

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

Response to Referee #1

Referee comments in red

Our responses in blue

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

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 CO₂ 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 XCO₂ 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 CH₄, 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 CH₄ enhancements are caused by fire activity? Is CH₄ expected from agricultural waste burning?

We appreciate the reviewer's comment regarding the source attribution for the observed CH₄ 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 CH₄ 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; Saunio et al., 2020). The observed incremental increases in CH₄ 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.”

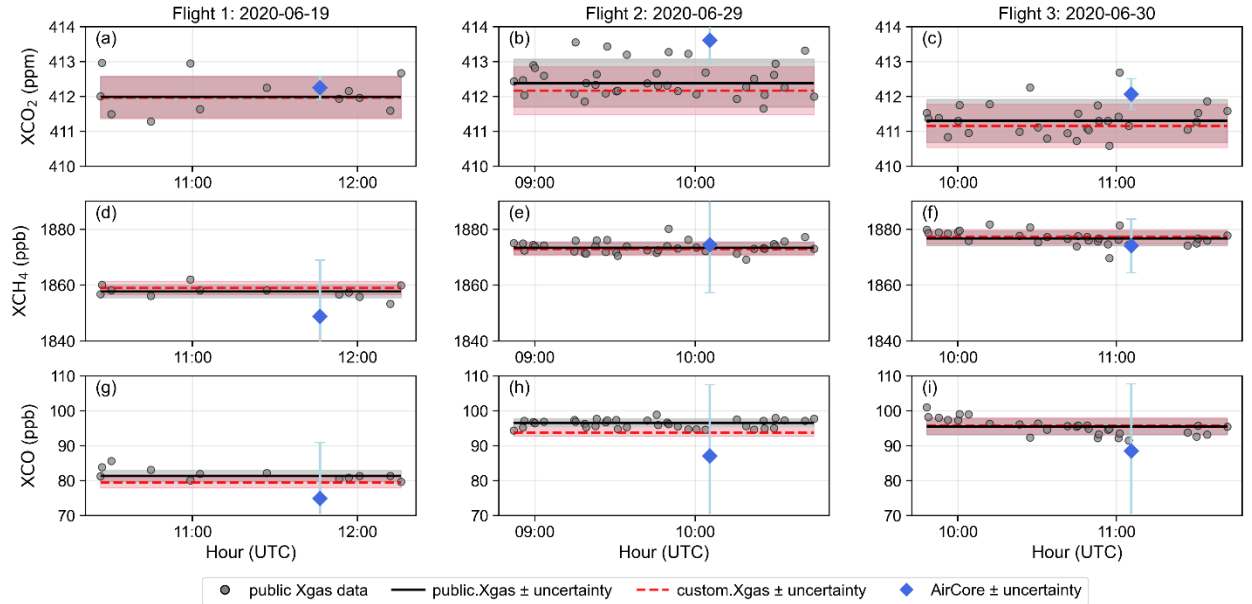


Figure 5: Comparison of the Nicosia FTS data with the integrated in situ profiles. AirCore flights took place on the June, 19, 29 and 30 June 2020. The blue diamonds representing the AirCore total column are positioned at the AC landing time. Grey circles represent XCO₂ ((a)-(c)), XCH₄ ((d)-(f)) and 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} $\pm$ 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} $\pm$ 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 XCO₂ on June 29? According to Figure 4, there’s a substantial near-surface CO₂ 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 XCO₂ 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 CO₂ and CO enhancement at about 1.4 km altitude, but the ground-based in situ measurements showed a substantial CO and CH₄ 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 XCO₂ 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 XCO₂; 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 XCO₂.

1) AirCore profile characteristics and ground-level data: On this flight, the AirCore measured a near-surface enhancement in CO₂ 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 CH₄ 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.XCO₂ compared to only 0.02 ppm for flights 1 and 3 (Table S4). In general, all AC.XCO₂ uncertainties are larger for flight 2 compared to the other two flights, reflecting the greater ambiguity in constructing the full profile.

2) FTS observations during the flight window: 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 $X\text{CH}_4$ and $X\text{CO}$ (see Fig. S10, '2020-06-29', (b2), (c2)), suggesting temporal evolution of the atmospheric state.

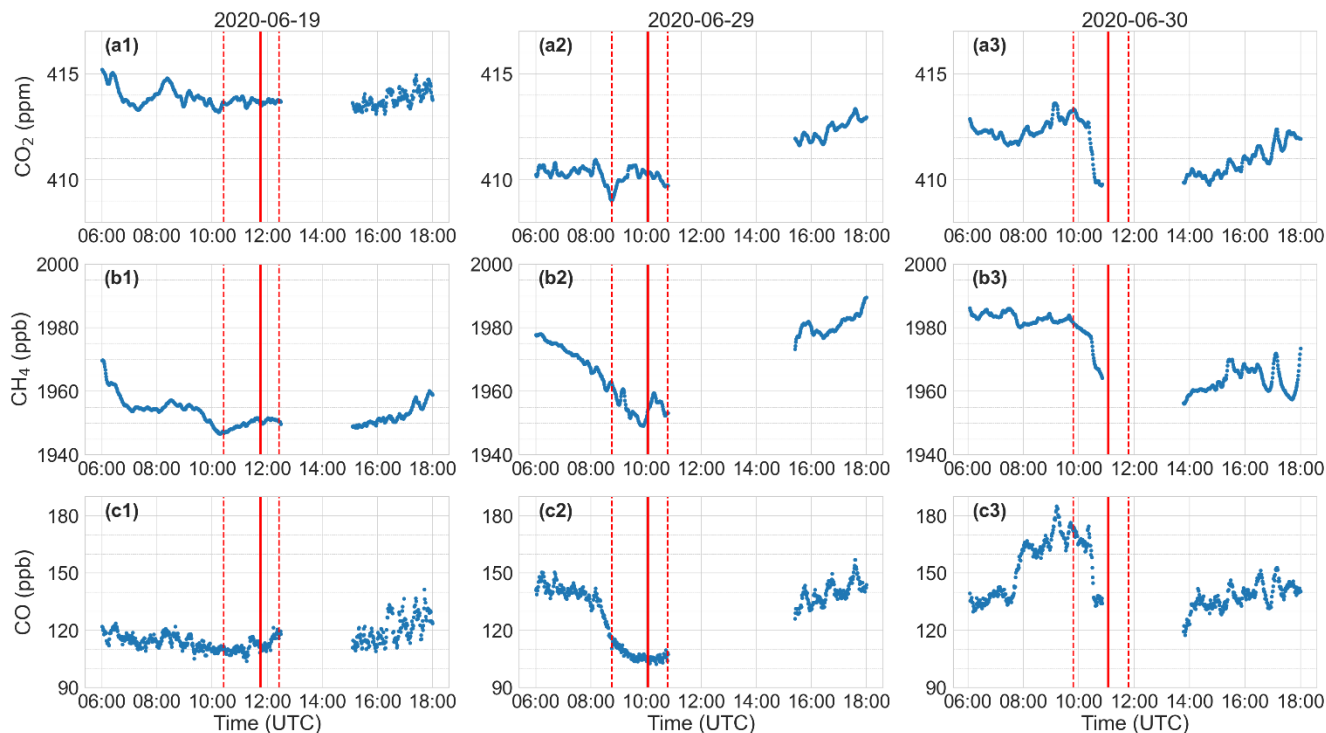


Figure S9: Time series of CO₂ ((a1)-(a3)), CH₄ ((b1)-(b3)) and CO ((c1)-(c3)) in dry-air mole-fraction, measured by the ground-based Picarro G2401 during the three days of the AirCore flights. Red solid line indicates AirCore landing time and dashed lines the ± 1 h time window around AirCore central time. The gap in the measurements' time-series is due to the AirCore analysis.

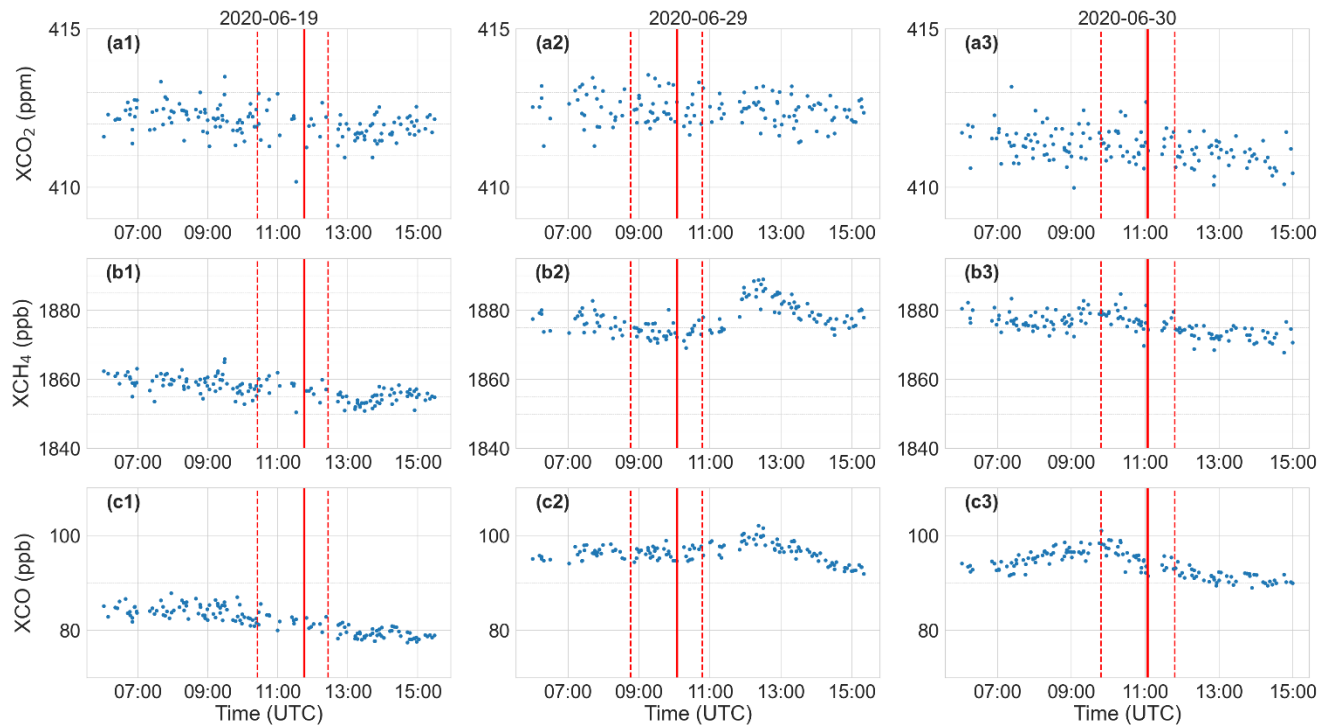


Figure S10: Time series of XCO_2 ((a1)-(a3)), XCH_4 ((b1)-(b3)) and XCO ((c1)-(c3)) measured by TCCON Nicosia during the three days of the AirCore flights. Red solid line indicates AirCore landing time and dashed lines the ± 1 h time window around AirCore central time.

3) Meteorological analysis: 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.

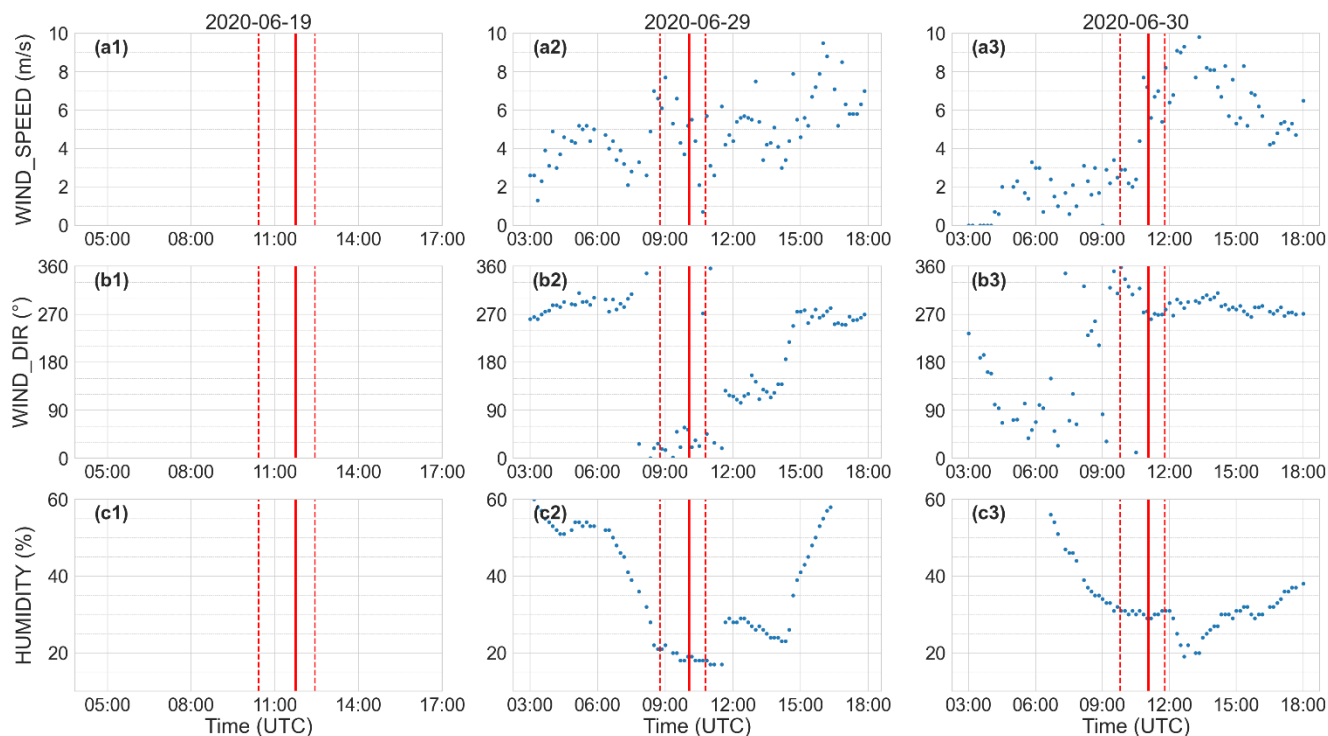


Figure S11: Time series of wind speed (WIND_SPEED, (a1)-(a3)), wind direction (WIND_DIR, (b1)-(b3)) and humidity (HUMIDITY, (c1)-(c3)) measured by the Athalassa meteo station in the forested park southeast of the Nicosia FTS (35.15°N 33.4°E, 162m asl) during the three days of the AirCore flights. There 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.

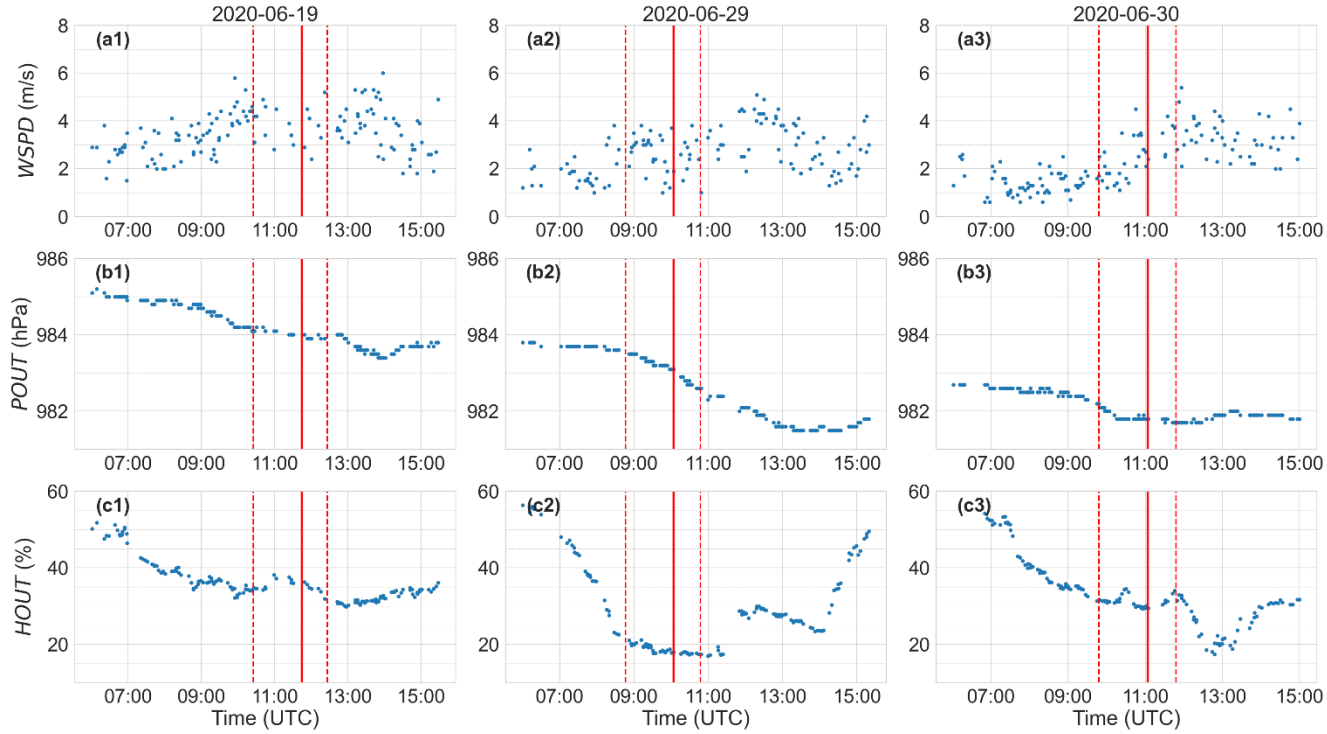


Figure S12: Time series of wind speed (WSPD, (a1)-(a3)), ambient pressure (POUT, (b1)-(b3)) and humidity (HOUT, (c1)-(c3)) measured by TCCON Nicosia meteo station during the three days of the AirCore flights. Red solid line indicates AirCore landing time and dashed lines the ± 1 h time window around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

4) Spatial sampling mismatch: An additional complication arises from the geometric sampling differences between instruments. Near the AirCore landing time ($\sim 10:05$ 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 ($\sim 12^\circ$) 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 CO₂ 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 CO₂ 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:

$$X_{\text{wet}} = X_{\text{dry}} / (1 + X_{\text{H}_2\text{O}})$$

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 CO₂ dry-air mixing ratios around 410 ppm.

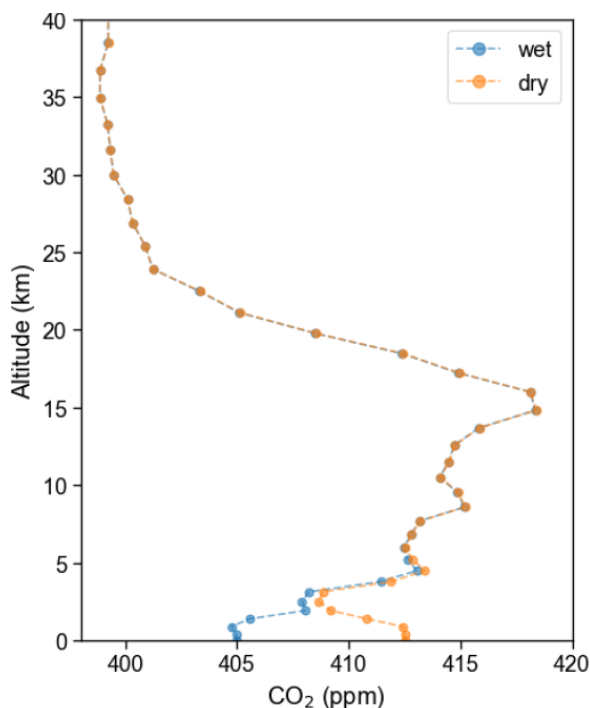


Figure AC1: AirCore CO₂ profile for the flight of 2020-06-30, re-gridded to the GGG2020 grid. Blue marker denotes the 'wet' profile (used in the custom GGG2020 retrievals) and orange marker denotes the 'dry' profile.

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 (CO₂, 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 CO₂ 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 CO₂. 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 $\pm$ 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 O₂ 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 O₂ 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 O₂ 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 O₂ column (VC_{O₂}) 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).”