

Reviewer 1

Review of egusphere-2026-2644: “Methane in the Asian Monsoon Anticyclone and global UTLS behavior observed in ACE-FTS satellite data” by You Yi et al.

We thank the reviewer for the positive comments and valuable suggestions. We have revised the manuscript and please see the track-changes file for these revisions. All line numbers in our responses refer to the clean version of the revised manuscript.

The manuscript by You Yi and colleagues addresses the impact of the Asian Summer Monsoon (ASM) on the distribution of methane in the upper troposphere and lower stratosphere (UTLS). For this the authors use satellite data from ACE-FTS to describe the vertical and horizontal distribution of methane as well as the seasonal cycle of methane in this region. They show that methane has its maximum at higher altitudes than a comparable tracer, CO, and that the decrease of methane concentrations into the stratosphere starts at higher altitudes than for CO. This is attributed to the longer lifetime of methane. Their results are supported by in situ observations from AirCore and aircraft measurements. Together with data for surface methane emissions, they can also demonstrate the effectiveness of the lifting process within the ASM – while emissions peak during summer, the peak methane concentrations in the UTLS occur in autumn. The authors also analyze trends based on the ACE-FTS data which are in line with previous findings.

Methane is a highly relevant constituent in the atmosphere with increasing importance in discussions centered around climate change. Analysis of the global distribution and sources of methane are of relevance and fit well into the scope of ACP. The manuscript addresses an interesting question, particularly based on observational data. Such data is often required to validate chemistry climate models and might also be relevant for trend studies. Therefore, the paper will be a great addition to the scientific literature. In my opinion, the manuscript is overall already in a good shape. The scientific reasoning is sound, the figures are appropriate and fit to the story. The overall thematic flow of the paper is clear and comprehensible. However, this is the case if the reader is already an expert in the topic. For all others, I think the manuscript would benefit from more information and extended discussion at several

points. This is also my main concern on which I will give some examples below. Otherwise, I think the paper is on a good path to be published and I recommend a publication after minor revision. I choose minor revision here because my comments are mainly about providing more information and not about a new or extended analysis or about reasoning.

My major concern is that although all relevant information is touched upon in each section, the often very brief presentation of the content gives the impression that the authors have reduced the material too much. Since this occurs in many places throughout the manuscript, the overall impression is that important information necessary for understanding and proper contextualization is missing or treated too superficially. Some examples are given below:

We have expanded the relevant sections, as detailed in our responses to the specific comments below.

1. In the introduction, I am missing a sentence or two about methane sources, especially in South-East Asia to emphasize why this region is so important for the global methane budget not only from a transport perspective but also from an emission perspective. This could be part of the first paragraph (l. 28ff) or of the paragraph starting in line 43.

We added two sentences to describe the methane sources in south-east Asia and emphasize the strong seasonality of the sources.

In lines 40-42, “South and Southeast Asia are major CH₄ source regions, with emissions dominated by agriculture (including rice cultivation and livestock), waste, wetlands. Emissions from these sources increase during the ASM season, likely due to enhanced rainfall (Yu et al., 2023; East et al., 2024; Subramanian et al., 2026).”

2. Since CO is also widely discussed throughout the manuscript, it might deserve a small introductory paragraph, at least to contrast it to methane in the introduction.

We added some introductions of ACE-FTS CO related studies in lines 62-75. “Previous studies have used ACE-FTS observations to investigate the regional transport signals and large-scale tracer variability. Park et al (2008) documented enhanced CO and other tropospheric tracers within the Asian monsoon anticyclone, providing evidence of

convective transport and chemical isolation. CO is an effective tracer of vertical transport because its free-tropospheric lifetime (~1 month) is substantially longer than typical deep convective transport timescales. Enhanced CO in the UTLS can therefore indicate recent deep convective transport of polluted air, while correlations between CO and other trace gases can help identify source characteristics and common transport pathways.

Park et al. (2013) examined the global distributions and seasonal variability of CO and hydrocarbons in the UTLS based on ACE-FTS measurements. These tracers exhibited semi-annual cycle in the tropical upper troposphere related to seasonally varying sources and deep tropical convection, and a maximum tied to the Asian monsoon anticyclone. Above the tropical tropopause, these species reveal a strong annual cycle related to annual variation of the upward branch of BDC.”

3. The paragraph about ACE-FTS (l. 47ff) would benefit from some references. There are several statements in this five lines which could be filled with references. Also it would be good to inform the reader about other methane (and CO) related studies with ACE-FTS to put the results from this study more in perspective.

We added references Bernath et al., 2005 and Nassar et al., 2005 in line 56 and line 58, respectively. We added the paragraph describing the ACE-FTS methane and CO related studies on line 62-78.

“Previous studies have used ACE-FTS observations to investigate the regional transport signals and large-scale tracer variability. Park et al (2008) documented enhanced CO and other tropospheric tracers within the Asian monsoon anticyclone, providing evidence of convective transport and chemical isolation. CO is an effective tracer of vertical transport because its free-tropospheric lifetime is substantially longer than typical deep convective transport timescales. Enhanced CO in the UTLS can therefore indicate recent deep convective transport of polluted air, while correlations between CO and other trace gases can help identify source characteristics and common transport pathways.

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troposphere related to seasonally varying sources and deep tropical convection, and a maximum tied to the Asian monsoon anticyclone. Above the tropical tropopause, these species reveal a strong annual cycle related to annual variation of the upward branch of BDC. More recently, Sheese et al. (2025) used ACE-FTS measurements, including CH₄, to quantify the contributions of methane oxidation and circulation changes to stratospheric water vapor trends. To address the limited tropical sampling, they supplemented ACE-FTS observations with model simulations and applied multiple linear regression (MLR) to estimate CH₄ trends entering the stratosphere. ”

4. Line 62: What is the wavenumber 0.02 cm⁻¹? Please specify.

We have revised the sentence in lines 89-91. “The Atmospheric Chemistry Experiment–Fourier Transform Spectrometer (ACE-FTS), onboard the Canadian SCISAT satellite launched in 2003, is a high-resolution infrared Michelson spectrometer with a spectral resolution of 0.02 cm⁻¹ that measures solar occultation transmission spectra between 2.2–13.3 μm (Bernath et al., 2005).”

5. Line 68: Here you mean effective horizontal resolution? What is meant with oversampled at 1 km?

The ~3 km resolution refers to the effective vertical resolution, rather than the horizontal resolution. By “oversampled on a 1 km grid”, we mean that the retrieved CH₄ profiles are reported on a vertical grid with 1 km spacing, which is finer than the effective vertical resolution of approximately 3 km. We have revised the sentence to clarify this point in lines 95-96.

“This study uses the recent version of level 2 data, version 5.2 (v5.2), which provides interpolated data on a 1 km grid (Boone et al., 2023).”

6. Is there a specific reason why no measurement error is given for the AirCore data? (section 2.2.1).

We added one sentence to describe the measurement uncertainty in lines 123-124. “The average measurement uncertainty of CH₄ and CO are less than 10 ppb and 5 ppb below 20 km.”

7. Figure 1: the lapse-rate tropopause shown in this figure is derived from which data? Does this lapse-rate vary much between the individual flights? I asked whether I would like to know whether the differences between methane and CO which are discussed here might become even more prominent when all profiles would be plotted in a tropopause relative coordinate system.

In original figure 1 (now figure 2), the lapse-rate tropopause was determined from the temperature profiles measured by the radiosondes launched together with the AirCore, following the WMO definition. The tropopause altitude does vary but not too much ($17.5 \text{ km} \pm 0.5 \text{ km}$) among the individual flights, because all flights were conducted at the same location in August. Consequently, plotting the profiles relative to the tropopause produces minor changes.

8. In section 3 it is often mentioned that ERA5 data has been used. Since this occurs at multiple occasions, I would suggest to include a small subsection in Section 2 about the ERA5 data used in this study.

We have added a paragraph describing the ERA5 reanalysis used in the study on section 2.3.

Lines 152-159: “Meteorological fields from ERA5, the fifth-generation global reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF; Hersbach et al., 2020), are used to characterize the circulation associated with the observed CH₄ and CO distributions. We use ERA5 monthly pressure-level data provided on a regular 0.25° latitude-longitude grid, with 37 standard pressure levels ranging from 1000 to 1 hPa. The time periods are from 2005 to 2023, matching the period of the ACE-FTS analysis. ERA5-based lapse-rate tropopause heights are obtained from Hoffmann and Spang (2022). This product identifies the lapse-rate tropopause using the World Meteorological Organization

(WMO) definition in 1957. These heights provide a reference for interpreting the observed CH₄ and CO distributions relative to the tropopause.”

9. In Figure 3 the black lines show a stream function, how is this calculated? Which years are used, which values of the stream function are shown here and does this explain why the lines are only evident in the region of the ASM?

The horizontal stream function is calculated from ERA5 zonal and meridional winds using the Python package windspharm. The stream function is calculated by

$$\psi = \nabla_h^{-2} \zeta$$

Here, ψ is stream function, unit m² s⁻¹; ζ is relative vorticity, unit s⁻¹.

The stream function was averaged over JJA during 2005-2023. The selected contour levels are [4, 14, 25] × 10⁶ m² s⁻¹, chosen to illustrate the climatological location and horizontal extent of the ASM anticyclone, following the approach of Pan et al (2024). doi: 10.1073/pnas.2318716121.

We revise the Figure 4 (original Figure 3) caption to include the details. “Figure 4: Horizontal distributions of JJA climatological mixing ratios from ACE-FTS observations during 2005-2023. (a) CH₄ at 16.5 km and (b) CO at 14.5 km. The black solid contours show selected stream function levels ([4, 14, 25] × 10⁶ m² s⁻¹; based on the ERA5 data) at the corresponding altitudes, averaged over JJA during 2005-2023, to indicate the climatological location and horizontal extent of the ASM anticyclone. Note that the JJA map predominantly represents measurements over the midlatitudes in June, the northern subpolar region in July, and the tropics in August (see Fig. 1), rather than spatially uniform sampling throughout JJA.”

10. Also in Figure 3 it is not fully clear to me why 16.5 and 14.5 km have been chosen here for methane and CO? The text says that the maximum of CH₄ is around 16 km, and for CO 14 km. From Figure 4 would follow that the maximum for CH₄ is more 15.5 km and for CO 13.5 km to 14 km.

The levels of 16.5 km for CH₄ and 14.5 km for CO were selected because the horizontal enhancement associated with the ASM anticyclone is particularly clear at these levels. The sampling density in the ASM region is greater at higher altitudes than at lower altitudes. The heights of approximately 16 km for CH₄ and 14 km for CO quoted in the text were intended as approximate descriptions of the peak altitudes, rather than precise values. Given the 1 km vertical grid spacing in ACE-FTS profiles, we choose the level of 16.5 km for CH₄ and 14.5 km for CO where the maximum is mostly clear.

11. The lapse rate tropopause in Figure 4: has this been calculated by yourself? If so how and on which ERA5 data (pressure level, model level, monthly mean, daily, hourly data, horizontal and temporal resolution)?

The lapse rate tropopause shown here is downloaded from <https://datapub.fz-juelich.de/slcs/tropopause/> (Hoffmann et al., 2022). We revise the Fig. 5 (original Fig. 4) caption to clearly state the data source. “Figure 5: Meridional cross-sections of JJA climatological mixing ratios over the ASM region (20–120°E), derived from the horizontal maps shown in Fig. 4. Observed (a) CH₄ mixing ratios and (b) CO mixing ratios from ACE-FTS. The white dashed lines denote the JJA climatological lapse-rate tropopause obtained from ERA5 reanalysis during 2005-2023 provided by Hoffmann et al., 2022.” We have also introduced the tropopause product in sect. 2.3.

12. In Figure 5, the gray lines show the stream function: what is meant with composite here? Do I assume correctly that the data source is again ERA5? And did you calculate the vertical wind from the Lagrangian tendency of the pressure (ω)?

The gray lines are streamlines constructed from the meridional wind and vertical velocity. Our use of “composite” was imprecise. We intended to describe the combination of these two velocity components used to generate the streamlines. Both components are based on ERA5 data and averaged over 20-120°E during JJA 2005-2023. The vertical velocity was converted from the ERA5 pressure vertical velocity ($\omega = \frac{dP}{dt}$) using the hydrostatic relation

$w = -\frac{\omega}{\rho g}$. We have revised the caption to clarify the meaning of the gray streamlines and added the vertical velocity conversion statement.

“Figure 6: Meridional cross sections of the ASM enhancement in (a) CH₄ and (b) CO derived from ACE-FTS observations for JJA during 2005-2023, defined as the mean mixing ratio over 20°-120°E minus the background mean over all remaining longitudes. Blue lines indicate the lapse-rate tropopause provided by Hoffmann et al., 2021. Solid and dashed black contours represent westerly (10 and 20 m/s) and easterly winds (-10 and -20 m/s), respectively. Gray streamlines, shown only between 15-60°N to cover the ASM region and higher latitude potentially influenced by ASM transport, depict the circulation in the latitude-altitude plane and are constructed from the meridional wind (m/s) and vertical velocity (mm/s). All meteorological fields are averaged over 20-120°E during JJA 2005-2023 based on ERA5 reanalysis. Note that the vertical velocity is converted from pressure-coordinate vertical velocity using the hydrostatic relation.”

13. Why are there only gray lines between ~15°N to 60°N? And finally, I would have expected that the upwelling (tropics) and the downwelling (extratropics) would be evident in the stratosphere, but the arrows along the streamlines all point upward. Is this related to the region and time?

The gray streamlines are restricted to approximately 15-60°N because we focus on the ASM region and the higher-latitude regions influenced by ASM transport. They are constructed from the ERA5 meridional wind and vertical velocity averaged over 20-120°E and depict the circulation in the latitude-altitude plane within this longitude sector.

The tropical upwelling and extratropical downwelling mentioned by the reviewer characterize the Brewer-Dobson circulation, which is generally described using the zonal-mean residual circulation. Our streamlines instead represent the 20-120°E longitudinal mean wind field. Park et al. (2007) pointed out the upward circulation above the tropopause inside ASM anticyclone in the extra-tropical region. The upward structure shown in the Fig. 6 (original Fig. 5) therefore depends on the selected region and period.

14. The blue line is again the ERA5 lapse-rate tropopause? And the contour lines for the horizontal wind show magnitudes of +10 m/s and +20 m/s (solid) and -10 m/s and -20 m/s (dashed)?

Yes. We revised the Fig. 6 (original Fig. 5) caption to clearly describe the variable shown in the figure. “Figure 6: Meridional cross sections of the ASM enhancement in (a) CH₄ and (b) CO derived from ACE-FTS observations for JJA during 2005-2023, defined as the mean mixing ratio over 20°-120°E minus the background mean over all remaining longitudes. Blue lines indicate the lapse-rate tropopause provided by Hoffmann et al., 2021. Solid and dashed black contours represent westerly (10 and 20 m/s) and easterly winds (-10 and -20 m/s), respectively. Gray streamlines, shown only between 15-60°N to cover the ASM region and higher latitude potentially influenced by ASM transport, depict the circulation in the latitude-altitude plane and are constructed from the meridional wind (m/s) and vertical velocity (mm/s). All meteorological fields are averaged over 20-120°E during JJA 2005-2023 based on ERA5 reanalysis. Note that the vertical velocity is converted from pressure-coordinate vertical velocity using the hydrostatic relation.”

15. In Figure 7, OLR data is shown? Where does this come from and what exactly is shown here? At some places it seems that multiple lines are evident and not just one line for 220 K.

OLR data is obtained from Clouds and Earth’s Radiant Energy System Energy Balanced and Filled Top-of-Atmosphere Monthly means data product. The product uses reprocessed NOAA-20 data using GMAO MERRA-2 as the meteorology starting with April 2022 for fluxes and VIIRS clouds and scene type determination. The lines shown here are from 190 W/m² to 220 W/m² with interval of 10 W/m². We have added the OLR data description in the Section 2.3 in lines 159-164.

“Monthly mean outgoing longwave radiation (OLR) for 2005-2023 is obtained from the Clouds and the Earth’s Radiant Energy System (CERES) Energy Balanced and Filled top-of-atmosphere Edition 4.2 product (Loeb et al., 2017, 2024). We use the all-sky Top-of-Atmosphere (TOA) outgoing longwave flux, provided on a 1° latitude-longitude grid in W/m². Regions with OLR less than 220 W/m² are used as a proxy for deep convection. For

comparison with ACE-FTS observations in the tropics, climatological OLR fields are calculated for February, April, August, and October.”

The OLR data shown in the figure are the values less than 220 K ($OLR \leq 220$ K) to indicate deep convection. We choose the February for DJF, April for MAM, August for JJA and October for SON season to keep consistent with ACE-FTS observations in the tropics. We revised the caption to fully illustrate the data used in the figure.

“Figure 8: Climatological horizontal distributions of CH_4 at 16.5 km for (a) DJF, (b) MAM, (c) JJA and (d) SON seasons derived from ACE-FTS observations gridded at 5° latitude by 10° longitude, averaged over the period 2005-2023. The white contours represent outgoing longwave radiation (OLR) from 190 W/m^2 to 220 W/m^2 with interval of 10 W/m^2 , with lower values used as proxy for enhanced deep convection. Note that in the tropics, DJF, MAM, JJA and SON primarily represent observations in February, April, August and October, respectively. The OLR data are monthly means for February, April, August, and October in panels (a)-(d), respectively, to match the tropical ACE-FTS sampling.”

16. For the discussion around and the data in Figure 8, the region is extended to 15°S - 30°N and the entire zonal direction. How well does this represent the ASM region?

The domain used in Fig.9 (15°S - 30°N , encompassing all longitudes) is intended to examine the potential influence of ASM transport on the broader tropical CH_4 distribution, rather than to represent the ASM region itself.

17. Also for Figure 8 and the surface emission data: Can you include some more information about this surface data set, so that is not necessary to go the Saunois et al. paper.

We added one paragraph in section 2.3 to describe the surface flux in lines 166-176.

“The CH_4 surface flux dataset provided by Saunois et al. (2025) is constructed by combining bottom-up emission inventories and model estimate for individual source and sink categories. xThe prior flux draws on Emission Database for Global Atmospheric Research (EDGAR v7; Crippa et al., 2023) for anthropogenic emissions, with extension based on Food

and Agriculture Organization (FAO) agriculture data and includes an alternative configuration using the Greenhouse gas and Air pollutant Interactions and Synergies (GAINS) model for fossil fuel emissions (Höglund-Isaksson et al., 2020). Biomass-burning emissions are obtained from Global Fire Emission Database (GFED) v4.1 (van der Werf et al., 2017), and wetland emissions are represented by the monthly ensemble mean of 11 models reported by Saunois et al. (2020). Additional components include termite emissions, ocean emissions from Weber et al. (2019), geological emissions from Etiope et al. (2019), and soil methane uptake from the MeMo model (Murguía-Flores et al., 2018). These components are assembled into gridded surface flux fields for use as prior inputs to atmospheric inversions, with temporal variability determined by the underlying inventories and models.”

18. Is the LOTUS regression model the one available here on this web page: <https://usask-arg.github.io/lotus-regression/>. Can you provide further details about the model in your text, especially, on your setup (proxies and input data).

We added the model description in the Section 2.4 in lines 178-193.

“To estimate the trends and reconstruct monthly methane time series in the tropics, we apply the Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) regression code (SPARC/IO3C/GAW, 2019), following the standard multiple linear regression (MLR) framework described by Dubé et al. (2023). The model is fitted separately to the available observations in each latitude-altitude bin:

$$\begin{aligned}
 CH_4(t) = & \beta^{(2)}(t) + \beta_{trend} \times linear(t) + \\
 & \beta_{qboa}^{(2)} \times QBO_{(a)}(t) + \beta_{qbob}^{(2)} \times QBO_{(b)}(t) + \\
 & \beta_{solar} \times F_{10.7}(t) + \beta_{enso} \times ENSO(t) + \\
 & \beta_{aod} \times AOD(t) + R(t)
 \end{aligned} \tag{1}$$

Here, each β is a regression coefficient for each term, the superscripts are the number of highest seasonal harmonic for a given term, $\beta^{(2)}(t) = const + A_1 \sin(2\pi t) + B_1 \cos(2\pi t) + A_2 \sin(4\pi t) + B_2 \cos(4\pi t)$, A_i and B_i are the sine and cosine coefficients, respectively, with

subscripts $i = 1$ and $i = 2$ denote the annual and semi-annual cycles. Time t is expressed in years. $QBO_{(a)}(t)$ and $QBO_{(b)}(t)$ are the first two principal components of the Singapore zonal winds, $F_{10.7}(t)$ is the solar flux at 10.7 cm, ENSO (t) is the multivariate ENSO index, and $R(t)$ is the residual. These predictors are further described in SPARC/IO3C/GAW (2019). Dubé et al (2023) applied this standard MLR framework to estimate stratospheric N₂O trends from ACE-FTS observations. ”

19. Figure 10 b): which bin size has been used here for this plot (in delta z and delta lat)? And could you provide potentially one sentence why the trend is larger at the tropical tropopause than above? Is this upwelling related or has this to do with the strength of lateral mixing?

A possible explanation is that CH₄ near the tropical tropopause responds more directly to the accelerating tropospheric increase, whereas air at higher reflects an earlier tropospheric CH₄ trends. This can lead to a smaller trend at higher altitudes over the same analysis period. From Figure 10 a), CH₄ accelerates beginning 2020. Lateral mixing may also contribute, however, the trend alone cannot distinguish its contribution from that of vertical transport. We have added the following sentence to acknowledge this interpretation in lines 373-376. “The larger trend near the tropical tropopause than above may reflect a more immediate response to the accelerating tropospheric CH₄ increase, whereas the response at higher altitude is delayed and smoothed by stratospheric transport and mixing”

20. ERA5 data should be listed in the Data availability section.

We added one sentence in lines 456-457. “ERA5 data can be downloaded from <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels-monthly-means?tab=download>”