egusphere-2025-1442

Rousogenous et al. “Extension of the Total Carbon Column Observing Network (TCCON) over the Eastern Mediterranean and Middle East: The Nicosia site in Cyprus”

Referee comments in red

Our responses in blue

Changes made to the paper are shown in “black block quotes”.

Response to Referee #1

This paper describes a relatively new TCCON station located near Nicosia, Cyprus. This location fills an important gap in carbon cycle monitoring, and it is therefore a welcome addition. The paper describes the location, measurements to date, and some comparisons with coincident AirCore profiles. A reference for these measurements will be very helpful, so I recommend publication after addressing the following comments.

We thank the reviewer for supporting the publication of our study and for providing valuable comments. Below, we respond to each of the specific comments.

Specific comments:

TCCON typically chooses 45 cm OPD for its spectral resolution to allow the spectra to distinguish the absorption lines of interest from the interfering absorption lines across a broad wavelength range while maintaining a high signal-to-noise ratio. You’ve chosen 64 cm OPD, presumably as a compromise between the TCCON- and NDACC-style measurements you wish to collect. Do you have a sense of how that choice impacts the TCCON measurements? Have you truncated the interferograms to show whether the additional 20 cm OPD improves or degrades the CO_2 retrieved? Please justify your choice of 65 cm OPD.

We would like to thank the reviewer for this comment. The Nicosia site uses a maximum optical path difference (MOPD) of 64 cm instead of the 45 cm typically used in TCCON, inherited from its previous configuration in Bialystok and selected by the University of Bremen to optimize spectral resolution (0.014 cm^{-1}) for improved precision in column retrievals. This choice enhances our ability to resolve weak absorption lines and separate interfering species, which is particularly beneficial given Cyprus's excellent clear-sky observing conditions. In addition, the higher spectral resolution lends itself well to the studies of other researchers working with trace gas retrievals. Future analysis will include a quantification of any potential systematic effects on retrieved X$_{CO_2}$ compared to standard TCCON resolution.

We added three sentences between L140 and L141:

> "The maximum optical path difference (MOPD) is set to 64 cm, consistent with the configuration used at the former site in Bialystok, Poland and other sites. This configuration exceeds the TCCON standard 45 cm, providing higher spectral resolution and thus making the spectra additionally valuable for independent spectroscopic trace-gas retrieval studies. In addition, the Nicosia site experiences relatively low cloud cover, so the slightly longer scan duration associated with the 64 cm MOPD does not significantly reduce data yield. "

Figure 2: What is the cause of the substantial increase in Xluft spread (stdev) in late 2019, and early-to-mid 2023? Did the density of data decrease in mid-2021 when you began NDACC-like measurements?

The substantial increase in Xluft spread in late 2019 was caused by the cleaning of the solar tracker mirrors, which slightly altered their inclination, affecting some spectra mostly during large solar zenith angles. This was then corrected; however, few spectra (not affecting the 500-spectra running median, 500-RMd) remained in the public data. Similarly, in early 2023 we replaced the solar tracker mirrors, causing solar pointing errors again, which was later corrected.

NDACC-type measurements commenced in early 2023. In May 2021, we replaced the internal laser, but the beam was initially improperly focused and diverging, leading to interruptions in measurements during the scanner's backward motion, causing sparse data. This issue was identified in January 2022, after which the laser was re-focused and re-aligned. Unfortunately, the focus remained non-perfect, with the beam slightly converging, further contributing to variability in the Xluft and Xgas measurements. We maintain an FTIR logbook for Nicosia to document any technical issues and maintenance activities. This logbook will be uploaded to the TCCON wiki and will be accessible to TCCON partners, although it will not be publicly available. Please also refer to our response to the point raised by Referee #2 on L198.

Figure 3: What caused the sparsity in measurements in early 2021?

The sparsity in measurements begun after May 2021 when the internal laser was replaced. Please see the previous comment.

Section 3.2.2: There are several reasons proposed for the seasonal cycle in CH_4, but earlier in the paper, it was stated that Nicosia measures outflow from Europe, Africa, and Asia. Could you perform an analysis that distinguishes airmasses from each of these continents to confirm your earlier assertion? A back-trajectory analysis or a climatological analysis would be helpful to interpret your results. Can you make use of your HCHO and HCN measurements to strengthen your argument that CH_4 enhancements are caused by fire activity? Is CH_4 expected from agricultural waste burning?

We appreciate the reviewer's comment regarding the source attribution for the observed CH_4 seasonal cycle. While our current study does not include a detailed back-trajectory analysis and multi-species correlation studies, we acknowledge their crucial role in understanding regional CH_4 sources and aim to address them comprehensively in a forthcoming study on greenhouse gas source identification in the EMME region, currently in preparation. Our present discussion builds upon previous research conducted at Nicosia (Kleanthous et al., 2014; Pikridas et al., 2018), which has mapped major transport pathways affecting surface measurements, highlighting dominant influences from Europe (north and northwest sectors), Africa (south-southwest sector), and the Middle East (east-southeast sector), each exhibiting distinct seasonal patterns. We have supplemented this analysis for TCCON's atmospheric column sensitivity through FLEXPART simulations at critical altitudes, 3 km for boundary layer air masses, 5.5 km for mid-troposphere, and 12-15 km for upper troposphere-lower stratosphere air masses – spanning 2018-2023. This serves as a foundation for source attribution in future studies.

Concerning HCHO and HCN measurements as fire tracers, our MIR observations began in early 2023, offering limited overlap with notable fire events like the summer 2021 fires in Greece and Turkey. However, these observations will be valuable for upcoming fire-season analyses. We recognize the expected emissions from agricultural waste burning, which are extensively documented in literature (Amiridis et al., 2010; Korontzi et al., 2006; Sciare et al., 2008; Stohl et al., 2007; Saunois et al., 2020). The observed incremental increases in CH_4 and correlations with XCO during fire seasons imply preliminary evidence of biomass burning influence. Nonetheless, as previously discussed, we agree that a quantitative source apportionment necessitates the comprehensive multi-tracer, back-trajectory analysis planned for our forthcoming studies, focusing on variability drivers beyond this technical site description.

We have edited Introduction (from L85) to state this more clearly. The text now reads:

> “The aim of this paper is to a) describe the new TCCON Nicosia site and its setup, and b) present the first four (4) years of quality-controlled data from this new site. More specifically, Sect. 2 provides a description of the site characteristics and the experimental methods used. Section 3 presents the initial time series of selected retrieved gases, including a brief discussion on their temporal variability and a comparison with coincident AirCore measurements. Finally, Sect. 4 summarizes key findings and outlines directions for future work.

> We note that the present study is intended as a technical site description and performance assessment study. Comprehensive analyses of the regional greenhouse-gas variability, air-mass origins, and transport mechanisms influencing the site will be addressed in forthcoming, dedicated scientific studies."

And the first paragraph of Sect. 3.2 now reads:

> "A more extensive analysis of the temporal variability of these gases with back-trajectories and source attribution will be presented in follow-up studies."

Figure 5: I find this to be a difficult way to visualize the comparison between the AirCore and TCCON measurements. It would be helpful to show the TCCON data time series spread out across each panel as a function of the hour of the day, with horizontal lines in black and red representing the medians of the public TCCON and custom TCCON retrievals, respectively. Then, the AirCore diamond (in blue) should be positioned at the time of the lowest altitude AirCore measurement, so we can compare any trends in the TCCON measurements over the +/- 1 hour with the AirCore columns. With the current visualization, the reader cannot see if there are trends in the TCCON measurements throughout the comparison period.

We acknowledge its importance in enhancing the clarity and visual impact of our findings. Below, you will find the requested figure, which we hope meets the reviewer's expectations and provides a clearer illustration of the key points discussed.

This figure, with edited caption, has now replaced Fig. 5 in the paper and the first lines of Sect. 3.3.2 have been edited to reflect the description of the new figure.

> "Figure 5 shows the Nicosia AC.X_{gas} in blue diamonds along with GGG2020 retrieved public data (grey circles and black line as the median). The custom.X_{gas} value (dashed red line as the median of custom retrievals) (see Sect. 2.2) help assess the influence of trace gas prior profiles, used in simulating the NIR spectra, on TCCON retrievals."

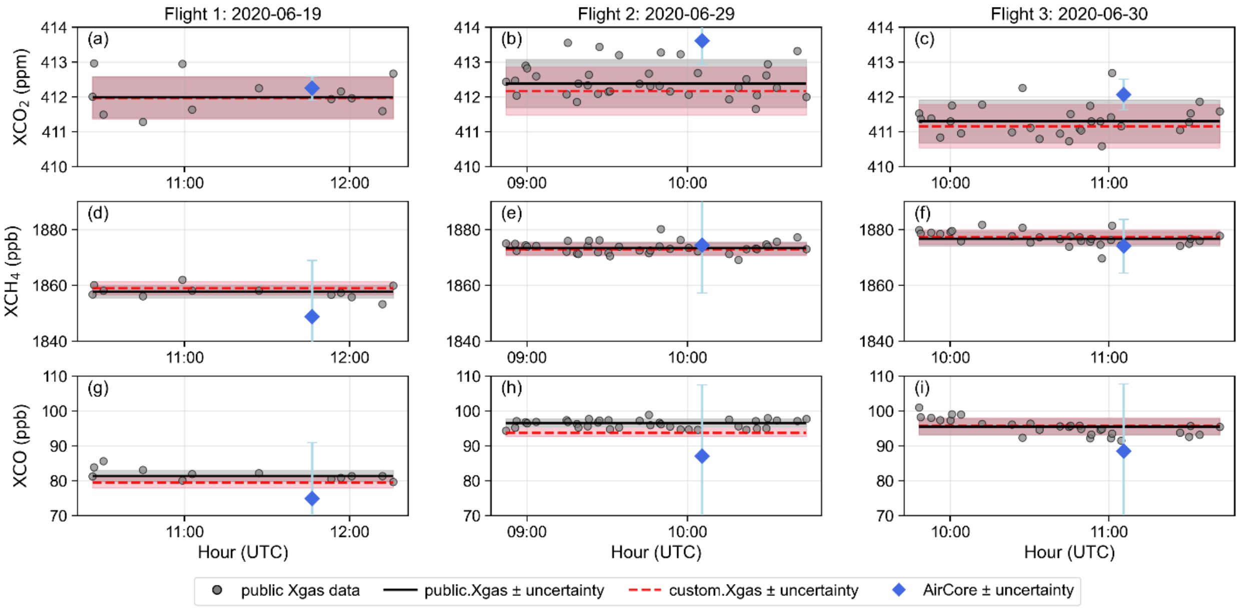

Figure 5: Comparison of the Nicosia FTS data with the integrated in situ profiles. AirCore flights took place on the June, 19, 29 and 30 June 2020. The blue diamonds representing the AirCore total column are positioned at the AC landing time. Grey circles represent XCO_2 ((a)-(c)), XCH_4 ((d)-(f)) and XCO ((g)-(i)) Nicosia data versus time in hours (UTC) during the AirCore 'flight window' used for the comparison (±1 h around the AC central time). The black solid line represents the median of the X_{gas} data and grey shaded area represents the total uncertainty (public.X_{gas} ± uncertainty). Using the AirCore assembled profiles as trace gas priors in GGG2020, the custom retrieved data (custom X_{gas}) yield a corresponding median represented as a red dashed line and red shaded area represents the total uncertainty (custom.X_{gas} ± uncertainty). The public and custom X_{gas} uncertainty includes random effects caused by measurement variability and uncertainty caused by a not ideal X_{luft}. The AC.X_{gas} uncertainty (blue uncertainty bars) include AC measurement uncertainty, stratospheric and ground uncertainty. For the detailed calculation of the uncertainty budget, refer to Sect. S2.6 in the supplementary material. Please note that some uncertainty bars in AC.X_{gas} extend outside the y-axis limits."

Also, what is the cause of the disagreement in XCO_2 on June 29? According to Figure 4, there's a substantial near-surface CO_2 enhancement on June 29, and the AirCore profile does not appear to provide data below ~2 km on that day. Do you have surface data to fill in the bottom of the profile on that day?

The 29 June flight indeed presents a complex case that merits detailed discussion.

The disagreement in XCO_2 on June 29 can be explained by (a) atmospheric heterogeneity and (b) spatial sampling differences.

(a) On that day, AirCore measurements detected a near-surface CO_2 and CO enhancement at about 1.4 km altitude, but the ground-based in situ measurements showed a substantial CO and CH_4 drawdown (Fig. S9), possibly due to a meteorological shift that advected cleaner air from the north (Fig. S11). This discrepancy between the near-surface measurements and the

AirCore's lowest measurement contributes to increased ground uncertainty (see Table S4 in supplement).

(b) Meanwhile, spatial sampling differences occur because the FTS and AirCore follow distinct paths and observe different air masses (see updated Fig. S3). The AirCore's trajectory, influenced by its descent, samples air that is not aligned with the column observed by the FTS, which measures in a sun-looking direction. This discrepancy is emphasized during meteorological transitions, such as wind direction changes, which cause significant horizontal gradient differences in gas concentrations across the area, complicating the interpretation of data collected by both instruments.

We have added a new subsection in the supplement (S2.7) that includes a discussion for the 29 June flight titled "S2.7 Case study: Spatial and temporal variability during “flight 2” – 29 June 2020", that presents detailed analysis with new figures (S9-S12 and new S3), and reference it in the main text discussion of Fig. 5 and Table 2 results. Please find below the added section.

> “**S2.7 Case study: Spatial and temporal variability during “flight 2” – 29 June 2020**
>
> The 29 June flight exhibited a larger difference between the AirCore and retrieved XCO_2 values than the 19 June flight. This is a complex case that merits detailed discussion. The 30 June flight also showed a larger difference in XCO_2; we note that the 30 June flight exhibits similar characteristics to the 29 June case: (1) a near-surface enhancement (but smaller) around 1 km altitude captured by the AirCore, (2) a substantial drawdown in ground-based in situ measurements during the flight window, (3) a local meteorological shift, (4) a modest decrease in XCO later in the day, and (5) comparable geometric sampling differences between the FTS line-of-sight and AirCore trajectory. For brevity, we focus our detailed discussion on the 29 June flight, but the observations, analysis, and conclusions are largely transferable to 30 June. The relevant figures for both flights are provided here (Figs. S9-S13). In the following paragraphs, we discuss the various factors contributing to these larger differences in XCO_2.
>
> 1) <u>AirCore profile characteristics and ground-level data:</u> On this flight, the AirCore measured a near-surface enhancement in CO_2 and CO around 1.4 km altitude (see Fig. 4 (a), (c), grey profiles; main paper) around 1.4 km altitude, which was the AC’s lowest measurement (‘floor’). We used the ground-based in situ measurements at 185 m ASL to fill the missing values between 180-420 m (see Fig. S8 and Sect. S2.4). However, these ground-based measurements do not show a similar enhancement. On the contrary, there is a substantial drawdown in both CH_4 and CO after 08:00 UTC (see Fig. S9). This discrepancy between the ground-based in situ and the last AC measurement causes the large ground uncertainty (ϵ-ground) for flight 2: 0.20 ppm for $AC.XCO_2$ compared to only 0.02 ppm for flights 1 and 3 (Table S4). In general, all $AC.XCO_2$ uncertainties are larger for flight 2 compared to the other two flights, reflecting the greater ambiguity in constructing the full profile.

2) <u>FTS observations during the flight window:</u> The TCCON X_{gas} measurements during the AirCore flight window (±1 hour around the central flight time) do not show any enhancement corresponding to the near-surface feature captured by the AirCore (see Fig. S10, '2020-06-29'). However, a slight enhancement is visible later in the day, between 12:00-13:00 UTC in both XCH_4 and XCO (see Fig. S10, '2020-06-29', (b2), (c2)), suggesting temporal evolution of the atmospheric state.

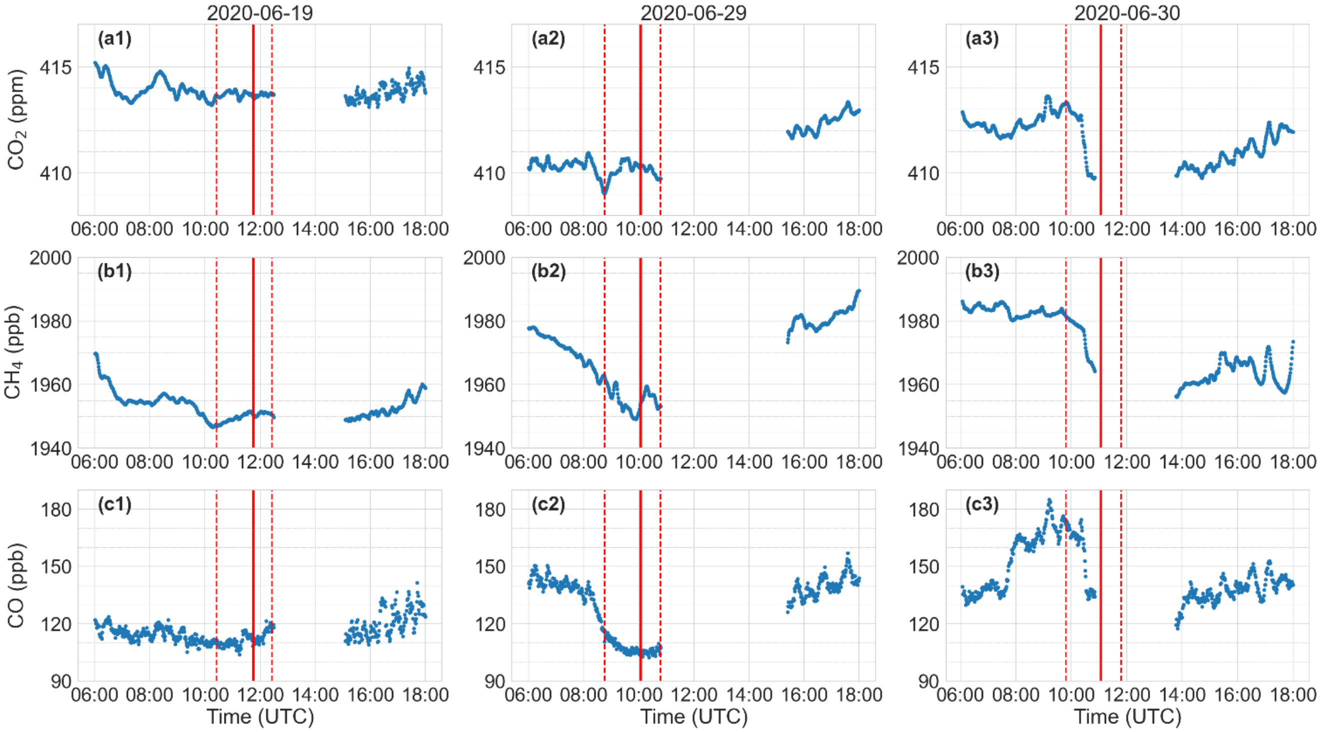

Figure S9: Time series of CO_2 ((a1)-(a3)), CH_4 ((b1)-(b3)) and CO ((c1)-(c3)) in dry-air mole-fraction, measured by the ground-based Picarro G2401 during the three days of the AirCore flights. Red solid line indicates AirCore landing time and dashed lines the ±1 h time window around AirCore central time. The gap in the measurements' time-series is due to the AirCore analysis.

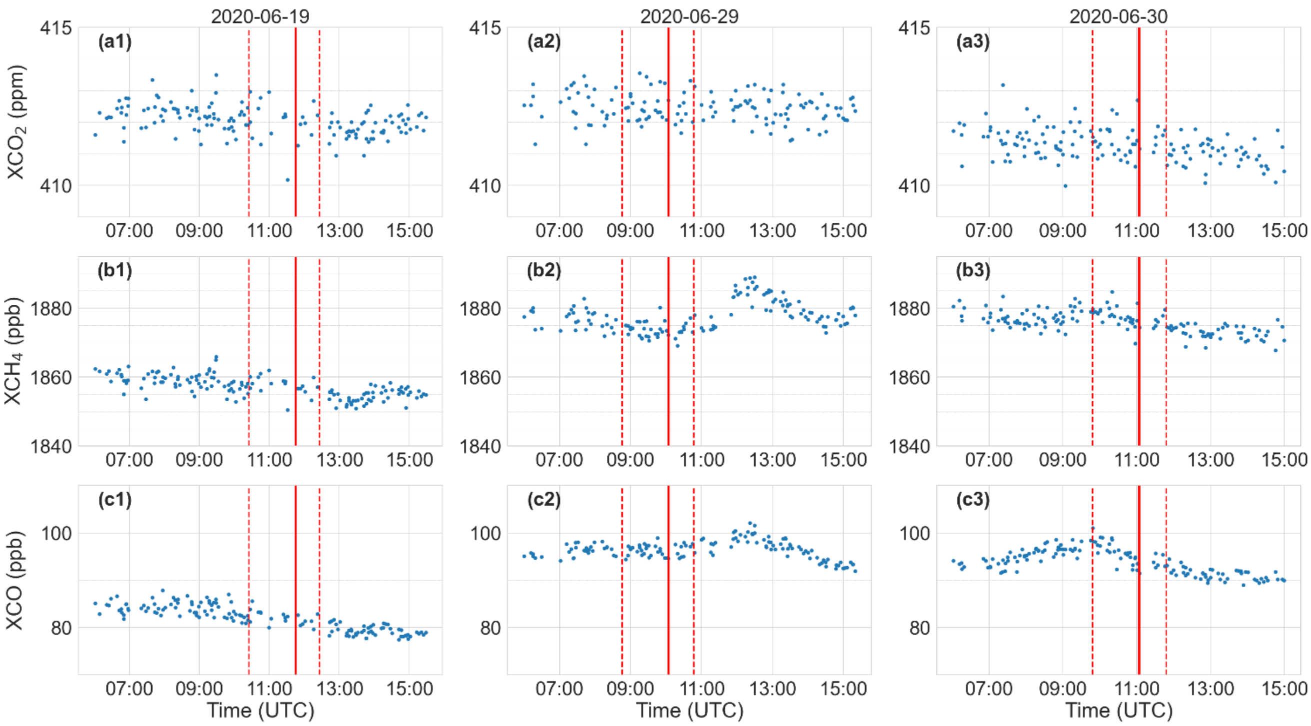

Figure S10: Time series of XCO_2 ((a1)-(a3)), XCH_4 ((b1)-(b3)) and XCO ((c1)-(c3)) measured by TCCON Nicosia during the three days of the AirCore flights. Red solid line indicates AirCore landing time and dashed lines the ±1 h time window around AirCore central time.

3) <u>Meteorological analysis:</u> To understand these observations, we examined the local meteorology during the flight using data from two sources: (1) the nearest Department of Meteorology station (Athalassa, station 1666, 35.15°N 33.4°E, 162 m ASL, ~1.5 km from the FTS), and (2) the meteorological station co-located with the Nicosia FTS (Fig. S11 and S12, respectively).

The data reveal a significant meteorological shift starting around 08:00 UTC:

- Wind direction changed from 270° (West) to 0°-45° (N-NNE) (Fig. S11 (b2))
- Relative humidity dropped substantially (Figs. S11 and S12, (c2)), and
- Mean wind speed increased (Fig. S11 and S12, (a2)).

This near-surface wind shift appears to have advected cleaner air toward the ground-based in situ site, as evidenced by the pronounced drawdown in CH_4 and CO after 08:00 UTC (Fig. S9 (b2), (c2)). This indicates that the enhancement observed by the AirCore was likely confined to an elevated layer between approximately 200 m and 2 km and was not well coupled to the boundary layer sampled at the surface.

It is also plausible that the cleaner air mass had not yet reached the AC landing location at the time of sampling. Because the ground-based in situ site (co-located with the TCCON instrument; see Fig. S3) is located north of the AC landing site, and the wind shift was from the north, the cleaner air would be expected to arrive at the in situ station first, consistent with the observed timing.

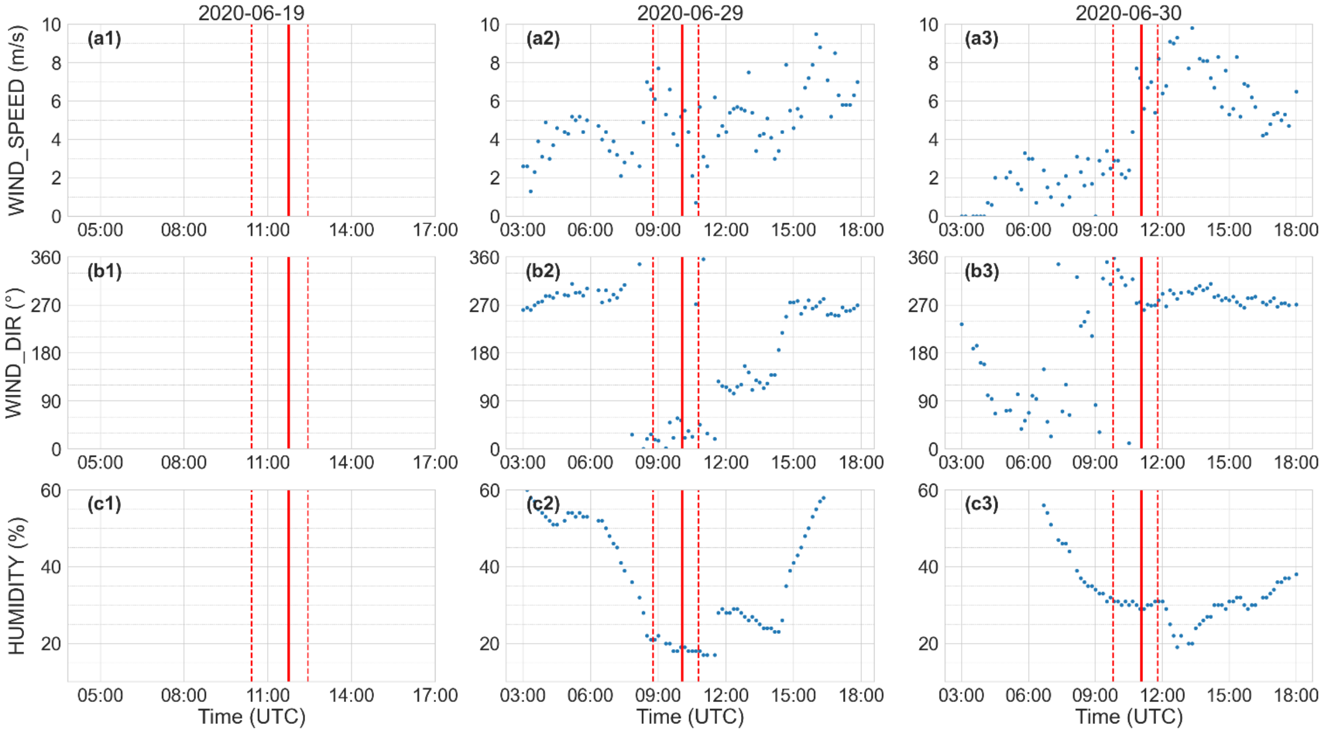

Figure S11: Time series of wind speed (WIND_SPEED, (a1)-(a3)), wind direction (WIND_DIR, (b1)-(b3)) and humidity (HUMIDITY, (c1)-(c3)) measured by the Athalassa meteo station in the forested park southeast of the Nicosia FTS (35.15°N 33.4°E, 162m asl) during the three days of the AirCore flights. There are no data recorded on 19 June 2020. Red solid line indicates AirCore landing time and dashed lines the ±1 h time window around AirCore central time.

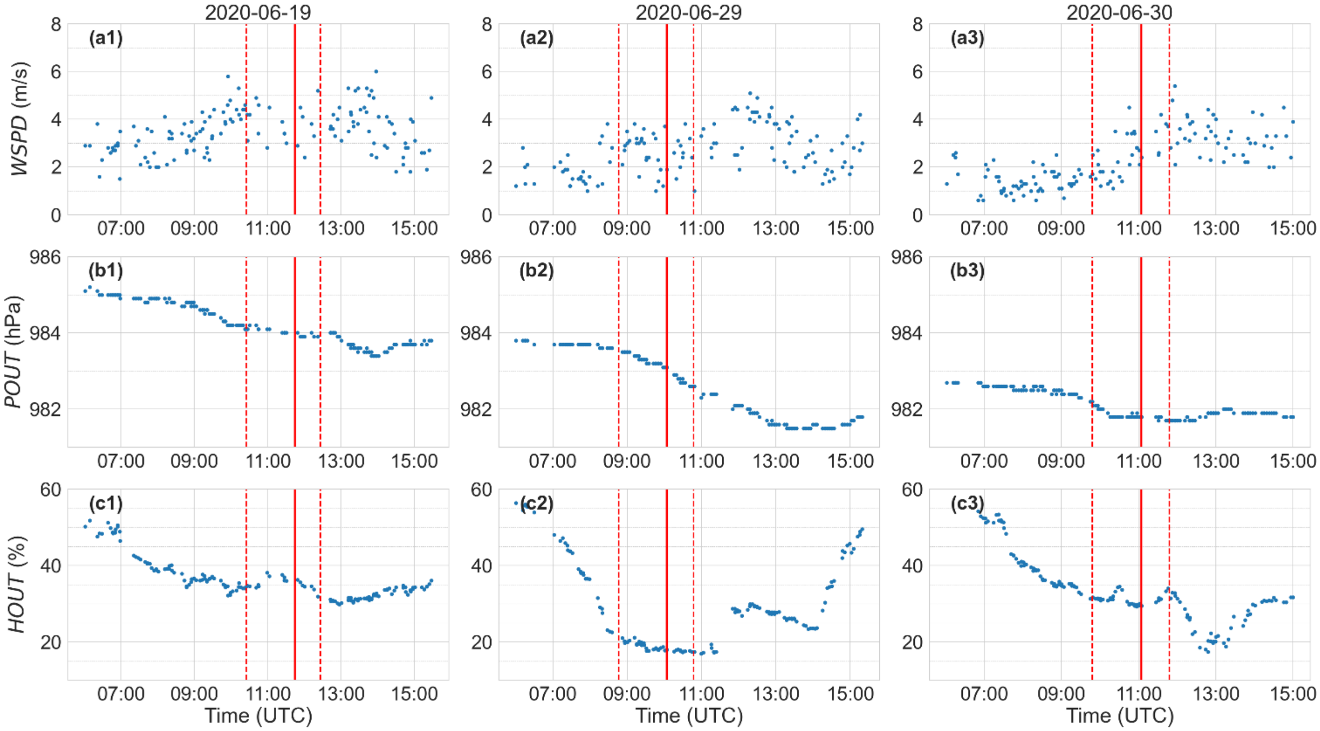

Figure S12: Time series of wind speed (WSPD, (a1)-(a3)), ambient pressure (POUT, (b1)-(b3)) and humidity (HOUT, (c1)-(c3)) measured by TCCON Nicosia meteo station during the three days of the AirCore flights. Red solid line indicates AirCore landing time and dashed lines the ±1 h time window around AirCore central time.

4) <u>Spatial sampling mismatch:</u> An additional complication arises from the geometric sampling differences between instruments. Near the AirCore landing time (~10:05 UTC), the FTS line-of-sight (see Fig. S13, orange dashed lines) was markedly different from the AirCore trajectory (Fig. S13, AirCore 'landing' in orange marker). More specifically:

- The solar azimuth angle was 190°-195° (SSW direction), while the AirCore was heading eastward
- The solar zenith angle was small (~12°) during landing, meaning the FTS was sampling high in the atmosphere
- The AirCore trajectory: the AC descended from the West, heading to the East, passing under but laterally displaced from the FTS line-of-sight (see Fig. S3)

Therefore, it is reasonable to conclude that the two instruments sampled different air masses, particularly at lower altitudes where the horizontal gradients were likely strongest due to the meteorological transition.

5) Limited improvement from custom retrievals: One might expect that replacing the GGG2020 priors with the true AirCore profiles in custom retrievals would yield custom.X_{gas} values much closer to AC.X_{gas} than the public.X_{gas}. However, this was not the case (see Table 2). Several factors explain this:

- Partial profile replacement: we replace only three trace-gas profiles (CO_2, CH_4, and CO) while numerous other profiles – including H_2O, temperature, and pressure – remain unchanged
- Re-gridding smoothing: re-gridding the high-resolution AirCore profiles to the coarser GGG grid levels reduces some of the profile variability
- Spatial mismatch propagation: If the FTS and AirCore sampled air masses with genuinely different profiles, using the AirCore instead of the prior does not eliminate error from an incorrect prior shape

Conclusion – Implications for comparison: given these considerations, we believe the disagreement on June 29 reflects genuine atmospheric heterogeneity and spatial sampling differences rather than systematic instrumental biases. The fact that:
1) flight 1 shows good agreement for XCO_2 while flights 2 and 3 present similarly complex cases (Table 2),
2) the disagreement on flight 2 falls within the combined uncertainties when the individual uncertainties are properly accounted for (all larger in flight 2 compared to flights 1 and 3, see Table S4 for XCO_2),
3) the custom retrieval does not improve agreement (supporting the spatial mismatch hypothesis);
support the interpretation that this case demonstrates the challenges of comparing column and in situ measurements in spatially heterogeneous conditions, rather than indicating a systematic problem with the TCCON Nicosia data.

Figure S8: How are the profiles extended down to the surface? The text seems to imply that the lowest AirCore measurement is dropped straight to the surface ("flat-extrapolation"), but replaced in the bottom two grid levels by the surface in situ measurement. However, the right panel of Figure S8 does not appear to show that. Please clarify whether these are two different profiles, or why the near-surface assembled profile is >8 ppm different between the left and right panels.

We thank the reviewer for requesting this clarification. The reviewer is correct; the bottom two GGG grid levels are handled differently from the intermediate levels.
The near-surface portion of the assembled profile (0–880 m) is constructed as follows:
1. Levels 1–2 (0 m and 420 m): Filled using the ground-based in situ measurements at 185 m ASL (the FTS height)
2. Level 3 to AirCore floor (880 m to ~1400 m): Filled by flat-extrapolation of the lowest AirCore measurement

Note that for flight 1 (June 19), this flat-extrapolation step is not required because the AirCore floor altitude (830 m) lies below the 880 m level (see Table S1).

Explanation of the ~8 ppm difference between panels:

The left and right panels of Figure S8 show the same assembled profile but in different representations:

- Left panel (wet profile): Shows CO_2 in wet mole fractions as required for input to the GGG2020 custom retrievals. The inset zoom clearly displays the near-surface fill described above.
- Right panel (dry profile): Shows CO_2 in dry mole fractions, as used for total-column integration via the pressure weights approach (Eq. 2). This panel does not include an inset zoom of the near-surface region, which may have caused confusion.

The ~8 ppm apparent difference between the two panels at the surface arises from the water vapor correction. Due to high water vapor content near the ground (<2 km altitude), the conversion from dry (the original AirCore profile) mole fractions to wet (https://tccon-wiki.caltech.edu/Main/AuxiliaryDataGGG2020, last access 16 December 2025):

$$\mathrm{f}_{\mathrm{gas}}^{\mathrm{wet}} = {\mathrm{f}_{\mathrm{gas}}^{\mathrm{dry}}} \Big/ \left(1 + \mathrm{f}_{\mathrm{H_2O}}^{\mathrm{dry}}\right),$$

where $\mathrm{f}_{\mathrm{gas}}^{\mathrm{dry}}$ is the dry mole fraction of CO_2 in this case, produces a substantial shift (see both profiles in one graph in Fig. AC1 below).

With typical near-surface water vapor mole fractions of ~1.5-2% in Cyprus during summer, this correction decreases the wet mole fraction by approximately 6-8 ppm for CO_2 dry-air mixing ratios around 410 ppm.

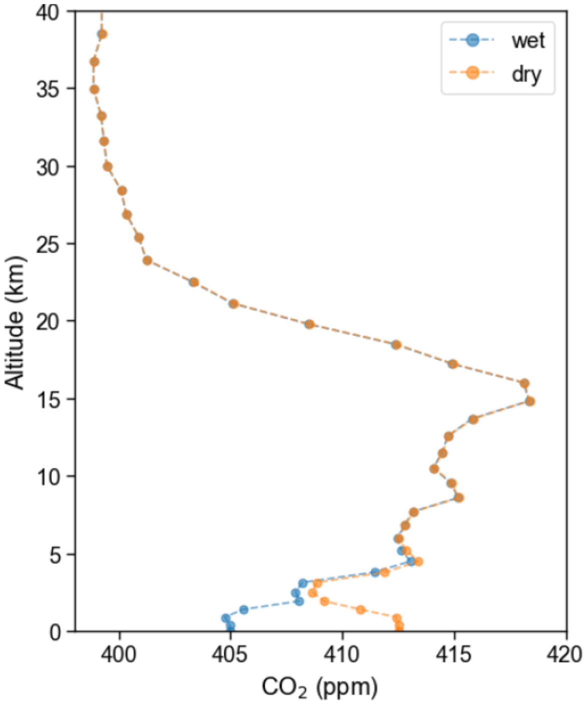

Figure AC1: AirCore CO_2 profile for the flight of 2020-06-30, re-gridded to the GGG2020 grid. Blue marker denotes the ‘wet’ profile (used in the custom GGG2020 retrievals) and orange marker denotes the ‘dry’ profile.

We have revised the Figure S8 caption to explicitly state:

- That both panels show the same assembled profile
- The left panel is in wet mole fractions, the right panel is in dry mole fractions
- The ~8 ppm difference is due to the water vapor correction, not different profile construction methods

Figure S8 caption now reads:

“Figure S8: This figure shows a schematic of the approach followed to construct a full vertical profile. For comparability with the FTS prior, the in situ profile needs to extend from 0 m (a.s.l.) to 70 km. Both left and right panels show the same assembled profile (CO_2, 30 June flight); however, the left profile is in wet mole fractions and the right profile in dry mole fractions. Left (wet profile): Example of an assembled AirCore (AC) profile for the flight on 30 June, 2020, showing CO_2 in wet mole fractions. This vertical resolution profile, was used for the GGG2020 custom retrievals (see Sect. S2.5). Red stars represent the re-gridded AC profile, while a flat extrapolation of the lowest AC measurement to near-ground levels is shown as red crosses in the inset. The grey shading around the main AC profile indicates the uncertainty bounds; which is very small for CO_2. The FTS prior profile is depicted as grey circles connected by a grey line, with the prior used to extend the in situ profile upwards shown as grey circles connected by a red line. The horizontal dashed line marks the altitude of the last AC grid level. Near-surface in situ measurements are represented by the median (orange 'x') and the mean ± standard deviation (green triangle). The inset focuses on the lower 3 km, showing near-surface variability and the comparability between the prior and in situ measurements. A complete profile is constructed by assembling 1) the re-gridded AC profile (red stars), 2) the FTS prior above the highest AC measurement (gray circles with red line), 3) flat extrapolation of the lowest AC measurement to near-ground levels (red cross at 0.88 km), and 4) the in situ surface median (orange 'x') for the lowest two levels (0 and 0.42 km). Right (dry profile): Assembled AirCore profile in full resolution (in dry mole-fractions). This profile was used as the true profile, x, in Eq. 2, main paper. The ~8 ppm difference near the ground of the left- and right-panel profiles is due to the difference between wet and dry mole fraction; which is largest at the surface due to the concentration of water there."

Technical comments:

L30: "mid-infrared (MIR) spectrum" should be "mid-infrared (MIR) spectral region"

It is now corrected to "mid-infrared (MIR) spectral region".

L74: "north hemisphere" should be "northern hemisphere"

It is now corrected to "northern hemisphere".

L93: remove "shall"

We have removed "shall".

L96: TCCON Network seems redundant -> use just TCCON or just Network

It is now corrected to "TCCON".

Equation (1): missing 'gas' subscript on the central equation

We thank the reviewer for pointing out this omission. Equation (1) is now corrected with the missing "gas" subscript.

L182: It is not just spectroscopic errors that cancel in the ratio. Alignment errors, pointing errors, some spectroscopic uncertainties can partially cancel.

We thank the reviewer for this correction.

The text is now revised to:

> "The use of this ratio not only cancels out spectroscopic effects common to both gas and O_2 columns, but also other systematic effects including alignment and pointing errors, while some spectroscopic uncertainties can partially cancel (see Appendix A(d) of Wunch et al. 2011 and Mendonca et al. 2019)."

L187: The O_2 is retrieved from a 250 cm^{-1} wide window that is centred at 7885 cm^{-1}, and not from a single line. The retrievals are based on multiple O_2 absorption lines. See Mendonca et al. (2019) for reference for this comment and the previous one (L182).

We thank the reviewer for this correction.

The text is now revised to:

> "Here, we use X_{luft} (the total column average of dry air), derived from surface pressure and the O_2 column (VC_{O_2}) retrieved within a ~250 cm^{-1} window centered at 7885 cm^{-1} (Mendonca et al., 2019), as a quality diagnostic indicator (Laughner et al., 2024)."

Response to Referee #2

This article reports on the installation of a new TCCON site in Nicosia and describes quality control procedures applied on the measured TCCON data starting in 2019.

In the introduction and conclusions, the site is advertised as strategic due to its unique location: it can measure different airmass from Europe, Asia and Africa and bring new insights in regional sources and sinks for the EMME region. With three AirCore profiles and their back-trajectory analysis, the material presented in the article demonstrates the stated benefits of this site to a limited extent. The authors should include material that supports their claims made in the conclusion and introduction.

We thank the reviewer for this important remark. We acknowledge that the presented analysis does not yet exploit the full scientific potential of the TCCON Nicosia site in terms of regional source attribution or airmass characterization. Nonetheless, the primary focus of this manuscript is to offer a detailed technical and methodological overview of the new TCCON site, covering its setup, data quality control, and initial data records, which aligns with other TCCON site description papers. Our claim of the site's strategic importance is firmly based on previously published studies demonstrating Cyprus's role as a receptor site of long-range transported pollution from Europe, Asia, and Africa:

- Lelieveld et al. (2002) described the Eastern Mediterranean as a "crossroads of air pollution."
- Kleanthous et al. (2014) quantified boundary-layer airmass origins and seasonality over Cyprus using back-trajectories, showing distinct seasonal contributions from all three continents.
- Pikridas et al. (2018) and Vrekoussis et al. (2022) further confirmed the dominance of transported versus local pollution over the island.

To clarify this, we have edited the Introduction to explicitly reference these studies and specify that our claim relies on their findings rather than new analysis.

The text now reads: (Introduction, after L60):

> "Furthermore, previous studies have shown that long-range transported pollution dominates over local emissions in Cyprus, with distinct seasonal air-mass regimes originating from Europe, west Asia (including the Middle East), and North Africa (Kleanthous et al., 2014; Lelieveld et al., 2002; Pikridas et al., 2018; Vrekoussis et al., 2022; Germain-Piaulenne et al., 2024). This diversity of source regions, which currently exhibit diverse GHG emissions trends (https://globalcarbonatlas.org/, last access: 1 March 2025), renders Cyprus a unique receptor site at the crossroads of continental outflows, making TCCON Nicosia strategically positioned for regional GHG monitoring."

L139: please add a motivation why this max opd deviates from the TCCON standard of 45cm.

Please refer to our response to the same point raised by Referee #1.

L182: I believe this cancels not only spectroscopic, but any systematic error common to both gas and O2 columns.

We agree with the above comment. We modified the sentence to clarify that the ratio VC_{gas}/VC_{O_2} cancels systematic effects common to both columns (e.g., spectroscopy, instrument line-shape, air-mass path).

The text now reads:

> “The use of this ratio not only cancels out spectroscopic effects common to both gas and O_2 columns, but also other systematic effects including alignment and pointing errors, while some spectroscopic uncertainties can partially cancel (see Appendix A(d) of Wunch et al. 2011 and Mendonca et al. 2019).”

L198: I was confused with this sentence: at the beginning of the § the problematic period is in 2022 (L194), but here the start of the period is April 2021. Please clarify.

We thank the reviewer for pointing out this inconsistency. The underlying hardware issue (a gradually loosening scanner cable) was present since the initial installation in 2019, but its impact became evident only in 2022 when sufficient data allowed us to observe increased Xgas and Xluft variability. The reference to April 2021 in the original text pertained to a separate event – a broken internal laser and subsequent poor refocusing – which temporarily reduced measurement frequency and delayed the identification of the cable issue. We have clarified the timeline and causal relationships in the revised text to avoid misunderstanding.

This information is included in the text (last ¶ of Sect. 2.1.4) as:

> “The TCCON Nicosia instrument experienced increased X_{gas} and X_{luft} variability due to a gradually loosening scanner electronic cable, present since installation in 2019 but identified and fixed only in November 2024. The issue led to longer scan durations and increased data spread, which became evident in 2022 when sufficient measurements were available. In parallel, the internal laser failed in April 2021, and its subsequent mis-focus after replacement reduced the number of valid scans, delaying the detection of the cable-related problem. During the affected period, we applied an empirical filter based on the O_2 line (7885 cm^{-1}) frequency shift (O_2_fs) to remove spectra outside the nominal X_{luft} range before public data release. Applying the O_2_fs filter removed approximately 40 % of measurements, while most of the removed data lie within the 2022 period. Figure 2 shows the corrected X_{luft} time series. Upcoming GGG2020 releases aim to address X_{luft}-correlated X_{CO_2} biases (Laughner et al., 2024), potentially restoring the filtered data. The underlying issue causing the longer scan durations has since been resolved and no further occurrences have been observed after late 2024.”

L214: “This evaluation exercise is only visual”: why? If the CFs are derived from a larger ensemble of in situ profiles, it would remain meaningful to interpret the observed differences between the TCCON and AirCore measurements (cf the comments on Eq(2)).

We would like to clarify that the limited availability of AirCore (AC) profiles, only three in number, prevented us from deriving statistically significant correction factors (CF). Deriving CF requires a multi-site ensemble approach, as implemented across the network in GGG2020 (Laughner et al., 2024). Additionally, these three AC flights occurred within a narrow temporal window, which may overlook significant seasonal variability that flights conducted in different seasons could uncover. Consequently, our objective was to ensure internal consistency within uncertainties, rather than to conduct a site recalibration.

This comment is now addressed in the text (L214-215):

> “Because only three AirCore profiles were available, the comparison was limited to a consistency check and interpretation of observed differences. A quantitative derivation of new correction factors for Nicosia would not be statistically robust and is already handled at the network level within GGG2020.”

We have also expanded our supplementary material with a new section (Sect. S2.7) including a more elaborate discussion on interpreting the observed differences and revised our results in Sect. 3.3.2 accordingly. **We have revised the paragraph after L360 as:**

> “Differences between X_{gas} and AC.X_{gas} can arise from multiple sources:
>
> 1) Gas prior assumptions in the retrievals. For example, a vertical shift in the gas prior or an enhancement in prior CO concentrations can introduce biases of up to 1.5% in X_{CO} retrievals (Laughner et al., 2024). The custom retrievals help isolate this effect by replacing GGG2020 priors with AC profiles.
>
> 2) Spatial and temporal sampling mismatches. The AC lands at a different location from launch and measures from the highest altitude downward, sampling a gas profile that is neither vertical nor coincident with the FTS line of sight (see Fig. S3 in supplement). Therefore, discrepancies between the AirCore trajectory and FTS line of sight may contribute to observed differences, particularly in spatially heterogeneous conditions (see Sect. S2.7 in the supplement). For instance, if the AirCore follows a west-to-east trajectory along a concentration gradient while the FTS observes toward the south, spatial variations in sampled air masses can lead to differences.
>
> 3) Atmospheric heterogeneity and boundary layer dynamics: Flight 2 (29 June 2020) exemplifies these challenges. The AirCore captured a near-surface enhancement around 2 km altitude (see Fig. 4a, dark grey profile), while ground-based in situ

> measurements showed a concurrent drawdown in CH_4 and CO (see Fig. S9) due to a shift in wind direction from westerly to northerly around 08:00 UTC (see Fig. S11, S12 in Sect. S2.7). This difference is reflected in the large ground uncertainty (ϵ-ground = 0.20 ppm for AC. X_{CO_2} versus 0.02 ppm for other flights, see Table S4 in Sect. S2.6). Combined with geometric sampling differences (small solar zenith angle and eastward AC trajectory versus SSW-directed FTS line of sight; see Fig. S3), the two instruments likely sampled different air masses. The fact that custom retrievals do not improve agreement supports the spatial mismatch hypothesis rather than indicating site-related biases. Despite these complexities, all comparisons agree within their combined uncertainties, demonstrating the robustness of the TCCON Nicosia measurements. A detailed case study analysis is provided in Sect. S2.7 in the supplementary material."

Eq(2): how can gamma be determined from the public TCCON data?

The gamma (γ) is the volume mixing ratio scale factor (VSF). The γ can be defined as the ratio between retrieved (xgas) and prior column (prior_xgas) gas amounts, available in public TCCON data. The ratio of the retrieved profile (posterior) to the prior gas profile is also gamma, however only the prior profile is available in the public data.

The text (L224-225) now reads:

> "The retrieval scaling factor quantifies the ratio of the retrieved to the prior column abundance. Both the retrieved and prior column averages are provided within the public TCCON data (i.e. 'xgas' and 'prior_xgas')."

Eq(2): the main purpose of calculating AC.Xgas and its comparison to TCCON is a reduction in the comparison error budget (cf Rodgers 2003). This paragraph should be extended with an uncertainty budget estimate on the difference between the AirCore and TCCON data (not the full detail of the error contributions (eg spectroscopy, noise ,…), but the text must link it to the uncertainties reported along with the measurement data so that a reader may reproduce the results).

We thank the reviewer for this constructive suggestion. We agree that quantitative comparison of TCCON and AirCore data should be interpreted in the context of their respective uncertainties to assess the statistical significance of the observed differences.

Our goal here, however, is not to derive new correction factors or recalibrate the Nicosia data, but to provide the reader with a transparent comparison between the publicly available, WMO-tied TCCON products and coincident AirCore measurements. The complete description of how the individual TCCON and AirCore uncertainties are calculated is provided in Supplement S2.6, where we detail random and systematic effects, and AirCore-related components following Laughner et al. (2024) and Wunch et al. (2010).

In the TCCON framework, uncertainty propagation is handled empirically rather than through full covariance-matrix propagation as in the formal Rodgers and Connor (2003) approach often used in NDACC.

To clarify this we edited the last paragraph of Sect. 2.2 to clearly point to where we calculate the total uncertainty.

The text after L236 now reads:

> "Details on constructing the full in situ profiles (x) (Sect. S2.3-S2.4), selecting FTS data (Sect. S2.2) and the derivation and quantification of the individual uncertainties comprising the empirical total uncertainties for the compared quantities (public.X_{gas} and AC.X_{gas}) (Sect. S2.6) are detailed in the supplementary material, following a similar – but not identical – approach as Laughner et al. (2024)."

Also which pairs of Xgas values should be considered so that their difference allows an error budget reduction: public.Xgas minus AC.Xgas, or public.Xgas minus the unchanged AirCore, or ... ?

We thank the reviewer for this request for clarification. In this study, the comparison is performed between, public.Xgas – the median of the publicly available TCCON Xgas values measured within ±1 hour around the AirCore central time – and AC.Xgas which represents the total-column dry-air mole fraction obtained from integrating the in situ AirCore profile after applying the TCCON averaging kernel and a priori profile (Eq.2). This was stated in the paper in L229-230 and first sentence of Sect. 3.3.2. The application of the averaging kernel renders the smoothing component of the uncertainty negligible.

We emphasize that our aim here is not to achieve an error-budget reduction, but rather to verify that the publicly distributed, WMO-referenced TCCON data for Nicosia are consistent with coincident AirCore profiles within their combined uncertainties. To prevent confusion, the revised manuscript explicitly states the pairing methodology and clarifies that we apply the TCCON averaging kernel.

We have edited the text in Sect. 2.2 after L227 to clearly define the comparison pair and clarify the exclusion of the smoothing uncertainty from the uncertainty budget (as per the next comment):

> "In this study, the comparison pair corresponds to public.X_{gas} (the median of measurements within ±1 hour window around the AirCore flights' central time) and AC.X_{gas}, the AirCore-derived column after application of the TCCON averaging kernel (k) (see Eq.2). The public X_{gas} data, entail uncertainties from a) imperfect spectroscopy and b) imperfect (wrong shape) priors. Applying the averaging kernel reduces the smoothing component of the uncertainty, such that the smoothing uncertainty becomes negligible for the comparison (see Laughner et al. (2024) and Wunch et al. (2010)). In order to disentangle uncertainties of type (a) from (b), we run the GGG2020 retrievals on TCCON spectra using the AirCore profiles (true profile shape) as the priors – i.e. a "custom retrieval" – which yields a "custom" X_{gas} (custom.X_{gas}) (see also Sect. S2.5 in supplement). Both public and custom X_{gas} data in this study include the Network-wide in situ correction, i.e. the airmass-independent correction factors (AICF; see Laughner et al., 2024)."

Which uncertainty should be used to evaluate the differences for each such pair? Eg is the smoothing uncertainty part of the uncertainty budget on the difference? This information is not available here nor in the supplement.

We appreciate this question and agree that the meaning of the comparison uncertainty should be stated explicitly. In our analysis, the total uncertainty of each of public.Xgas and AC.Xgas is obtained as the sum of the uncertainties arising from systematic effects plus the root-sum-square (RSS) of the uncertainties arising from random effects, detailed in Supplement S2.6, following Laughner et al. (2024).

The smoothing uncertainty – as defined by Rodgers & Connor (2003) after Eq. (24) – becomes negligible when the TCCON averaging kernel is applied to the AirCore profile. This assumption is standard practice in TCCON intercomparisons (Wunch et al., 2010; Laughner et al., 2024). Consequently, we do not include an additional smoothing term in the uncertainty budget of the difference.

Please also see response to previous comment.

L231 "Differences amongst these two quantities will be due to the difference in the measurement principle": this is unclear and must be clarified (which quantities?, which uncertainty term is canceled? cf the previous remark on Eq(2)).

We thank the reviewer for pointing out this ambiguity. We agree that this sentence is not accurate, because it would be true for the Xgas and the individual measurements collected in situ by the AirCore comprising the profile, but not for the public.Xgas and the AC.Xgas as the latter is calculated, not measured.

This sentence starting in L231 is now removed.

In Figure 5 the different Xgas values are plotted and the author presents it as a "visual-only comparison": this is not sufficient for a scientific publication: an uncertainty budget must be specified to properly interpret a comparison.

The reviewer is right to highlight this point, and we agree that referring to it as a "visual-only comparison" may not seem sufficient. We have removed all instances in the paper where we refer to the comparison as "visual only". However, Fig. 5 offers the visual aspect of the comparison, while Table 2 provides the quantitative analysis, including the total uncertainties for each compared quantity. We have placed the detailed uncertainty budget in Section S2.6 of the supplement because it is technical and not crucial for the broader audience trying to grasp the main points of the paper. To maintain the paper's flow, we've reserved this section for supplemental material. However, the caption for Fig. 5 includes a brief mention of the individual uncertainties that contribute to the uncertainty budget.

The text (L214-215) is revised as per the previous comment and Table 2 typo caption to refer to the correct supplement section (S2.5 instead of B5 and S2.6 instead of B6). The caption of Table 2 now reads:

> "Table 2: Retrieved and calculated X_{gas} quantities. The public.Xgas (official Nicosia data) flight median ± total uncertainty value is compared to the AirCore derived comparison quantity (AC.X_{gas} ± uncertainty). The custom retrieved Nicosia data (custom.X_{gas} ± total uncertainty) (see Sect. 2.2 and S2.5 in supplement) are also shown here for comparison. The detailed uncertainty budget for all X_{gas} products is presented in Sect. S2.6 in the supplementary material. Here, 'total uncertainty' denotes the combined uncertainty obtained by the reported random and known systematic contributions (see Sect. S2.6). Values are rounded to the nearest decimal."

L227: typo: The results presented here are obtained using the "pressure weights" method

L227 corrected to:

> "The results presented here are obtained using the "pressure weights" method."

Discussion in §3.2 would benefit from a more clear link with the plots in Fig 3: eg where in the plot is the location of the minor peak in xCH4 around mid-spring (L287)

The reviewer is right in requesting a clearer connection between the text and Figure 3. We have enhanced the text accordingly.

The text (L287) is modified to:

> "A minor peak of X_{CH_4} in Fig. 3b is observed around mid-spring, most evident in spring 2020, which is likely associated with agricultural waste burning in Eastern Europe (Amiridis et al., 2010; Korontzi et al., 2006; Sciare et al., 2008; Stohl et al., 2007)."

Suggestion to revise the document to follow the GUM terminology and replace "error" with "uncertainty" where necessary (see §2.2 from GUM 2008)

We thank the reviewer for referring us to this terminology guide. All instances of 'error' were revised to 'uncertainty', except when describing a residual or offset, consistent with the Guide to the expression of uncertainty in measurement (GUM 2008, https://www.iso.org/sites/JCGM/GUM/JCGM100/C045315e-html/C045315e.html, last access 13 October 2025).