**Response to Referee #2**

This is an interesting and important study, which merits its publication in ACP. The scientific content, the quality of the study and its presentation is good, however I suggest some revisions before publication by ACP.

General comment:

My principle concern is that the role of convection within the study by Zhu et al. (2025) is not discussed sufficiently. 'The complex interaction between monsoon dynamics and surface emissions to determine the upper tropospheric methane' is highlighted as main result of the paper. However, the definition of 'monsoon dynamics' remains unclear. My impression is that 'monsoon dynamics' stands here for the spatial-temporal variability of the Asian summer monsoon anticyclone in the upper troposphere and lower stratosphere (east-west and south-north shift, Iranian and Tibetan mode). However, convection that uplift methane to altitudes of the upper troposphere plays a major role within the monsoon dynamics. Maybe there is a misunderstanding, therefore, I recommend improving the study by clarify the role of convection. More specific comments to this issue will follow below.

We sincerely thank Referee #2 for the thoughtful and constructive comments, which have significantly improved the quality and clarity of our manuscript. We have carefully addressed all points raised in the revised version. Reviewer comments are presented in black, with our responses provided in blue. Page and line numbers from the updated manuscript are underlined. The main revisions made to the manuscript are summarized below:

* We have clarified the role of the monsoon dynamical system in methane transport, with particular emphasis on the rapid vertical lifting by deep monsoon convection and the influence of the relative position between the AMA and organized monsoon convection during the slow upwelling from the outflow level to the UTLS region. To better illustrate this, we have expanded the relevant background discussion on rapid lifting and slow upwelling in the Introduction, thoroughly revised Section 3.2, and added panels on deep convection and lower tropospheric methane to Figure 4.
* To improve the description of the AMA mode classification, we have extensively revised Section 2.2 and added Figure 1 to more intuitively illustrate the spatial morphology of different modes and the statistical distribution of anticyclone centers.
* Several previously ambiguous terms in the manuscript, such as the definitions of “anomalies” and “enhancement,” as well as the earlier inadequate use of “transport pathway,” have been revised for greater accuracy and clarity.

**Major comments:**

1. p1 L26: 'The AMA center over the Iranian Plateau suppresses the vertical transport'. This formulation is confusing. Over the Iranian Plateau shallower and less intense convection occurs during summer compared to regions further east (e.g Indian subcontinent, Bay of Bengal, China). Therefore, a lower amount (or rather no) methane can be transported from surface levels to the upper troposphere over the Iranian Plateau (see Fig. 3 in Zhu et al., 2025). Thus, if the anticyclone is over IP far off the strong convective sources (e.g. Indian subcontinent, Bay of Bengal, China), methane cannot be uplifted locally over the Iranian Plateau into altitudes of the anticyclone in contrast to the TP mode. What is meant with 'suppresses the vertical transport'? That the location of the AMA over the Iranian Plateau suppress convection over the Iranian Plateau? Please clarify.

We thank the reviewer for pointing out the ambiguity in our original formulation. We agree that the previous statement "The AMA center over the Iranian Plateau suppresses the vertical transport" was not sufficiently precise and may have led to misunderstanding. Our intended meaning was that when the AMA center is located over the Iranian Plateau, it is positioned far from the primary monsoon convective regions (e.g., the Indian subcontinent and the Bay of Bengal), and therefore it suppresses the vertical transport of air from these organized monsoon convective sources—specifically from their convective outflow levels to higher altitudes in the upper troposphere and lower stratosphere (UTLS). In such a configuration, horizontal redistribution within the anticyclone becomes more dominant, rather than further vertical uplift into the UTLS.

We have revised the relevant sentence in the abstract to clarify this point as follows:

“The AMA center around 80°E favors the upward transport from organized monsoon convective sources over the Indian subcontinent and Bay of Bengal while the AMA center around 105°E favors the source from southwest China transported to the upper troposphere. When the AMA shifts over the Iranian Plateau, vertical transport from the convective outflow level further to the upper troposphere is weakened and the horizontal redistribution becomes dominant.”

And we also rewrote the relevant parts in sec. 3.2 first paragraph in the conclusion in a much clearer way, which is also responsible for 15th and 16th major comments below.

1. p2 L40: '(Park et al., 2009; Pan et al., 2016; Randel et al., 2010; Rosenlof et al., 1997; Yu et al., 2017)' Please add here some more recent publications e.g. from aircraft campaigns that measured air within the AMA during StratoClim 2017 and ACCLIP 2022 showing enhanced tropospheric tracers within the anticyclone.

We thank the reviewer’s suggestion. These recent flight campaigns nicely supported this point. The following relevant references have been added in P2 L43 of the revised manuscript:

[1] Pan, L. L., Atlas, E. L., Honomichl, S. B., Smith, W. P., Kinnison, D. E., Solomon, S., Santee, M. L., Saiz-Lopez, A., Laube, J. C., Wang, B., Ueyama, R., Bresch, J. F., Hornbrook, R. S., Apel, E. C., Hills, A. J., Treadaway, V., Smith, K., Schauffler, S., Donnelly, S., … Newman, P. A. (2024). East Asian summer monsoon delivers large abundances of very short-lived organic chlorine substances to the lower stratosphere. Proceedings of the National Academy of Sciences, 121(12). https://doi.org/10.1073/pnas.2318716121

[2] Bucci, S., Legras, B., Sellitto, P., D’Amato, F., Viciani, S., Montori, A., Chiarugi, A., Ravegnani, F., Ulanovsky, A., Cairo, F., & Stroh, F. (2020). Deep-convective influence on the upper troposphere–lower stratosphere composition in the Asian monsoon anticyclone region: 2017 StratoClim campaign results. Atmospheric Chemistry and Physics, 20(20), 12193–12210. https://doi.org/10.5194/acp-20-12193-2020

1. p2 L2: 'with a vertical velocity of about 1–1.5 K/day' This value depends on the used reanalysis. 1–1.5 K/day is related to ERA-Interim. Please clarify.

We appreciate the reviewer’s comment and agree that the vertical velocity value of 1–1.5 K/day is specific to ERA-Interim (Vogel et al.,2019; Ploeger et al., 2017). The original sentence did not make this clear. Indeed, this estimate is based on previous studies using ERA-Interim (e.g., Schoeberl et al., 2012; Garny and Randel, 2016), which have shown to overestimate the diabatic heating rate by about 30–40%, likely due to longwave radiative heating biases and a cold temperature bias in the tropical tropopause layer (TTL) (Wright and Fueglistaler, 2013). This implies that the more realistic upwelling rates should be in the range of ~0.3–0.8 K/day, consistent with measurement-based evaluations (e.g., von Hobe et al., 2021). Moreover, its newer generation ERA5 provide a more accurate representation of ASM transport processes. ERA5 shows stronger convective detrainment, especially over the Tibetan Plateau, and slower large-scale upwelling above 380 K compared to ERA-Interim (Legras and Bucci, 2020; Vogel et al., 2024). The overall upwelling in ERA5 is generally slower, aligning better with in-situ and satellite-based estimates.

In response, we have revised this estimate of upwelling to ‘~0.3–0.8 K/day’ and added following references. Additionally, we have revised this paragraph in the introduction to better descript the monsoon transport system, which includes fast convective transport from the boundary layer to the outflow level, and the slower, large-scale ascent from the outflow level to the UTLS (P2 L55). We hope this improves the clarity of the ASM vertical transport structure.

[1] Wright, J. S. and Fueglistaler, S.: Large differences in reanalyses of diabatic heating in the tropical upper troposphere and lower stratosphere, Atmos. Chem. Phys., 13, 9565–9576, https://doi.org/10.5194/acp-13-9565-2013, 2013.

[2] Garny, H. and Randel, W. J.: Transport pathways from the Asian monsoon anticyclone to the stratosphere, Atmos. Chem. Phys., 16, 2703–2718, https://doi.org/10.5194/acp-16-2703-2016, 2016.

[3] Legras, B. and Bucci, S.: Confinement of air in the Asian monsoon anticyclone and pathways of convective air to the stratosphere during the summer season, Atmos. Chem. Phys., 20, 11045–11064, https://doi.org/10.5194/acp-20-11045-2020, 2020.

[4] von Hobe, M., Ploeger, F., Konopka, P., Kloss, C., Ulanowski, A., Yushkov, V., Ravegnani, F., Volk, C. M., Pan, L. L., Honomichl, S. B., Tilmes, S., Kinnison, D. E., Garcia, R. R., and Wright, J. S.: Upward transport into and within the Asian monsoon anticyclone as inferred from StratoClim trace gas observations, Atmos. Chem. Phys., 21, 1267–1285, https://doi.org/10.5194/acp-21-1267-2021, 2021.

[5] Vogel, B., Volk, C. M., Wintel, J., Lauther, V., Clemens, J., Grooß, J.-U., Günther, G., Hoffmann, L., Laube, J. C., Müller, R., Ploeger, F., and Stroh, F.: Evaluation of vertical transport in ERA5 and ERA-Interim reanalysis using high-altitude aircraft measurements in the Asian summer monsoon 2017, Atmos. Chem. Phys., 24, 317–343, https://doi.org/10.5194/acp-24-317-2024, 2024.

1. p3 L3: 'The debate persists over whether the seasonal increase of UT methane in the Asian monsoon region is due to enhanced summer emissions from regional rice paddies (Zhang et al., 2020) or the upward transport by the monsoonal circulation'. Could it also be the combination of both?

Yes, we agree that both enhanced regional emissions and monsoonal transport contribute to the observed seasonal increase in upper tropospheric methane. In fact, our conclusion also supports the role of both mechanisms (dynamical effect dominant). The original sentence in the Introduction may not have accurately reflected this nuance. Our intended point was to highlight that the relative importance of these two processes remains under debate. To clarify this, we have revised the sentence as follows:

“The debate persists over which factor plays the dominant role in the seasonal increase of UT methane over the Asian monsoon region—enhanced summer emissions from regional rice paddies (Zhang et al., 2020) or the strong upward transport by the monsoon convection and circulation (Zeng et al., 2021) —as both are known to contribute.”

1. p3 Sect. 2.1: Please provide some information about the treatment of convection in the GEOS-Chem model. Is there an additional convection scheme included or is just used the convection included in MERRA-2?

The treatment of convection in GEOS-Chem is not simulated directly within the model but is instead derived from the meteorological fields provided by the MERRA-2 reanalysis. This explanation has been added in the revised manuscript (P4 L97).

1. p4 Sect. 2.2: A map showing the regions of the different modes (IP, WTP, ETP) would be very helpful.

Thanks for your suggestion. In the revised manuscript, we have added a new figure (Figure 1) along with a corresponding description in the Methods section to clarify how the AMA modes were identified and to detail the methodology employed (P6 L150-157).

1. p6 Sect. 3.1: Please provide a map showing the regional/spatial distribution (fluxes) of CH4 emission in Asia in the model at surface.

Note that the distribution CH4 fluxes has been provided in the supplementary Figure S1. In addition, we added a subfigure to show the map of near-surface methane VMR and low OLR contours (representing deep convection).

1. p5 L131: 'shows the anomalies of GPH as well as methane on 150 hPa' Please explain how 'anomalies' are defined / calculated here.

Thank you for the kind reminder. We have revised the caption of the new Figure 2 to include an explanation of the “anomalies of GPH and methane at 150 hPa.” and descried it the revised text (P7 L170-171).

p6 L157: 'The timing of this CH4 surge aligns closely with the seasonal emissions peak from rice paddy cultivation.' Please provide more information about subseasonal variability of CH4 at model boundary layer

Thank you very much for the suggestion. This information is mainly based on Fig. 3 in Zhang et al. (2020). They used Modis-based Enhanced vegetation index (EVI) to estimate the growth of rice paddies. And we saw its seasonal peaks mainly at late August. Thus, we added this reference here. In fact, our Figure 5 also show the emission peaks at middle to late August (mainly from agriculture section but not shown).

1. p7 L176: 'Under IP mode, the horizontal redistribution is remarkable with a weak vertical pathway.'

I think this statement should be made a bit clearer such as:  'Over the Iranian Plateau shallower and less intense convection occurs during summer compared to regions in WTP and ETP, therefore CH4 enhancements over the IP are caused by horizontal westward transport in the UT caused by the AMA and not by local vertical transport.'

Thank you for your suggestion. We have followed your advice and now present the OLR pattern for each mode in the new Figure 4. However, the statement that “shallower and less intense convection occurs over the Iranian Plateau during summer compared to regions in the WTP and ETP” does not totally true in our case. Our results show that, during the IP mode, the deep convection pattern shifts slightly westward and is also intensified over the South China Sea. The overall strength of convection, as interpreted from OLR, during the IP mode is comparable to that in the WTP and ETP modes.

Therefore, when considering both the convection patterns and the 3D methane distribution, our findings indicate that, when the AMA center is located over the Iranian Plateau, it is positioned farther from the primary monsoon convective regions (e.g., the Indian subcontinent and the Bay of Bengal). As a result, vertical transport of air from these organized monsoon convective sources into the upper troposphere and lower stratosphere (UTLS)—specifically from their convective outflow levels to higher altitudes—is suppressed. In this configuration, horizontal redistribution within the anticyclone becomes more dominant than further vertical uplift into the UTLS.

This also addresses the first major comment.

1. p9 L207: 'we demonstrate that variability in UTLS methane over the Asian region is influenced by two main factors: firstly, the dynamical east-west oscillation of the ASM, which substantially modulates methane distribution and influence the upward transport pathways; secondly, the increase in methane emissions from rice paddy cultivation in late August and early September'

I am missing in this discussion the role of convection. The upward transport depends on the location of strong convection. If the AMA anticyclone is over convective regions enhanced CH4 can be injected into the AMA (WTP, ETP), subsequently by horizontal displacement enhanced CH4 can be transported horizontally westward (IP) here no local injection of CH4 into the AMA by convection occurs.

Thanks for the suggestion. We deeply revised sec. 3.2. Firstly, a row of subfigures is added to Fig. 4 to show the pattern of deep convection (OLR), near-surface winds as well as methane in the lower troposphere. And accordingly, we rewrote this section to discuss the role of convection and the interplay between the convection and large-scale circulation (P10-16 L229-303).

1. p10 L211:  'ASM dynamics' = convection + horizontal shift of AMA?

Yes, you are correct. In general, three main factors determine UTLS methane levels: surface emissions, convective transport, and the large-scale circulation associated with the ASM. We use the term “ASM dynamics” to collectively refer to both convective transport and large-scale circulation. In revised version, we explicitly describe “ASM dynamics” before this at P16 L295-298: ‘the configuration of ASM subseasonal dynamical variability, including both the monsoon convection and AMA locations, influences the efficiency of tracer transport from the lower boundary to the upper troposphere’. Additionally, the variability of monsoon convection and the AMA are interrelated, this point is further addressed in the discussion section (P21 L417-421).

1. p10 L220-225: 'What about differences in strength and location of convection in your model between the different years from 2015 to 2020 such as modulations by ENSO?

Alladi et al (2024) shows, that during Asian monsoon 2015, a substantial reduction of the tropospheric species at 100 hPa and 146 hPa in contrast to 2022 where observed mainly attributed to the weaker updrafts in 2015 owing to strong El Nino conditions.

Hemanth Kumar Alladi, P.R. Satheesh Chandran, Venkat Ratnam M, Impact of ENSO on the UTLS chemical composition in the Asian Summer Monsoon Anticyclone, Atmospheric Research, Volume 309, 2024, 107551, ISSN 0169-8095, <https://doi.org/10.1016/j.atmosres.2024.107551>.

(<https://www.sciencedirect.com/science/article/pii/S0169809524003338>)

The lower CH4 mixing rations in 2015 shown in Fig. 5 (Zhu et al., 2025) could be caused by weaker updrafts in 2015.

We thank the reviewer for this important point. As noted by Alladi et al. (2024), the 2015 Asian Summer Monsoon season, which coincided with a strong El Niño event, exhibited noticeably weaker convective updrafts compared to neutral or La Niña years such as 2022. This reduction in convection led to substantially lower concentrations of tropospheric trace species—including methane—at 100 hPa and 146 hPa, consistent with our model results shown in Fig. 5. Thus, it worth to mention this point:“Note that the CH4 interannual variability in the UTLS can be related to other large-scale climate modes. For example, the relative low CH4 in the UTLS at 2015 is potentially attributed to suppressed updrafts influenced by ENSO-related dynamics (Alladi et al., 2024).” (P17 L331-333).

1. p13 L284-L287: 'the subseasonal oscillations of the Asian Monsoon Anticyclone (AMA) significantly influence the methane transport pathway and its efficiency from the lower boundary to the UTLS (upper troposphere and lower stratosphere' This sentence is somewhat misleading. Please clarify 'transport pathways'.

We appreciate your feedback. We recognize that our use of “transport pathway” was somewhat misleading. In response, we have revised the text to: “the subseasonal oscillations of the AMA significantly influence the methane distribution and its transport efficiency from the lower boundary to the UTLS.”(P20 L398). Additionally, we have replaced the inappropriate use of “transport pathway” throughout the manuscript.

1. p14 L295: 'Based on AMA mode composites, we confirm that the dynamic nature of the AMA, in terms of its subseasonal modes, modulates the vertical structure of CH4 over the monsoon region.' --> modulates the horizontal structure.  Please clarify.

This sentence, similar as few places with a similar statement, is revised as: “we confirm that the dynamic nature of the AMA, in terms of its subseasonal modes, modulates the horizonal distribution of methane as well as efficiency of vertical transport from the convective outflow upward to the upper troposphere over the monsoon region.” (P21 L410-412).

1. p14 L296: 'In particular, AMA centering around 80°E (WTP mode) favors the vertical transport of air from north India and Bangladesh to the upper troposphere, which contributes most significantly to the total CH4 monsoon plume at the UT.' -->

'The local coincidence of CH4 emissions, strong convection and the location of the anticyclone around 80°E (WTP mode) favors the vertical transport of air from north India and Bangladesh to the upper troposphere, which contributes most significantly to the total CH4 monsoon plume at the UT.'

We appreciate this nice suggestion and take this sentence in our revised manuscript (P21 L412-415).

**Minor/technical comments:**

1. p2 L34: 'upper atmosphere' -> 'upper troposphere' or 'UTLS'

Revised.

1. p4 L114: 'tracer transport' -> 'transport of trace gases'

Revised.

1. p4 L117: 'Our statistics show that the frequency of the Tibetan mode (the eastern phase of the distribution) is nearly twice that of the Iranian mode.' Please specify the time period for the statistics. 2015-2020?

Done.

1. p5 L130: 'on the vertical distribution of CH4 in 2020 summer'  -> 'on the horizontal distribution of ... at 150hPa'

Done.

1. p6 L157: 'in Figure.1' -> 'in Figure 1'

Done.

1. p7 L176: 'horizonal' -> 'horizontal'

Done.

1. p7 L179:  'in Figure.S1' -> ‘in Figure S1'

Done.

1. p10 L216:  'late-summer emissions' -> 'higher emission during the JAS than in other years tend to ....'

Done.

1. Fig. 5: The red and blue lines are very thin. Please make them a bit thicker for better visibility.

Done.

1. Add in the figure caption the meaning of the dashed red and black boxes that are related to table 1.

Revised.

1. Tab. 1: Please add CH4 [ppbv] as subtitle in the table.

Revised.