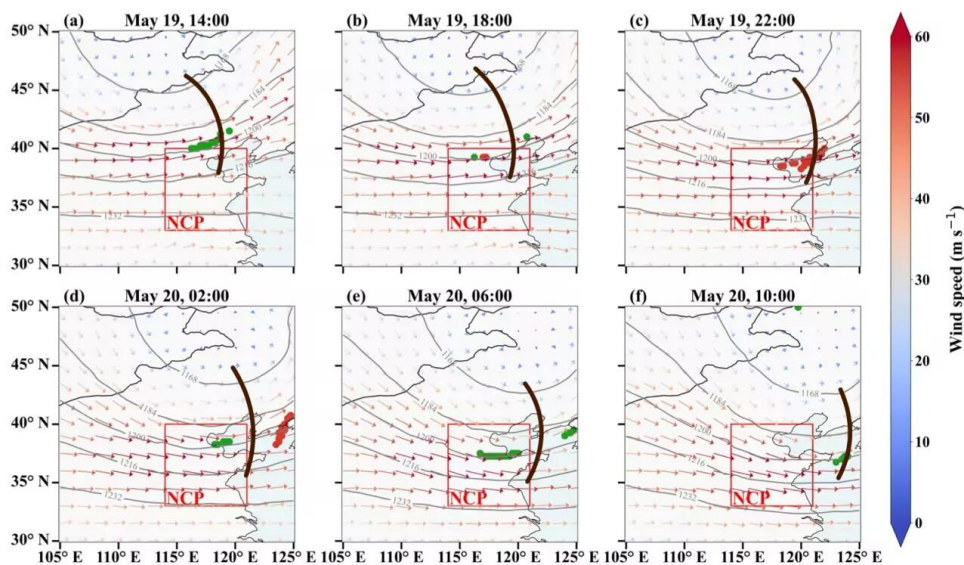


Fig. 1 Spatiotemporal evolution of medium and deep tropopause folds over the NCP on (a–c) May 19 and (d–f) May 20, 2019, shown at 4-hour intervals. Colors indicate fold type (green: medium, red: deep). Wind vectors (arrows) show 200 hPa wind speed and direction, scaled by color and length. Brown lines represent the upper-level trough, and the red box delineates the NCP. Gray solid lines indicate contours of the 200 hPa geopotential height (unit: dagpm).

The improved results and the related discussions have been added to the revised manuscript. Please see [Fig. 8](#), [Fig. S2](#) in the Supplement, [L259](#) and [L263-265](#) in the revised manuscript. Thanks a lot for the suggestion.

Q2.7: Sect. 3.2.3. I think this is not a good case. I would suggest using an event with tropospheric air entering the stratosphere, which would be more interesting and would also avoid overlap with existing studies.

A2.7: We thank the reviewer for this valuable suggestion. We acknowledge that TST events are indeed an interesting topic in STE research. However, as clarified in our previous response **A2.2**, stratosphere-to-troposphere transport (STT) and troposphere-to-stratosphere transport (TST) are two distinct processes of stratosphere–troposphere exchange (STE). Our database specifically focuses on tropopause folding events, which represent an important mechanism of STT and are only weakly related to TST. Therefore, selecting a TST case to validate our database would not be appropriate. Thus, we keep this case as it is. We appreciate the reviewer’s understanding regarding this choice.

Response to Reviewer #3

We greatly appreciate Reviewer #3's recognition of the novelty and usefulness of our folding dataset for China and surrounding regions. We also sincerely thank the reviewer for the constructive suggestions. Our point-to-point response to the comments is provided below.

Specific comments:

Q3.1: *In the introduction, the authors emphasised the importance of STT, particularly regarding tropospheric ozone. They could expand this to include ozone precursors (such as Br and I) and stratospheric aerosols, based on recent studies. For example, Schill et al. (2025) reported that STT can inject them into the Arctic free troposphere, impacting tropospheric ozone chemistry. Additionally, I noticed that a widely cited review paper, although somewhat dated, on STE by Stohl et al. (2003) was not mentioned.*

A3.1: We sincerely thank the reviewer for this helpful suggestion. We have expanded the Introduction section to highlight the important role of STT in transporting ozone-depleting precursors and stratospheric aerosols into the troposphere. We have also added the relevant references such as Schill et al. (2025) and Stohl et al. (2003) in appropriate places according to the reviewer's suggestion. The revised sentences are as follows:

“Beyond ozone transport, recent studies also indicate that STT in the Arctic injects ozone-depleting precursors (such as bromine and iodine) and stratospheric aerosols into the free troposphere, influencing local tropospheric chemistry (Schill et al., 2025).”

“STT is the general process of air mass transport from the stratosphere to the troposphere, playing a critical role in introducing ozone-rich stratospheric air into the troposphere (Hong et al., 2024; Stohl et al., 2003; Langford et al., 2015).”

Please see [L25-27](#) and [L29-31](#) in the revised manuscript for these modifications.

Technical corrections:

Q3.2: Line 5: “decade-long coverage”: this statement is incorrect, as 2014-2023 only covers ~10 years.

A3.2: We have modified the statement to “10-year long coverage (2014–2023)” for clarify. Thanks a lot for the correction.

Q3.3: Line 27: Change “Akritidis et al., 2016; Lin et al., 2015; Akritidis et al., 2010” to Akritidis et al., 2016, 2010; Lin et al., 2015”

A3.3: We have merged references with the same author according to the suggestion. Thanks.

Q3.4: Line 63: Tibetan Plateau (TP) - TP should be defined early when it appear in the first time, eg in line 13, rather than here. Line 90: isofurface should be isosurface.

A3.4: We thank the reviewer for the careful reading and suggestions. We now give the definitions of abbreviations such as “Tibetan Plateau (TP)” at their first appearance (e.g., L13 in the revised manuscript). However, for clarity, we also repeat the definition if an abbreviation reappears much later in the manuscript, in case the readers have forgotten its meaning. Other than that, we have removed all the redundant definitions of the abbreviations. We have also corrected the word “isofurface” according to the suggestion. Thanks.

*Q3.5: Line 100: Physical variables like *sfold*, *mfold*, and *dfold* should be better expressed in italic to distinguish them from normal words.*

A3.5: We have expressed the physical variables *sfold*, *mfold*, and *dfold* in italics throughout the manuscript. Thanks for the suggestion.

Q3.6: Lines 109-111: I cannot see how “These cases demonstrate that our dataset can

successfully capture the complete evolution of tropopause folds during stratospheric intrusion events.” Maybe you should add: “As shown below in Section XYZ, we demonstrated” If this is the case.

A3.6: We thank the reviewer for the helpful suggestion. We have modified the expression as:

“Additionally, we adopted three prior case studies on tropopause folds to further verify the accuracy of our dataset in identifying short-term folding events. As demonstrated in following sections 3.2.1 – 3.2.3, our dataset can successfully capture the complete evolution of tropopause folds during stratospheric intrusion events.”

Q3.7: *Line 117: When you see “a folding belt over China”, you need to specify their locations, e.g. between latitude A and B, for readers who are not familiar with the local topography.*

A3.7: We have specified the range (20°N–35° N, 70°E–135°E) of the folding belt over China in the revised manuscript. Please see **L137**. Thanks for the suggestion.

Q3.8: *Lines 125-126: “The difference is the highest (~209%) in spring and the lowest (~114%) in summer. “ Are they relative differences? And how did you calculate them?*

A3.8: The reported values represent relative differences. To clarify it, we have explained it in the revised manuscript and added the formula as follows:

“The relative difference in folding frequency f between our dataset and that of Lin et al. (2024) is calculated as $(f_{\text{our dataset}} - f_{\text{Lin}}) / f_{\text{Lin}}$”

It should be noted that during the revision, we revisited the definition of total folding frequency. We noted that previous studies (e.g., Lin et al., 2024; Škerlak et al., 2015) typically exclude very shallow folding events ($\Delta p < 50$ hpa). In contrast, our *fold* variable encompasses all events, including these weak cases. To ensure a fair comparison, we re-calculated the frequencies by summing only shallow, medium, and deep folds,

consistent with the literature. The revised manuscript now includes updated results and figures (Fig. 2, Fig. 4, and Fig. 5) reflecting this adjustment. Now, the relative difference in folding frequency f between our dataset and that of Lin et al. (2024) is $\sim 87\%$ in spring and $\sim 59\%$ in summer. Furthermore, the updated results show that our dataset consistently reports lower frequencies than the ETH dataset. This discrepancy is likely attributable to the different time periods and the different resolutions of the meteorological data used in these studies. The ETH dataset was derived from the 1° ERA-Interim reanalysis data with 60 model levels. The higher vertical resolution of the reanalysis data underlying the ETH dataset likely explains its higher folding frequencies compared to our results derived from data with 37 pressure levels. However, our dataset features higher temporal (1 hr) and horizontal (0.25°) resolutions. In contrast, the dataset of Lin et al. (2024) uses the 1° ERA5 reanalysis data with 37 pressure levels. As a result, although the vertical resolution is the same, the folding frequency reported by Lin et al. (2024) is lower than ours, likely due to the coarser horizontal resolution of their reanalysis data. Please see [L190-198](#) for the discussions.

Q3.9: *Line 148: remove “(TP)”*

A3.9: We have removed all the unnecessary definitions.

Q3.10: *Line 174: again, either use PT or Tibet Plateau.*

A3.10: We thank the reviewer for the helpful suggestion. As mentioned in our previous response **A3.4**, we give the definitions of abbreviations at their first appearances. However, in Section 3.2, because the first appearance of TP occurs much earlier, we briefly restate its meaning at the beginning of the section to help readers follow. All other redundant definitions have been removed. Thanks again for this suggestion.

Q3.11: *Line 154: Dfold should be dfold, as it is not a word.*

A3.11: Corrected. Thanks.

Q3.12: *Line 165: for $y=x$ line, it is better to use 1:1 line.*

A3.12: We replaced the “y = x line” by “1:1 line”. Thanks.

Q3.13: *Line 194: Dfold should be dfold in itaiic.*

A3.13: We modified Dfold to *dfold* in italics throughout the manuscript.

Q3.14: *Line 231: Tibetan Plateau (TP) and the Sichuan Basin (SCB), see my comments above.*

A3.14: All the unnecessary abbreviation definitions are removed. Thanks for the suggestion.

Reference

- [1] Hong, J., Wang, H., Wang, W., Zhu, J., Deng, H., and Wang, H.: Impacts of stratosphere-to-troposphere transport on tropospheric ozone in southeastern China: insights from ozonesonde observations, *Environ. Res. Lett.*, 19, 064068, <https://doi.org/10.1088/1748-9326/ad4ef9>, 2024.
- [2] Langford, A. O., Senff, C. J., Alvarez, R. J., Brioude, J., Cooper, O. R., Holloway, J. S., Lin, M. Y., Marchbanks, R. D., Pierce, R. B., Sandberg, S. P., Weickmann, A. M., and Williams, E. J.: An overview of the 2013 Las Vegas Ozone Study (LVOS): Impact of stratospheric intrusions and long-range transport on surface air quality, *Atmospheric Environment*, 109, 305–322, <https://doi.org/10.1016/j.atmosenv.2014.08.040>, 2015.
- [3] Schill, G. P., Froyd, K. D., Murphy, D. M., Williamson, C. J., Brock, C. A., Sherwen, T., Evans, M. J., Ray, E. A., Apel, E. C., Hornbrook, R. S., Hills, A. J., Peischl, J., Ryerson, T. B., Thompson, C. R., Bourgeois, I., Blake, D. R., DiGangi, J. P., and Diskin, G. S.: Widespread trace bromine and iodine in remote tropospheric non-sea-salt aerosols, *Atmos. Chem. Phys.*, 25, 45–71, <https://doi.org/10.5194/acp-25-45-2025>, 2025.
- [4] Stohl, A., Bonasoni, P., Cristofanelli, P., Collins, W., Feichter, J., Frank, A., Forster, C., Gerasopoulos, E., Gäggeler, H., James, P., Kentarchos, T., Kromp-Kolb, H., Krüger, B., Land, C., Meloen, J., Papayannis, A., Priller, A., Seibert, P., Sprenger, M., Roelofs, G. J., Scheel, H. E., Schnabel, C., Siegmund, P., Tobler, L., Trickl, T., Wernli, H., Wirth, V., Zanis, P., and Zerefos, C.: Stratosphere-troposphere exchange: A review, and what we have learned from STACCATO, *Journal of Geophysical Research: Atmospheres*, 108, 2002JD002490, <https://doi.org/10.1029/2002JD002490>, 2003.