# Reply to Referee #1 Report on “Modelling the deep convective transport of trace gases (CO, $NH_3$ and $SO_2$) from the planetary boundary layer to the Asian summer monsoon anticyclone” by Ma et al. (egusphere-2025-5587)

*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.

***Summary:*** *This study investigates the model representation of convective transport from the Asian boundary layer into the Asian summer monsoon anticyclone (ASMA) over the period 2010-2020. Three trace gases are considered in the analysis. The examined simulation indicates that convective transport tendency is strongest over the Tibetan Plateau for CO and NH3, and over India and China for SO2.*

We thank the anonymous referee for reading our manuscript carefully and providing constructive comments. Below are our point-by-point responses to referee’s comments in detail.

***Overall Thoughts:*** *Overall this is a well-written study that makes an important contribution, and I believe that it should eventually be published. The authors include and discuss a large amount of relevant literature, which is a nice feature of the work. My primary concern is that I do not believe that the lone simulation presented can be trusted as representative of the real ASMA without some comparison to available observations. As the authors point out in the introduction, there have been a number of satellite, ground-based, and airborne measurements in the ASMA region, and I believe leveraging these for evaluation prior to detailed analysis of the model results is an important but currently missing feature.*

The EMAC model had been evaluated in previous work by airborne measurements in the ASMA region, which is described and referred to the literature in Sect. 2 ‘Model description and setup’ of the manuscript. For the completeness of this work, we have added comparisons with satellite observations of deep convection frequency (diagnosed using the convective cloud top heights from DaYu-GCP), CO (from MLS), $NH_3$ and $SO_2$ (from MIPAS) in the ASMA regions, as suggested by the referee. Thanks to the referee, we believe these comparisons would bring an improvement of our manuscript.

***Recommendation:*** *Major revision*

***General Remarks:***

- *As mentioned above, the comprehensive literature review in this study is quite nice. One aspect* *that appears missing is the recent discovery of the importance of East Asian emissions for the composition of the ASMA (see for example Smith et al., 2025 already cited and Pan et al., 2024, https://doi.org/10.1073/pnas.2318716121). This seems point seems to be missing in the first Introduction paragraph.*

We have added this information (Smith et al., 2025 and Pan et al., 2024) to the first Introduction paragraph of the revised manuscript.

Page 2, Line 1-3:

Deep convection plays an important role in the vertical redistribution of trace gases and the pollution transport from the planetary boundary layer (PBL) to the upper troposphere and lower stratosphere (UTLS) (Chatfield and Crutzen, 1984; Dickerson et al., 1987; Lelieveld and Crutzen, 1994; **Pan et al., 2024**).

Page 2, Line 8-12:

Deep convection can transport Asian pollutants, especially those from South Asia **and East Asia**, to the Asian summer monsoon anticyclone (ASMA) (Hoskins and Rodwell, 1995), where they are confined by the ASMA flow, forming a distinct chemical regime in the UTLS of the Northern Hemisphere during summertime (Randel and Park, 2006; Park et al., 2007; Park et al., 2008; Randel et al., 2010; **Smith et al., 2025**).

- *On page 3 the authors imply that the DC3 campaign has fully characterized and quantified deep convective transport, which I don't think any airborne campaign could truly do. I suggest instead that this remark be reframed that airborne measurements alone, however valuable, are not sufficient to fully characterize and quantify deep convective transport due especially to limited sampling in space and time, thus necessitating the use of numerical modeling to provide such estimates. This can serve to nicely motivate the present study as well.*

  We have rewritten the sentence in the revised manuscript (Page 3, Line 18-23).

  The chemical composition of the convective inflow and outflow was measured during the Deep Convective Clouds and Chemistry (DC3) field experiment taking place in North America (Barth et al., 2015); these airborne measurements alone, while valuable, are not sufficiently to fully characterize and quantify deep convective transport due especially to limited sampling in space and time, and numerical modeling considering detailed chemical, physical and dynamical processes are still needed to provide such estimates (Barth et al., 2007;Barth et al., 2012;Barth et al., 2026).

- *The model representation of convective transport is integral to this study, but I don't see any mention or reference to how the CVTRANS submodel actually works. Moreover the cited Tost et al. (2006b) study does not seem to explicitly mention either the CONVECT or CVTRANS submodels. It would be helpful for the authors to provide some more information or documentation here for reader interest.*

  It is true that either the CONVECT or CVTRANS was mentioned in Tost et al. (2006b) although the two submodels were developed based on the work of Tost et al. (2006b). We are sorry for leaving out a literature, Tost et al. (2010) (which provides the names CONVECT and CVTRANS for the two respective submodels), in the original version of the manuscript. We have added this citation and provided a brief description of CVTRANS in the revised manuscript. More detailed information on CVTRANS can be found in Tost et al. (2010) and Jeske and Tost (2025).

Page 5, Line 3-4:

Convective cloud processes and convective tracer transport are calculated using the CONVECT and CVTRANS submodels (Tost et al., 2006b**; Tost et al., 2010**),

Page 5, Line 10-13:

CVTRANS calculates the tracer transport following the bulk approach ("leaky pipe") based on Lawrence and Rasch (2005). It is implemented with an interface to collect the required updraft and downdraft air mass fluxes and the respective entrainment and detrainment rates from CONVECT for a selected convection scheme (e.g. the Tiedtke-Nordeng scheme in this study) (Tost et al., 2010; Jeske and Tost, 2025).

- *Related to the above comment, it would be good if the authors could clarify whether convective transport tendency and convective transport efficiency calculations are performed within the model physics code immediately prior to and following convective transport. If not, I would expect that other processes would need to be considered too, such as horizontal transport from surrounding regions and chemical losses.*

Yes, the convective transport tendency calculations are performed within the model physics code immediately prior to and following CVTRANS. This information is provided in the first paragraph of Sect. 3.4 of the revised manuscript (Page 10, Line 2-7).

The tendency of a tracer due to convective transport alone can be obtained by extracting a corresponding variable (named 'xtte_cvtrans'), which is the difference in the tracer's mixing ratio before and after the implementation of CVTRANS. Simulated results for xtte_cvtrans are saved at 5-hr intervals as done for other variables, and these instantaneous values of xtte_cvtrans can be considered as averages over each time interval, with its unit changed from mol mol$^{-1}$ s$^{-1}$ to nmol mol$^{-1}$ hr$^{-1}$ (ppbv hr$^{-1}$) or pmol mol$^{-1}$ hr$^{-1}$ (pptv hr$^{-1}$). For the cases without convection, the tendency is set as zero and is accounted for when doing seasonal and climatic averaging.

For the original manuscript, the seasonally mean convective transport efficiency was calculated by using the seasonally averaged updraft mass fluxes over all the convective period. For the revised manuscript, we have changed the statistic method by calculating the individual convective transport efficiency from the instantaneous updraft mass fluxes in each convection column first, and then calculating the seasonally mean convective transport efficiency using its individual values for each convection case. This information is provided in the caption of Figure 6 of the revised manuscript. It appears that this change of the calculation method does not affect the results and conclusions described in the manuscript text.

**Figure 6.** EMAC simulated averages of deep convective transport efficiency (CVE), i.e., the ratio of the updraft mass flux (UMF) at 10 km height above sea level to its maximum in each convection column (expressed in percent), for CO **(a)**, $NH_3$ **(b)** and $SO_2$ **(c)**, in JJA during the years 2010-2020.

- *The first three sentences in Section 3 seem unnecessary to me, as the information should have already been made clear in Sections 1 and 2. The middle sentence in particular doesn't make sense to me, as there doesn't appear to be any "observed" convection involved in this study, only simulated convection.*

  We have deleted these sentences in the revised manuscript

- *It's worth noting that CAMS emissions of SO2 over China likely underestimate recent reductions due to environmental policies over 2010-2020, as described by an upcoming publication (https://doi.org/10.22541/essoar.175682819.92297398/v1). This might be the reason why SO2 convective transport is highest over China in the simulation presented herein. This could be mentioned as Figure 1c is described, as these model PBL values are mostly controlled by the emissions used as input.*

  We have added the following sentences in the revised manuscript (Page 6, Line 31 – Page 7, Line 2).

  It should be noted that CAMS emissions of $SO_2$ over China might underestimate recent reductions due to environmental policies over 2010-2020, which can result in an overestimation of its PBL abundance and convective transport to the upper troposphere over eastern China (Smith et al., 2025b).

- *Are the results in Figure 2 supported by observations? It seems that convection is mostly concentrated over high terrain and it's important to verify that with observations if we want to believe the subsequent model results of convective transport tendency. Figure 1 of Smith et al (2025, already cited) does not show this same signal in satellite observations over the Tibetan Plateau, albeit for a single and different year.*

  As suggested, we have added comparisons of our model results with satellite observations. Please see revised Figure 2 and added discussion in Sect. 3.2 of the revised manuscript (Page 7, Line 14 – Page 8, Line 3).

  In this study, we employed the all-day Global Cloud Product derived from a single-layer cloud retrieval model within the DaYu cloud analysis system (DaYu-GCP), based on the merged thermal infrared brightness temperature of the global geostationary satellite from the Gridded Satellite project (Knapp et al., 2011), to evaluate the EMAC model…….

  …….Our model results of enhanced deep convection frequency over the Tibetan Plateau are also supported by satellite observations presented in previous work (see Figure 2 of Fu et al. (2006), which has shown that number counts of convective clouds over the Tibetan are larger than those over the Tibetan southern slope at an altitude range of 11-16 km and those over the Indian monsoon region throughout all the altitude range.

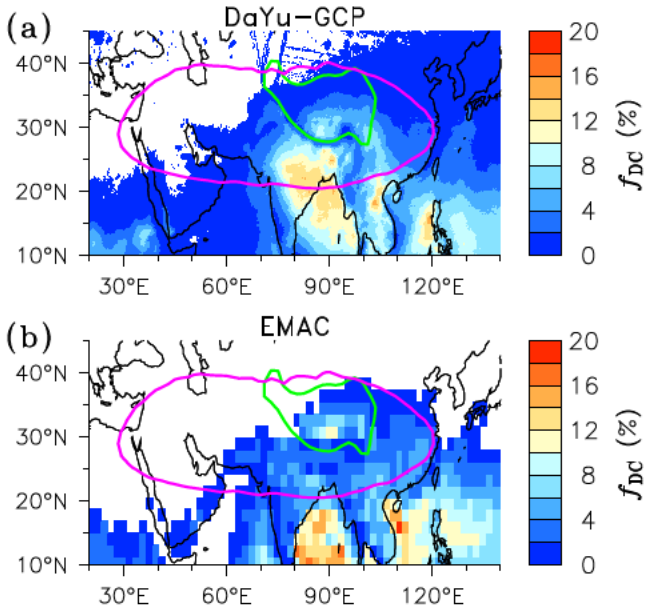
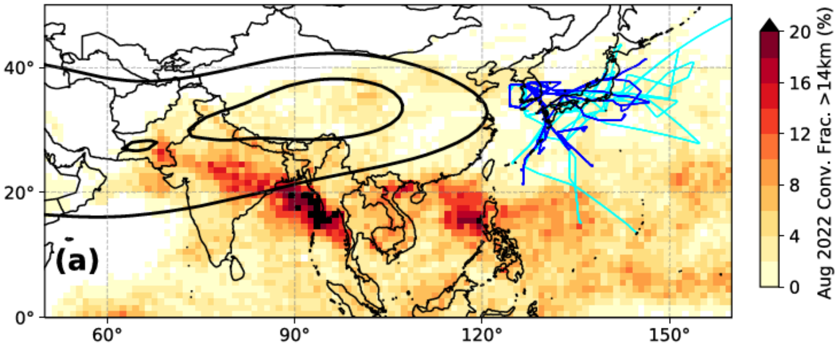


**Figure 2.** Comparison of EMAC simulated relative deep convection frequency ($f_{DC}$ in percent) for convective cloud top heights reaching above 14 km above sea level with DaYu-GPC satellite data **(a)** in JJA during the years 2010-2020. Purple lines are the 16.64 km geopotential height contour at 100 hPa, highlighting the main ASMA area (see Figure S1). Green lines represent the 3 km terrain height contour, highlighting the Tibetan Plateau.

In addition to Fu et al. (2006) cited in the revised manuscript, recent analysis of FY-4B geostationary satellite data by Zhao et al. (2025) also shows that there are enhanced deep convection system number counts over the central (66611) and southern (67477) Tibetan Plateau during the summer period.



**Smith et al., 2025** (https://doi.org/10.1029/2024JD042732), Figure 1: flight tracks overlain on a distribution of deep convective occurrence fraction, calculated as the fraction of August 2022 where a given location featured a convective cloud top altitude of at least 14 km. Convective cloud top altitudes are derived from CloudSat/CALIOP satellite observations using the method described by Pfister et al. (2022).

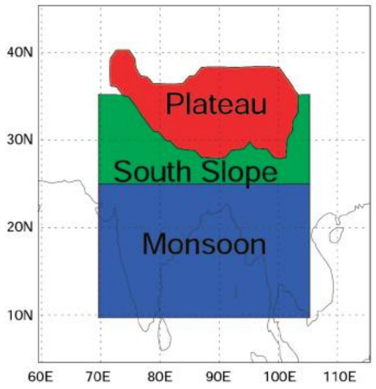
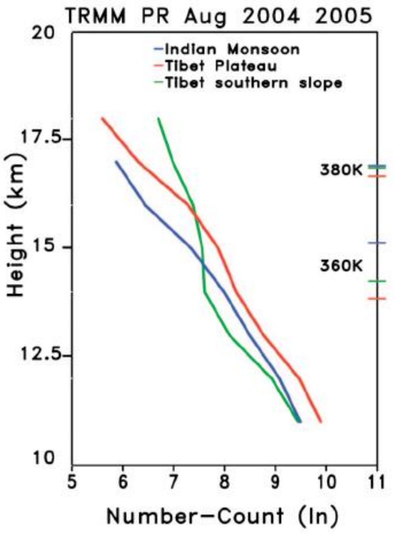
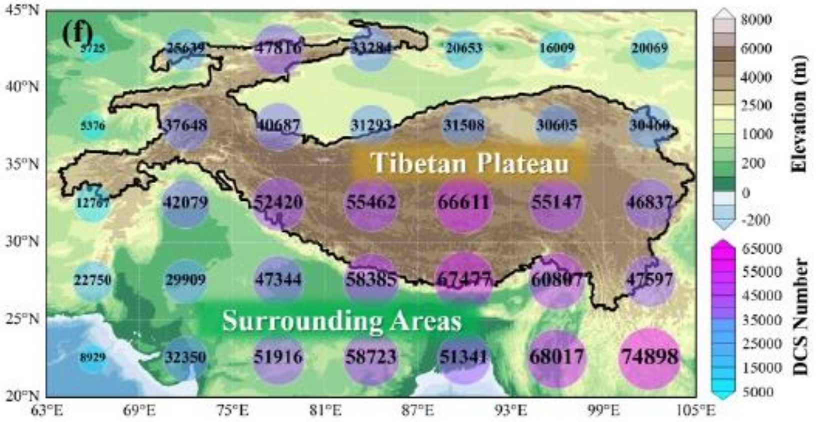


**Fig. 1.** Regions defined in this study. The TP is defined as the area with an elevation of >3 km within 70–105°E and 25–40°N, the Plateau south slope is defined as the area with elevation <3 km within 70–105°E and 25–35°N, and the monsoon area is defined as 70–105°E, 10–25°N.



**Fu et al., 2006** (http://www.pnas.org/content/103/15/5664.abstract), Figure 2: Number counts of convective tops > 10 km as a function of altitude over the TP (red), Plateau south slope (green), and monsoon region (blue) during the period of August 2004 and 2005 derived from TRMM PR rain rate (product2A25). The tropopause (380 K) and 360 K in these three regions are indicated on the right axis with the same color as defined for the profiles.



**Zhao et al., 2025** (https://doi.org/10.1029/2025GL118433), Figure 1: The spatial distribution of the deep convection system number and elevation across the study area during the summer of 2022-2024 from the Fengyun-4B satellite observations.

It appears that there are some disagreements in the distribution of deep convective occurrence over the Tibetan Plateau and surroundings between different satellite observations, perhaps due to the differences in sensor's sensitivity, overpass time, cloud filtering, and statistic method.

- *As suggested above, I think it is also important to compare the results presented in Figure 3 (volume mixing ratios) with available observations to demonstrate the simulation's realism. Otherwise it is hard to know whether the subsequent model results are likely to be representative of the real ASMA environment.*

  We have added comparisons of our model results with MLS CO and MIPAS $NH_3$ and MIPAS $SO_2$. The comparison results indicate that EMAC can well simulate deep convective transport of typical pollutants like CO from the PBL to the ASMA. Please see added Figure 3 and detailed description of comparisons in first three paragraphs of Sect. 3.3 of the revised manuscript (Page 8, Line 9 - Page 9, Line13).

  We evaluate the model's performance in simulating CO, $NH_3$ and $SO_2$ within the ASMA, using satellite measurements of CO from the Aura Microwave Limb Sounder (MLS) (Livesey et al., 2018;Yan et al., 2019 and reference therein), $NH_3$ and $SO_2$ from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (Höpfner et al., 2015b;Höpfner et al., 2016)……

  ……The comparisons presented here have provided the regional distribution characteristics of trace gases in the ASMA and its surroundings under cloud-free conditions. Since convective transport is generally associated with cloud processes, below we analyse the model results using the data for both the clear-sky and cloudy conditions.

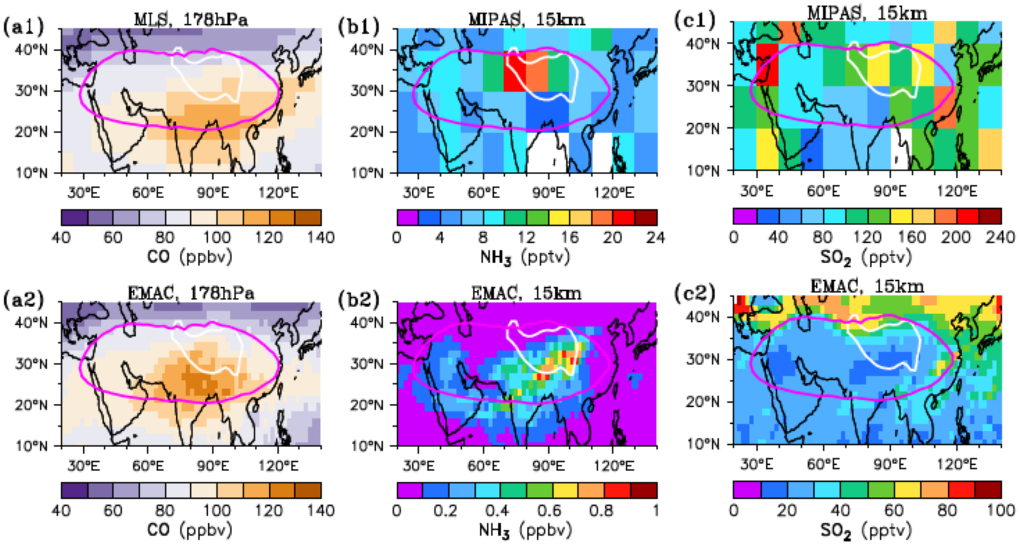
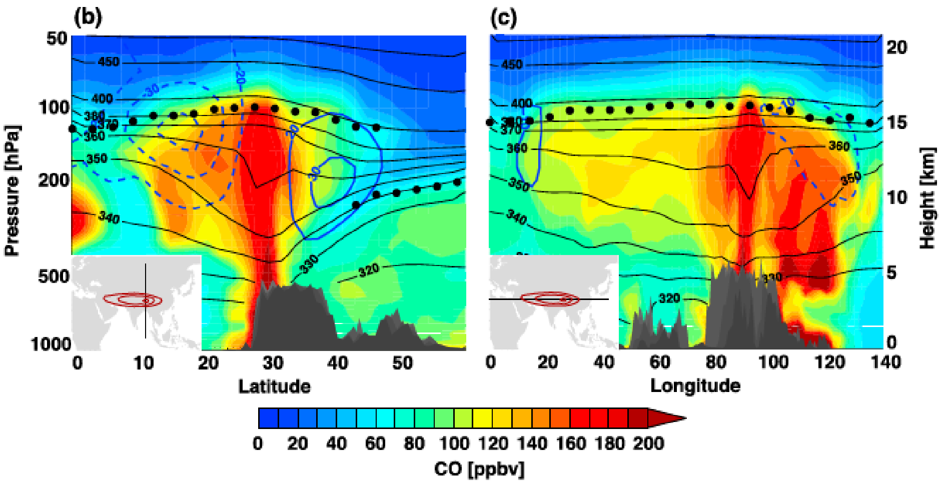


**Figure 3.** Comparisons of EMAC simulated cloud-free CO (**a2**) with MLS observed CO (**a1**) at 178 hPa for JJA over the years 2010-2020 and EMAC simulated cloud-free $NH_3$ (**b2**) and $SO_2$ (**c2**) with MIPAS observed $NH_3$ (**b1**) and $SO_2$ (**c1**) at 15 km above sea level for JJA 2010-2011. Purple lines show the 16.64 km geopotential height contour at 100 hPa, highlighting the main ASMA area. White lines represent the 3 km terrain height contour, highlighting the Tibetan Plateau. White grid cells in (**b1**) and (**c1**) indicate the default values in MIPAS dataset.

- *I question how useful the convective transport efficiency calculation presented in Figure 5 is, as it seems to just highlight the same region where most of the model convection is (the Tibetan*

*Plateau, Figure 2). Perhaps transport efficiency is high there because of the enhanced convection, but the Plateau is a region where emissions are comparatively low (Figure 1) so this efficient transport still shouldn't impact ASMA composition all that much.*

It is true that emissions are very low in the Tibetan Plateau, but pollutants from the surroundings (e.g., South Asia) can be transported to the lower troposphere over the Tibetan Plateau (at least over its southern edge by convergence flow as shown in Fig. 1 of this study) and further transported to the ASMA by enhanced convection there. Although the amounts of pollutants transported to the Tibetan Plateau are very small compared to their emission source regions, they can impact ASMA composition due to efficient convective transport there (e.g., for CO). These have been shown in previous studies, e.g., Fu et al., 2006 (http://www.pnas.org/content/103/15/5664.abstract) and Pan et al., 2016 (http://dx.doi.org/10.1002/2016JD025616) (see a copy of figure below). On the other hand, we showed that if the amounts of pollutants transported to the Tibetan Plateau are extremely small, due to efficient wet scavenging while being transported, they would not impact ASMA composition above the region, despite the enhanced convection there (e.g., for $SO_2$). Here we would like to highlight high convective transport efficiency of the pollutants over the Tibetan Plateau.



**Pan et al., 2016** (http://dx.doi.org/10.1002/2016JD025616), Figure 2: (b) Latitude-pressure/altitude cross section of CO (ppbv) along 90 E (as shown on the locator map at the lower corner). (c) Same as Figure 2b but for longitude-pressure/altitude cross section.

- I don't believe that the title of "Discussion" for Section 4 is appropriate, I would suggest something related to model scavenging processes instead. It seems to me that this section is meant to provide additional analysis to give context to what was presented in Section 3. In my view a discussion is a reflection of past analysis rather than a presentation of new analysis.

As suggested, we have removed this title and merged Sect. 4 in to Sect. 3 using a new section title name of ‘Results and discussion’.

- I believe that the conclusions section is missing some big-picture link(s) back to ASMA research as a whole. The early literature review is nice, and I think it would help to discuss how previous studies can be put into context by these targeted model results, or specifically how future research in this field should be guided. Compatibility of the simulation with observations will add critical confidence that the real ASMA behaves in a similar way to support such claims.

We have added the following sentences to the last paragraph of the revised manuscript (Page 14, Line 15-22).

The ASMA has unique physical-chemical features, influenced by deep convective transport of pollutants from the Asian PBL, with the Tibetan Plateau acting as a well-defined conduit. In this study, our model simulations, together with satellite-based observational data analysis, further demonstrate the role of deep convection over the Tibetan Plateau in effectively transporting CO, an insoluble reactive gas, from the Southern Asian PBL to the ASMA. Our model simulations show that deep convective transport to the ASMA over the Tibetan Plateau is also effective for $NH_3$, but ineffective for $SO_2$. However, these model results for $NH_3$ and $SO_2$, the two soluble reactive gases, are not entirely supported by the satellite observations. The causes of the discrepancy between model simulations and satellite observations of $NH_3$ and $SO_2$ in the ASMA cannot be determined in this study, posing a challenge for modeling and remote sensing of these two gases in future research.

***Technical Remarks and Typos:***

- *Page 1 Line 24: typo, remove “is”.*

  Done.

- *Page 2 Line 7: I recommend removing “a convective manifestation”.*

  Done.

- *Page 2 Line 15: consider replacing “outside it” with “its surroundings”.*

  Done.

- *Page 2 Line 18: I see that the term “smokestack” appears once in the Yu et al. (2017) study, but I think the “vertical conduit” terminology from Bergman et al. (2013) is much more widely accepted. I believe it should be used throughout this paragraph.*

  We have changed “an efficient smokestack” to “a vertical conduit” in the revised manuscript (Page 2, Line 18).

- *Page 3 Line 4: I suggest removing “dynamic”.*

  Done.

- *Page 3 Line 16: The appropriate citation for the ACCLIP campaign is the recently published overview paper (Pan et al., 2025, https://doi.org/10.1029/2025JD044417).*
  Added.

- *Page 6 Line 30: "mPa" should be "hPa".*
  Corrected.

- *Page 7 Line 7: whether a 10% frequency is "high" is subjective. I would rephrase to just say that the frequency reaches 10%. The same thing occurs on Page 8 Line 23.*
  Rephrased.

- *Page 7 Line 16: I don't think that "respectively" is required in this case.*
  Deleted.

- *Page 7 Line 21: I suggest replacing "model study before" with "past model studies".*
  Done.

- *Page 8 Line 30: missing period.*
  Added.

- *Page 12 line 6: missing period.*
  Added.

- *Figure 7 caption: I suggest changing both instances of "in the rains" to "in precipitating downdrafts".*
  Done.

- *Figure S1 caption: typo, "hPa".*
  Corrected.

**Many thanks!**