

Reply to Referee #2 Report on “Modelling the deep convective transport of trace gases (CO, NH₃ and SO₂) 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 author’s tracked-changes version of the revised manuscript.

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

Summary: *This study uses the EMAC chemistry–climate model to diagnose deep-convective transport of CO, NH₃, and SO₂ from the planetary boundary layer (PBL) into the Asian summer monsoon anticyclone (ASMA) during JJA for 2010–2020, and interprets inter-species differences using convective cloud partitioning and wet deposition diagnostics.*

The topic is relevant and potentially informative. However, key conclusions are not sufficiently supported because (i) the diagnostics are interpreted beyond what they can uniquely demonstrate, and (ii) the manuscript lacks an observational evaluation of the modelled convection and UTLS tracer distributions that underpin the results.

We thank the anonymous referee for reading our manuscript carefully and providing constructive comments. As mentioned in the manuscript, the model results in the ASMA area have been previously largely evaluated with in situ and remote sensed observations (e.g. Gottschaldt et al., 2017; Lelieveld et al., 2018; Tomsche et al., 2019; Johansson et al., 2020; Ma et al., 2019; Rosanka et al., 2021; Xenofontos et al., 2024; Becker et al., 2025). Nevertheless, we have added comparisons with satellite observations of deep convection frequency (diagnosed using the convective cloud top heights from DaYu-GCP), CO (from MLS), NH₃ and SO₂ (from MIPAS) in the ASMA regions, as suggested by the referee. The comparison results show that EMAC can simulate the general features of deep convection and associated transport to the ASMA. These have been added to the revised manuscript.

Overall assessment / recommendation

Major revision. *The current evidence is not yet sufficient to substantiate the stronger claims about the “dominant role” of deep convection and tracer-specific pathways into the ASMA, especially given the reliance on seasonal averages, the lack of explicit budget attribution (e.g.,*

horizontal advection vs convective injection), and the potential influence of non-PBL SO₂ sources.

In this study we focus on the role of deep convection on the enhancements of selected tracers within the ASMA from a climatology point of view. Therefore, we calculated the seasonal averages of the convective transport tendencies (CVTs) of CO, NH₃ and SO₂ (Fig. 4 and old-Fig. 3) and compared them with the seasonal averages of the mixing ratios of CO, NH₃ and SO₂ (Fig. 5 and old-Fig. 4). Comparison results clearly show the consistence in the location between the CVT maximums and the mixing ratio maximums for all the selected tracers, indicating a role of deep convection in the enhancements of these tracers within the ASMA. Even so, we agree with the referee that it would be better to use ‘**a role of deep convection**’ than ‘a dominant role of deep convection’ in the revised manuscript (Page 10, Line 14).

We had also used the seasonally-averaged mass fluxes to calculate the mean deep convective transport efficiency (CVEs) of CO, NH₃ and SO₂ (Fig. 6 and old-Fig. 5). As suggested, we have used instantaneous mass fluxes to calculate CVEs for each convection case first, and then averaged them to get the seasonal mean values of CVEs. No matter which methods used, the CVEs are found to be higher over the Tibetan Plateau than its surrounding areas. It should be noted that the amounts of a tracer transported to the upper troposphere via the Tibetan Plateau are determined not only by tracer’s CVEs, but also by tracer’s amounts available in the PBL and lower troposphere in the area. To make this point more clearly, we have changed the phrase ‘is an effective pathway’ to ‘**can be a potentially effective pathway**’ in the revised manuscript (Page 10, Line 28).

An explicit budget analysis might show the potential influence of various processes (e.g., horizontal advection vs convective injection) on the loadings of tracers in a relatively large area, e.g., the ASMA. But the horizontal advection tendency of a tracer in a model grid cell is determined by both the winds (speed and direction) and the tracer mixing ratios in this and surrounding cells. It may not be suitable for investigating the sources of a tracer in a relatively small area, e.g., one or several model grid cells, due to high variability of wind fields. Especially, the tracer mixing ratios used to calculate the horizontal advection fluxes are influenced by the convection injection, making the separation between the two processes difficult for a relatively small area, e.g., over southern Tibetan Plateau. Our model simulations have shown that SO₂ levels are generally lower inside the ASMA than its surroundings due to limited convective transport from the PBL. The non-PBL SO₂ sources, e.g., volcanic erupted SO₂ plumes, can influence SO₂ levels within the ASMA to some extent, as shown in added figures (Fig.3a and Figs. S4 of revised manuscript). Since such kind of non-PBL sources are from the outside of the Asian summer regions, their impacts should be smaller inside the ASMA than its outside due to a dilution effect during transport.

Major comments

1. *The manuscript makes a broad novelty statement (“for the first time... quantify the deep convective transport efficiency...”). As written, this is too broad, as convective “efficiency” metrics and convective injection diagnostics are used in the broader convection–chemistry literature. The paper does not clearly delineate what is new (e.g., the specific CVTRANS/UMF framework applied to a multi-year ASMA climatology for these tracers), versus an application of existing diagnostics.*

We have deleted the phrase ‘for the first time’ in the revised manuscript (Page 13, Line 26).

2. *The convective transport tendency (CVT) is defined as the difference in mixing ratio before and after the CVTRANS step, isolating the convective effect. However, the manuscript states that the mean CVT is calculated by averaging across all time intervals, not only deep convection events. But a time-mean over all intervals blends convective and non-convective periods and is not equivalent to a convective-conditional tendency. Yet the Results/Discussion uses correspondence between CVT and seasonal-mean mixing ratios to argue a “dominant role” of deep convection. This inference is not robust without explicitly demonstrating the relative roles of other processes that shape ASMA composition (horizontal advection/recirculation in the anticyclone, large-scale ascent, mixing, chemical loss, wet scavenging). This is particularly important for CO, which is long-lived and readily redistributed horizontally after injection.*

We did calculate the CVTs for each deep convection event individually, and then average the CVTs across all time intervals, including no deep convection cases (i.e., CVT = 0). In this way, the individual CVTs are weighted by number counts of deep convection, and derived seasonally mean CVTs can be compared to the seasonally mean mixing ratios reasonably.

Here we may take two different areas (A and B) to illustrate the rationality of our calculation method. For instance, over a period with 100 of time intervals, there are 50 deep convection events over Area-A and 1 deep convection event over Area-B, with a CVT value of 10 pptv/hr for each event. We get a period-mean CVT of 5 pptv/hr for Area-A (by $10 \times 50 / 100$), and a period-mean CVT of 0.1 pptv/hr for Area-B (by $10 \times 1 / 100$). If we had calculated an average only for the deep convection events (i.e., neglecting the number counts of deep convection), we could get a mean CVT of 10 pptv/hr for both Area-A and Area-B, which would not match to the changes in mixing ratios due to deep convection over the two areas during the entire period. Note that we do not focus on one or several deep convection events in this study.

Tracers tend to undergo dilution process during horizontal transport. We cannot assume any strong emission sources of CO, NH₃ and SO₂ existing in the UTLS to explain their

enhancements within the ASMA. The chemical loss and wet scavenging would reduce the tracer mixing ratios. Large-scale ascent, mixing and redistribution horizontally of tracers (e.g., CO, as pointed by the referee) can occur in the ASMA. But these transport processes might increase the tracer mixing ratios of transport-targeted areas only after injection of higher levels of tracers by deep convection to transport-sourced areas in the ASMA. While the latter (deep convection effect) is demonstrated by our analysis of CVT, the former (follow-up effect after injection) is not the focus of this study.

3. *The model configuration includes explosive volcanic SO₂ plumes during 2010–2020, added to the UTLS background SO₂. Because the central goal is PBL to ASMA convective transport, this introduces a significant attribution ambiguity on the UTLS/ASMA SO₂ burden. The diagnostics (including CVE/CVT interpretations) presented here may not reflect boundary-layer Asian emissions alone. The manuscript notes this issue only briefly, but it directly affects the interpretability of SO₂ spatial patterns and transport conclusions.*

The Nabro volcano erupted on 12–13 June 2011 is a typical case that impacted SO₂ in the UTLS over the Asian summer monsoon region. We examined the case of the year 2011 (see Figs. A1-A3 below) in comparisons with the climatically averages of 2010-2020 (Figs. 4-6 of revised manuscript). It appears that the impacts of explosive volcanic SO₂ plumes on the calculated CVE/CVT within the ASMA are limited, although the increases in the SO₂ mixing ratio outside the ASMA are significant. This can be explained by the facts that the ASMA is a transport barrier separating trace gases between inside and outside and that the exchanges can take place to some extents along the edge of it.

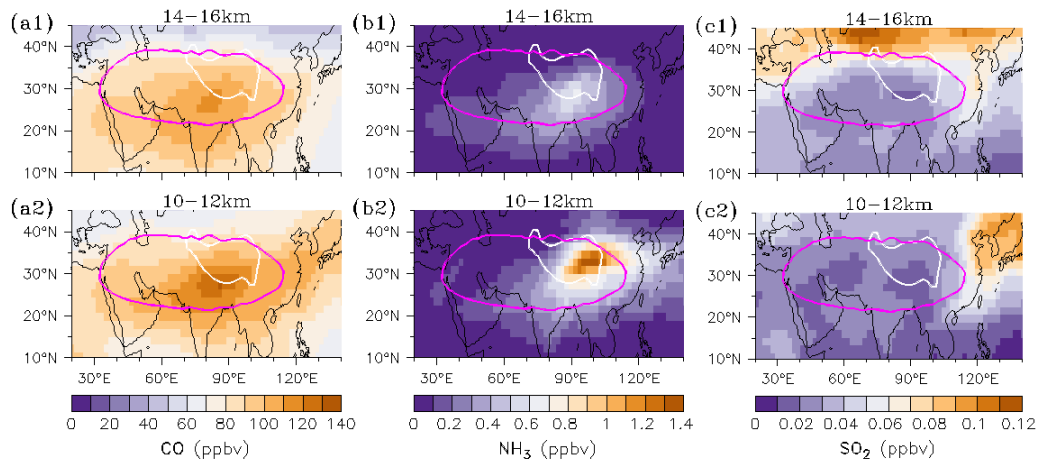


Fig. A1 Same as Fig. 4 (old-Fig. 3), except for 2011

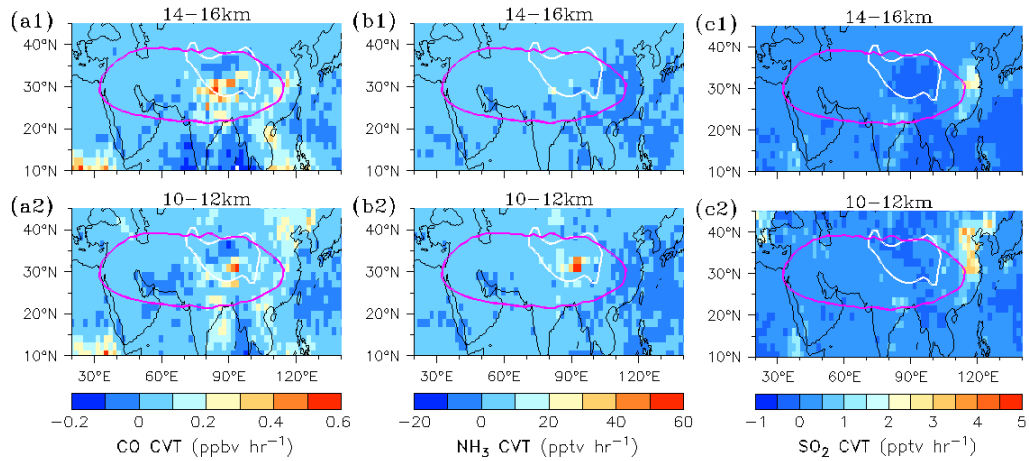


Fig. A2 Same as Fig. 5 (old-Fig. 4), except for 2011

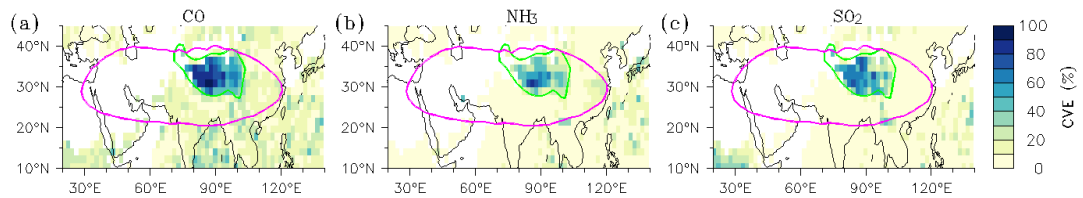


Fig. A3 Same as Fig. 6 (old Fig. 5), except for 2011

4. *The manuscript references prior evaluations of EMAC but does not provide a focused evaluation of the modelled deep convection frequency and vertical reach in JJA over the ASMA region, and UTLS distributions of CO, NH₃, and SO₂ during the study period with observations. Given that the paper’s conclusions hinge on convection and scavenging processes, this absence weakens confidence in the interpretation.*

We have added comparisons of model results with satellite observations in the revised manuscript. 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.

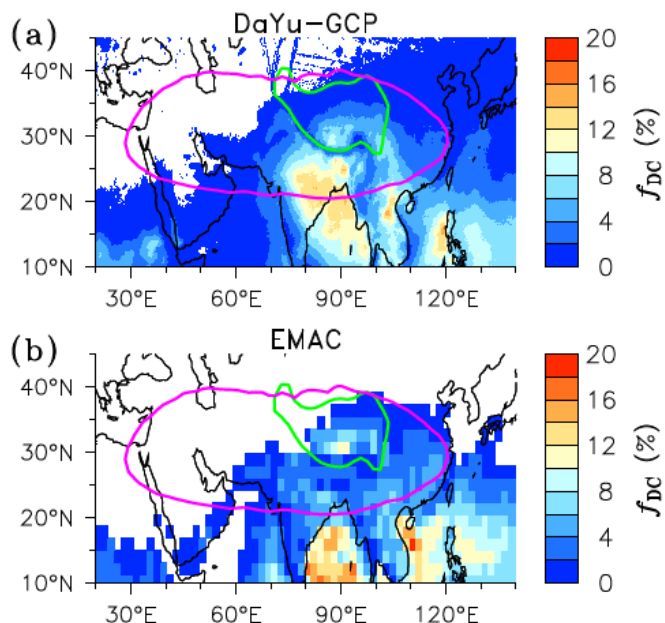


Figure 2. Comparison of EMAC simulated relative deep convection frequency (f_{DC} in percent) for convective cloud top heights reaching above 14 km above sea level with DaYu-GPC satellite data **(a)** in JJA during the years 2010-2020. Purple lines are the 16.64 km geopotential height contour at 100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

Also 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, NH₃ and SO₂ 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), NH₃ and SO₂ 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.

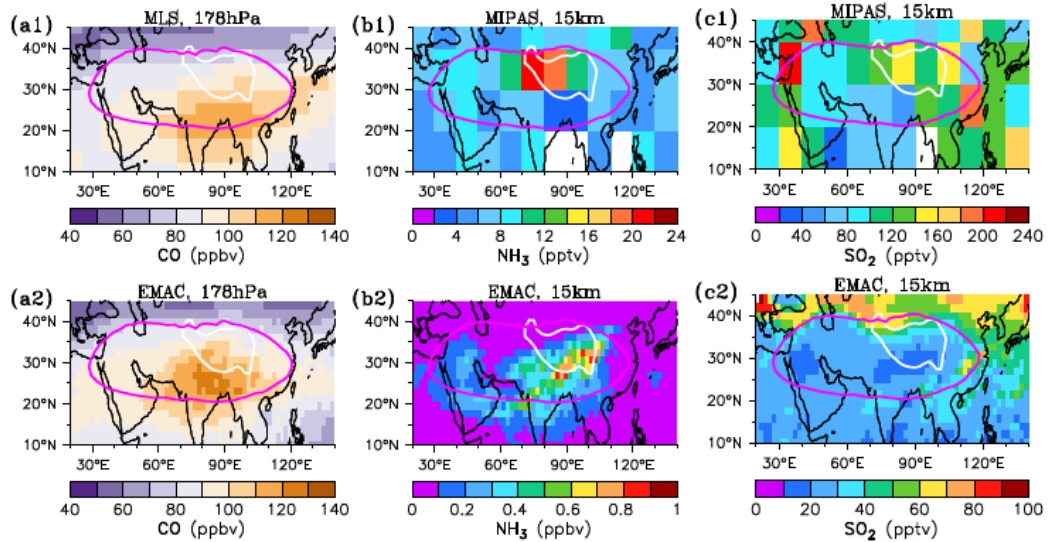


Figure 3. Comparisons of EMAC simulated cloud-free CO (a2) with MLS observed CO (a1) at 178 hPa for JJA over the years 2010-2020 and EMAC simulated cloud-free NH₃ (b2) and SO₂ (c2) with MIPAS observed NH₃ (b1) and SO₂ (c1) at 15 km above sea level for JJA 2010-2011. Purple lines show the 16.64 km geopotential 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.

Minor/technical comments

1. In the abstract, “there is can even be a decrease...” needs correction
Done (see Page 1, Line 26).
2. There appears to be a latitude typo (20–40 N) and a pressure-unit typo (100 hPa) in lines 6-7.
Corrected (see Page 7, Line 9-10).
3. CVT is defined as a before/after CVTRANS mixing ratio difference, but the reported tendency units (ppbv hr^{-1}) require explicit time normalization; this step is not clearly stated in the methodology description.

We have added following description in 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 ‘x_{tte_cvtrans}’), which is the difference in the tracer's mixing ratio before and after the implementation of CVTRANS. Simulated results for x_{tte_cvtrans} are saved at 5-hr intervals as done for other variables, and these instantaneous values of x_{tte_cvtrans} can be considered as averages over each time interval, with its unit changed from $\text{mol mol}^{-1} \text{s}^{-1}$ to $\text{nmol mol}^{-1} \text{hr}^{-1}$ (ppbv hr^{-1}) or $\text{pmol mol}^{-1} \text{hr}^{-1}$ (pptv hr^{-1}). For the cases without convection, the tendency is set to be zero and is accounted for when doing seasonal and climatic averaging.

4. *In the introduction, “a convective manifestation observed...” is a vague term; it should be revised.*

The phrase ‘a convective manifestation’ has been removed in the revised manuscript (Page 2, Line7).

5. *Figure 1 caption; correct “overlayed” to “overlaid.*
Done.

6. *In section 3.2, correct the unit “pptbv”*
Done.

7. *What do you mean by “in the rains” in figure 7 caption?*

It has been changed to ‘in the precipitating downdrafts’ in the revised manuscript.

Many thanks!