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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 #2

Referee comments in red

Our responses in blue

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

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).