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

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Abstract. Long-term greenhouse gas (GHG) measurements are essential for understanding the carbon cycle, detecting trends in atmospheric composition, and assessing the efficiency of climate change mitigation strategies. However, observational gaps over large geographic areas such as the Eastern Mediterranean and Middle East (EMME), a well-known regional GHG hotspot, are likely to increase uncertainties in estimations of their sources and sinks. Here, we describe a new Total Carbon Column Observing Network (TCCON) observatory for solar absorption spectroscopy measurements that has been operating in Nicosia, Cyprus, since September 2019. The site helps bridge a regional observational gap in the EMME, a strategic location at the crossroads of air masses from Europe, Asia, and Africa. Using near-infrared (NIR, InGaAs detector) solar absorption spectra, TCCON-Nicosia measures total column average dry-air mole fractions (X_{gas}) of key trace gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), hydrogen fluoride (HF), water vapor (H_2O), and semi-heavy water (HDO). These continuous observations, spanning more than four years, are presented along with a description of the quality control procedures, compliant with the TCCON standards, to ensure total column atmospheric data with minimal errors.

In 2023, observations were extended into the mid-infrared (MIR) spectrum with the addition of a liquid-nitrogen-cooled InSb (LN_2-InSb) detector enabling the retrieval of additional trace gases such as formaldehyde (HCHO), carbonyl sulfide (OCS), nitrogen monoxide (NO), nitrogen dioxide (NO_2), and ethane (C_2H_6), herewith further contributing to the global Network for the Detection of Atmospheric Composition Change (NDACC).

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To tie the TCCON Nicosia with the WMO reference scale, an AirCore (AC) campaign conducted in June 2020 over Cyprus provided vertical in situ profiles, which were converted into total column quantities ($AC.X_{gas}$) and compared to TCCON observations (X_{gas}). The TCCON/in situ comparison showed agreement well within their respective error budget.

1 Introduction

Efforts to reduce greenhouse gas (GHG) emissions are crucial for mitigating climate change. In this context, observational networks play a key role in monitoring the spatial and temporal variations of these gases in the atmosphere (Ciais et al., 2014), providing valuable data for inferring sources and sinks and therefore, enhancing global GHG reporting (Deng et al., 2022).

The Total Carbon Column Observing Network (TCCON, Wunch et al., 2011), is a spatially sparse network of high-resolution Fourier transform spectrometers (FTS), measuring in the near-infrared (NIR) region. It is designed to provide long-term (multi-year), accurate and precise retrievals of several atmospheric trace gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), semi-heavy water (HDO), hydrofluoric acid (HF) and carbon monoxide (CO) (Wunch et al., 2011). TCCON data products are column-averaged dry-air mole fractions (DMFs) of these gases, denoted as X_{gas}. TCCON columnar observations are widely used to estimate GHG fluxes (Fraser et al., 2013; Keppel-Aleks et al., 2012), assess urban GHG emissions (Babenhauserheide et al., 2020; Hedelius et al., 2017), and serve as reference values for satellite validation and model evaluation (Byrne et al., 2023; Sha et al., 2021).

Although crucial for atmospheric monitoring, the TCCON network, with currently 29 operational sites, has large spatial gaps, particularly across large regions such as Africa, Central and West Asia, Siberia, the Mediterranean and Middle East region, and South America (https://tccondata.org/, last access: 1 March 2025). These gaps limit the comprehensive validation of satellite measurements and the evaluation of model simulations which are essential for inferring global GHG fluxes with reduced uncertainty (Bastos et al., 2020; Schimel et al., 2015). To address this, a new TCCON site was established in September 2019 in Cyprus, aimed at filling the observational gap in the Eastern Mediterranean and Middle East (EMME) region (Fig.1a).

Cyprus (Fig. 1b) is the third largest and most eastern Mediterranean island, with low local GHG emissions, raking 24th in EU27 with a total emissions share of 0.3 % in 2022 (https://www.eea.europa.eu/en/analysis/publications/annual-european-union-greenhouse-gas-inventory, last access: 1 March 2025). As such, it stands as a strategic receptor site at the outflow of 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); regions which currently exhibit diverse GHG emissions trends (https://globalcarbonatlas.org/, last access: 1 March 2025). Located in the EMME region, Cyprus is experiencing significant regional climate change (Ntoumos et al., 2020; Zittis et al., 2022). This has led to conditions, such as increased electricity

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demand for cooling, that contribute to higher GHG emissions (Gurriaran et al., 2023). Currently, the EMME region is poorly monitored for GHG concentration levels even though it holds nearly 60 % of the world's proven crude oil reserves (https://asb.opec.org/index.html, last access: 1 March 2025). This region is the third largest CO_2 emitter in the world and fourth for CH_4, with continuous fast-increasing GHG emissions, pointing out this region as a globally relevant GHG hotspot largely driven by the oil and gas sector (Bourtsoukidis et al., 2024; Germain-Piaulenne et al., 2024; Janssens-Maenhout et al., 2019; Paris et al., 2021).

Long-term GHG observation sites in the EMME region are scarce, primarily relying on ground-based in situ measurements, and have historically collected flask samples. These include the Weizmann Institute of Science in Israel (WIS) operational since 1995 (Lan, X. et al., 2024a, b, c; Petron, G. et al., 2024) and Finokalia (FKL), in Crete, Greece since 1993 (Gialesakis et al., 2023). The latter in situ GHG dataset reveals that while CO_2 levels reflect the general north hemisphere (NH) growth rate (~2.5 $ppm \cdot y^{-1}$ since 2014), CH_4 levels are ~13 ppb higher than the NH average. The new data acquired at the TCCON site of Nicosia will provide a new insight into the balance of CH_4 regional sources and sinks being at the forefront to detect future changes in regional GHG emissions.

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, section 2 provides a description of the site characteristics and the experimental methods used. Section 3 presents the time series of selected retrieved gases, including a short discussion on their temporal variability along with a comparison with results from AirCores. Finally, section 4 summarizes key findings and outlines directions for future work.

2 Methods

2.1 Site and instrumentation characteristics

2.1.1 Location

Cyprus is the third largest island in the Mediterranean Sea (Fig. 1b); it spans approximately 240 km from east to west, and 100 km from north to south, with a population of approximately 1.36M inhabitants (https://worldpopulationreview.com/countries/cyprus-population, last access: 1 March 2025). It has a subtropical climate – Mediterranean and semi-arid type – with two main seasons; mild winters resembling spring (from December to March) and warm-to-hot summers lasting about seven months (from April until October). Rainfall occurs primarily from November to April, with sunshine averaging from 160 to 400 hours per month (Michaelides et al., 2009; Pashiardis et al., 2017, 2023). These conditions are highly favorable for weather-dependent TCCON measurements that shall benefit from clear sky conditions. As such, the Nicosia site ensures excellent data coverage, among the highest within the TCCON Network, with approximately half the days of the year being sunny (i.e. < 20 % cloud cover) and less than 5 days per year being overcast (i.e. > 80 % cloud

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cover) (https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/nicosia_cyprus_146268, last access: 1 March 2025).

The ground-based FTS station is owned by the University of Bremen (Germany) and was previously located at the GHG TCCON measurement site in Białystok, Poland (Messerschmidt et al., 2012). It was relocated in 2019 to The Cyprus Institute (CyI) premises in a residential area southeast of Nicosia (see Fig. 1c), 185 m above sea level (ASL) (Fig. 1d). The site is relatively close to Nicosia (~4 km from the city center), the largest city of the island (~400k inhabitants) with an elevation of ~150 m ASL (Fig. 1c). The city is located in the plain of Mesaoria bordered on its northern and southwestern sides by two mountain ranges, the Kyrenia Range (1024 m ASL), and the Troodos Mountains (1952 m ASL), respectively. This topography creates a NW-SE corridor that channels low-altitude winds (see Fig. 1b). This location also ensures that the line of sight of the solar-viewing instrument is unobstructed by local terrain, and can thus measure up to a solar zenith angle (SZA) of 85°.

The TCCON Nicosia measurements are an integral part of the Cyprus Atmospheric Observatory (https://cao.cyi.ac.cy/, last access: 1 March 2025). The CAO operates a network of stations across Cyprus, covering diverse atmospheric environments, including urban, regional background, free troposphere, and marine areas. This network provides extensive long-term datasets on atmospheric composition in the EMME (Baalbaki et al., 2021; Bimenyimana et al., 2023, 2025; Christodoulou et al., 2023; Dada et al., 2020; Deot et al., 2024; Kleanthous et al., 2014; Papetta et al., 2024; Pikridas et al., 2018; Vrekoussis et al., 2022; Yukhymchuk et al., 2022). The observatory integrates remote sensing (TCCON) and in situ techniques for comprehensive GHG monitoring, including ground-level GHG measurements on Cyprus's west coast at the remote village of Ineia, following the Integrated Carbon Observation System standards (ICOS; Heiskanen et al., 2022). It also supports aerosol and reactive gas monitoring under the European Aerosols, Clouds, and Trace Gases Research Infrastructure (ACTRIS, Laj et al., 2024).
These ground-based atmospheric monitoring facilities are completed by the Unmanned Systems Research Laboratory (https://usrl.cyi.ac.cy/, last access: 1 March 2025), a unique drone facility with a private airfield and airspace near the CAO regional background station. This enables in situ atmospheric profiling of key atmospheric species, including GHG, up to 6 km altitude (Kezoudi et al., 2020, 2021).

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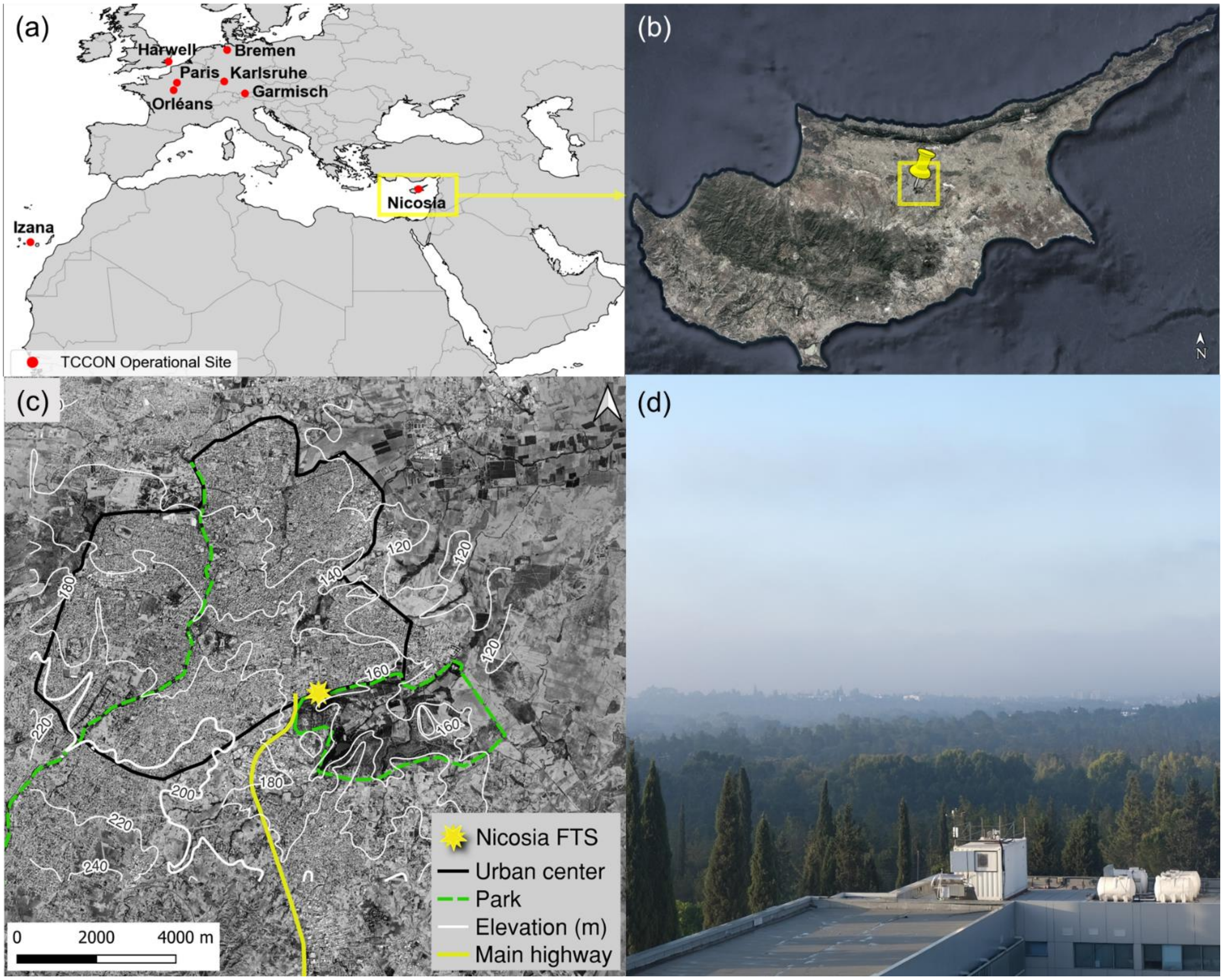

Figure 1: (a) A zoom-in of the TCCON network map with European active site locations indicated with red solid circles. The yellow rectangle frame shows Cyprus. (b) Cyprus, and the city of Nicosia depicted by a yellow square; yellow pin denotes the Nicosia FTS. Map from Google Earth Pro, © 2025 Google LLC. (c) An elevation (solid white contours) map of the area around the Nicosia city center (delimited with a black line). Forested parks are represented by a dashed green line, the main highway in a solid yellow line and the FTS container is represented by a yellow sun. (d) The FTS container with a south view at the Nicosia site. The container is placed ~15 m above ground level, and the Athalassa National Forest Park is visible in the background.

2.1.2 FTS instrument

The automated FTS system in Nicosia is based on a Bruker IFS 125HR spectrometer. A detailed overview of the system's setup and data acquisition is shown in Fig. 2 of Messerschmidt et al. (2012) with additional hardware details in the Appendix

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of the same reference. Measurements began in September 2019, with the measurements configuration summarized in Table 1. The detectors setup is depicted and described in Fig. S1 in the supplementary material.

[InGaAs detector (NIR)]: The detector chamber employs an indium gallium arsenide **(**InGaAs) detector for near infrared (NIR) measurements in the 4000–11000 cm^{-1} spectral region. The gas retrieval windows (TCCON) for this range are detailed in Laughner et al. (2024). Two types of measurements are conducted at Nicosia:

- High-resolution (NIR-HR) measurements performed at 64 cm Maximum Optical Path Difference (MOPD), and
- Low-resolution (NIR-LR) measurements at 1.8 cm MOPD, similar to the COCCON measurements (Frey et al., 2019).

The LR mode operates at a shorter scan time (~16.4 sec, at 10 kHz, for double-sided interferograms), compared to HR scans (~106 sec, at 10 kHz, for single-sided interferograms). Due to the shorter scan time, the LR data are particularly useful under partly cloudy conditions. The LR data, however, are stored separately from standard TCCON retrievals and are not included in the official TCCON products. These data can be retrieved using either the TCCON retrieval software (GGG, see Sect. 2.1.3), or PROFFAST, the official COCCON retrieval code (Alberti et al., 2022), providing more frequent measurements.

[InSb detector]: In December 2022, a liquid nitrogen–cooled indium antimonide detector (LN_2-InSb) was added to the Nicosia FTS, extending its sensitivity to the mid infrared (MIR; 1900 – 4200 cm^{-1}). The aim was to include Nicosia in the Network for the Detection of Atmospheric Composition Change (NDACC-IRWG, (De Mazière et al., 2018). High-resolution (0.005 cm^{-1}) solar absorption spectra recorded by NDACC FTIR spectrometers can provide precise documentation of multi-decadal trends of many tropospheric and stratospheric species, as well as insights into complex climate feedback processes (García et al., 2021; Vigouroux et al., 2015; Yamanouchi et al., 2023).

A 50/50 beam splitter (CaF_2, model BSW521 from THORLABS) is used which allows the MIR and NIR detectors to measure simultaneously (see Fig. S1 in supplement). This configuration uses five NDACC-IRWG band-pass filters (a-e) and one low-pass filter at 4200 cm^{-1} (f) in front of the InSb detector, enabling the recording of additional spectra at the following wavenumber ranges: a) 1900 – 2230 cm^{-1}, b) 1970 – 2650 cm^{-1}, c) 2400 – 3200 cm^{-1}, d) 2900 – 3500 cm^{-1}, e) 3950 – 4200 cm^{-1} and f) 1900 – 4200 cm^{-1}.

The MIR FTS technique enables the retrieval of several reactive gases in addition to the GHG, with the added potential of acquiring vertical information for a few of these species by exploiting the different retrieval sensitivity across the atmospheric layers (Buschmann et al., 2016; Chiarella et al., 2023; Zhou et al., 2019a, b).

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Table 1: Technical characteristics and observational capacity for TCCON Nicosia. Scanner speed at 0.32 $cm \cdot s^{-1}$ (laser modulation frequency 10 kHz) from 01-09-2019 to 24-02-2024 – except for 01-12-2022 to 09-01-2023 where it was at 0.64 $cm \cdot s^{-1}$ (20 kHz) – and 0.16 $cm \cdot s^{-1}$ (5 kHz) from 07-02-2023 to 10-03-2023 and from 25-02-2024 after. Scanner speed was changed back to the TCCON standard at 0.32 $cm.s^{-1}$ (10 kHz) on 29-11-2024.

Measurement name	MOPD (cm)	Resolution (cm^{-1})	Measuring detectors	Spectra wavenumber range (cm^{-1})	Measured since (year)	Frequency
NIR (TCCON)	64	0.016	InGaAs	4000 – 11000 (NIR)	2019	Daily
TCCON + MIR-1			InGaAs + InSb	NIR, 1900 – 4200	2023	Daily**
TCCON + MIR-2				NIR, 1900 – 2230		
TCCON + MIR-3				NIR, 1970 – 2230, 2400 – 2650		
TCCON + MIR-4				NIR, 2400 - 3200		
NIR-LR	1.8	0.555	InGaAs	NIR	2019	Daily
NIR-LR + low-pass			InGaAs + InSb	NIR, 1900 – 4200	2023	Daily**
NDACC/IRWG (*)	180	0.005	InSb	1900 – 2230	2023	2-3 times/week**
				1970 – 2230, 2400 – 2650		
				2400 – 3200		
				2900 – 3500		
				3950 – 4200		

*With alternating sequence of filters. **When the InSb detector is LN_2-cooled.

2.1.3 FTS dataset

The official (public) data products X_{CO_2}, X_{CH_4}, X_{CO}, X_{N_2O}, X_{HF}, X_{H_2O} and X_{HDO} are retrieved with the latest TCCON Network retrieval software, the GGG2020 (Laughner et al., 2024). In short, the TCCON retrieval process used GEOS prior meteorology (GEOS FP-IT; Lucchesi, 2015) before April 2024 and GEOS IT thereafter (https://gmao.gsfc.nasa.gov/GMAO_products/GEOS-IT/, last accessed 1 March 2025), and vertical profiles of atmospheric trace gases (priors) (Laughner et al., 2023) to simulate NIR solar absorption spectra. The latter are compared with the measured spectra. From the best fit between the simulated and measured spectra, the vertical column abundances of trace gases (VC_{gas},

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in molec.cm^{-2}) are retrieved, including that of oxygen (VC_{O_2}), a well-mixed gas with negligible relative variability. The DMF of a gas species (X_{gas}) is then defined as the ratio of the gas column (VC_{gas}) to the total column of air (VC_{air}):

$$X_{gas} = \frac{VC}{VC_{air}} = 0.2095 \times \frac{VC_{gas}}{VC_{O_2}} \qquad (1)$$

The use of this ratio cancels out spectroscopic errors common to both gas and O_2 columns (see Appendix A(d) of Wunch et al. 2011).

2.1.4 Data quality and performance checks

To ensure consistency across all the TCCON sites, standard quality diagnostic checks are implemented to identify potential instrumental-related issues affecting data precision. Here, we use X_{luft} (the total column average of dry air), derived from surface pressure and the retrieved O_2 column (VC_{O_2}) near the 7885 cm^{-1} line, as a quality diagnostic indicator (Laughner et al., 2024).

Ideally, X_{luft} should equal unity with a TCCON network nominal value of 0.999. Persistent deviations from the nominal X_{luft} can indicate instrumental issues. Laughner et al. (2024) found that deviations from the network median correlate with biases in other X_{gas} products, emphasizing the importance of maintaining a stable and close to nominal X_{luft}. Therefore, the standard TCCON quality control includes a check that X_{luft} (after temporal smoothing) remains between 0.995 and 1.003, to keep these related biases within acceptable limits.

In 2022, the TCCON Nicosia encountered unusual X_{gas} and X_{luft} spread due to a hardware issue (loose scanner electronic cable connection) that, since 22 November 2024, has been resolved. For the affected period, we applied an empirical filter on the O_2 line (7885 cm^{-1}) frequency shift (O_2_fs) values to exclude measurements falling outside the nominal X_{luft} range before public data release. The recorded O_2_fs fluctuations occurred with refocusing or replacing the internal laser and were more pronounced from April 2021 to November 2022 due to poor laser focus; though this co-existed with the hardware issue since we identified affected spectra from 2019. 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.

2.2 Evaluation of TCCON Nicosia against in situ vertical profiles (AirCores)

To tie the TCCON data to the World Meteorological Organization (WMO) reference scales (https://gml.noaa.gov/ccl/scales.html, last access: 1 March 2025) and to evaluate potential biases on the FTS data, TCCON applies a network-common multiplicative correction factor (CF) to each gas product, except for X_{CO}, as part of a post-retrieval data processing before public release. These CFs are derived from WMO-referenced airborne in situ profiling above the FTS stations (Deutscher et al., 2010; Geibel et al., 2012; Messerschmidt et al., 2011; Wunch et al., 2010).

In Cyprus, we have performed three (3) AirCore (AC) (Baier et al., 2023; Karion et al., 2010) flights on 19 June (flight 1), 29 June (flight 2), and 30 June (flight 3) 2020. These flights provided vertical profiles of CO_2, CH_4, and CO up to approximately

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22 km altitude (see Sect. S2.1 in supplement), providing valuable in situ information that extends well into the stratosphere. Data from the second and third flight are included in the most recent TCCON (GGG2020) "in situ correction" ensemble (Laughner et al., 2024). Although the GGG2020-derived CFs already incorporate information from these profiles, their limited contribution to the overall in situ dataset (2 out of 67 and 40 profiles for CO_2 and CH_4, respectively) suggests that evaluating the Nicosia measurements against these AirCores remains meaningful. This evaluation exercise is only visual, and does not aim to derive new CF values for Nicosia.

To compare FTS X_{gas} with vertically resolved mole-fractions, such as in situ profiles from balloons or aircraft (or even model profiles), we compute a column integrated value directly from the in situ profile (here, the AirCore) using the Rodgers and Connor (2003) equation as adapted by Wunch et al. (2010) (Eq. 2):

$$C_s = \gamma C_a + \boldsymbol{\alpha}^T (x - \gamma x_a) \quad (2).$$

Here, C_s is the column-averaged DMF, from hereafter the "AC.X_{gas}", C_a is the column-averaged DMF from integrating the prior, γ is the retrieval scaling factor, x and x_a are the in situ-measured (true) and the prior (model) profile respectively, and $\boldsymbol{\alpha}$ is an element-wise product of the TCCON column averaging kernel **k** and a pressure-weighting function (see also Eq. 9-11, Sect. 8.3.1 of Laughner et al., 2024).
The TCCON wiki (https://tccon-wiki.caltech.edu/Main/AuxiliaryDataGGG2020, last access 1 March 2025) describes two methods for calculating comparison quantities, using "pressure weights" and using the "integration operator"; both methods have been applied and yield comparable results. Here, the results are derived from using the "pressure weights" method.

The quantity AC.X_{gas} is compared with the median value of the official TCCON X_{gas} (i.e., public.X_{gas}) of the measurements within ±1 hour window around the central time of each AirCore flight.
Differences amongst these two quantities will be due to the difference in the measurement principle ("remote sensing" versus "in situ") and their respective errors. The public.X_{gas} data, entail errors from a) imperfect spectroscopy and b) imperfect (wrong shape) priors. In order to disentangle error (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).

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

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3. Results

A brief overview of the TCCON-Nicosia database acquired up to the end of 2023 is provided in the following, starting with instrument performance, followed by a 4-year X_{gas} time series, and concluding with a comparison of Nicosia X_{gas} with data derived from the in situ profiles (AirCores).

3.1 Instrument performance

Figure 2 shows the X_{luft} time series after applying the O_2_fs filtering, with metrics that can be used to assess the performance of the FTS, and provide an overview of the amount of valid TCCON data. After applying the O_2_fs filtering, the X_{luft} 500-spectra running median (500-RMd) remains within the TCCON nominal values (0.995-1.003). Nicosia has approximately 1240 days of measurements from 1 September 2019 to 31 December 2023, with missing data due to weather conditions and instrument failures (e.g. broken laser, solar-tracker failure, maintenance and testing). The filtering approach reduced the amount of collected spectra by approximately 40% for the period impacted by the mentioned hardware issue. During the longest days of the year, and under clear-sky conditions, the Nicosia FTS has recorded up to 290 TCCON measurements.

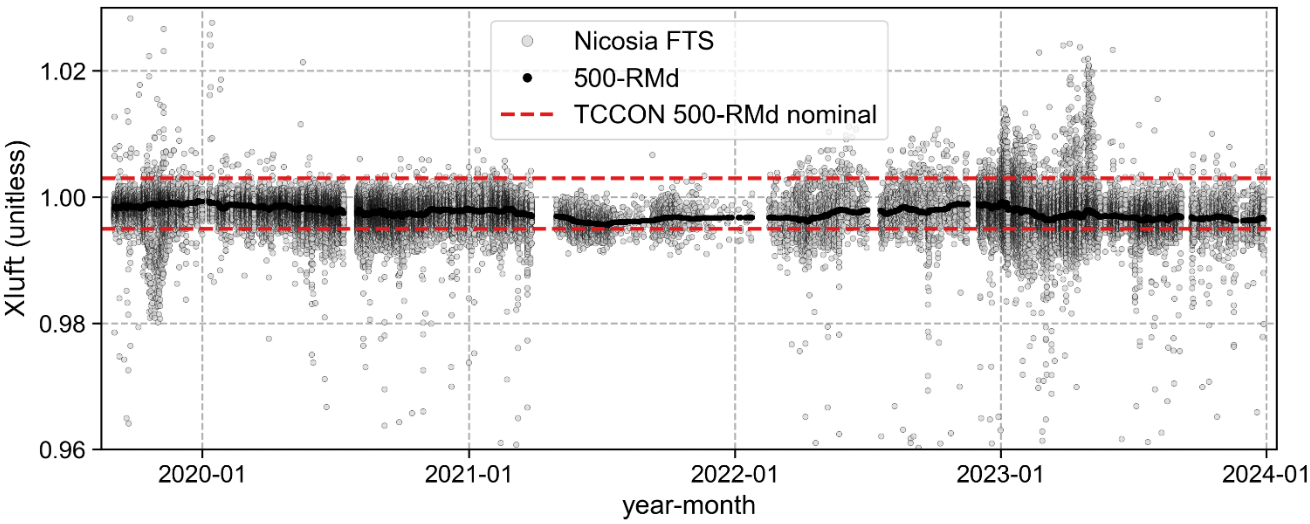

Figure 2: X_{luft} values after filtering out problematic data. Dashed red lines indicate the nominal values of 0.995 – 1.003 for the 500-spectra running median (500-RMd) (black line).

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3.2 Total column gases (X_{gases}) over Cyprus

This section presents the first publicly available columnar time series for the TCCON Nicosia site (and by extension over the EMME region) in the TCCON data repository, covering X_{CO_2}, X_{CH_4} and X_{CO}. A brief discussion of the observed temporal behavior of the aforementioned X_{gases} can be found below. A more extensive analysis of the temporal variability of these gases will be presented in follow-up studies.

3.2.1 X_{CO_2}

Figure 3a shows that the X_{CO_2} time series over Cyprus exhibits a pronounced seasonal cycle consistent with other Northern Hemisphere sites (Keppel-Aleks et al., 2011). The annual minimum occurs between August and September, while the maximum is observed between April and May, reflecting the dynamics of CO_2 sources and sinks that are primarily controlled by the seasonal cycles of photosynthesis and respiration (Randerson et al., 1997; Schimel, 1995). The overall increase over the years, driven by accumulation due to fossil fuel emissions (Keeling and Graven, 2021), occurs at a rate of 2.33±0.80 $ppm \cdot y^{-1}$ between 2020 and 2023, which is slightly below the reported 2.5 $ppm \cdot year^{-1}$ value obtained from ground-based observations performed in Crete (Greece) since 2014 (Gialesakis et al., 2023).

3.2.2 X_{CH_4}

Figure 3b shows the time series of X_{CH_4} at the TCCON-Nicosia site. Besides an overall continuous increase over the 4-year measurement period, a seasonal cycle can also be seen with minima observed between February and June. The maximum levels of X_{CH_4} occur during the second half of the year, from July to December, with notable peaks in December and during the July-to-August period.

The July-August peaks over Cyprus could be explained by a combination of the following factors:

- The forest fire season over the Mediterranean region, as evidenced by a simultaneous increase in X_{CO} (as a tracer of incomplete combustion) during the same period.
- Changes in the stratospheric amount of CH_4, driven by fluctuations in tropopause altitude (Washenfelder et al., 2003).

In addition, X_{CH_4} exhibits a step-wise increase in the second half of each year – most notably in 2021 (see also Sect. 3.2.3) – which could be attributed to intense summer forest fire events. Moreover, transported regional pollution, originating from the Middle East sectors, which typically occurs during the fall and winter months (Kleanthous et al., 2014; Pikridas et al., 2018) may also contribute to this enhancement.

A minor peak of X_{CH_4} is observed around mid-spring 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). A concurrent peak in X_{CO} (Fig. 3c) during this period corroborates this link.

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3.2.3 X_{CO}

Total column carbon monoxide does not exhibit any significant year-to-year trend. In contrast to X_{CH_4}, X_{CO} shows an opposite seasonality pattern (Fig. 3c), with a minimum observed during the second half of the year, from June to December, and a maximum during the first half, from January to May. As noted earlier, peaks in July-August coincide with the forest fires season in the Mediterranean (Eke et al., 2024; Kaskaoutis et al., 2024; Masoom et al., 2023), during which X_{CO} hourly values at our site exceeded 120 ppb. Due to the prolonged fires period in 2021, the mean X_{CO} (95.2 ± 5.9 ppb) was higher than the adjacent years; 91.3 ± 5.2 ppb in 2020 and 87.9 ± 6.8 ppb in 2022.

Aside from wildfire events, CO levels in the troposphere of the EMME region are significantly influenced by fossil fuel combustion. Lelieveld et al. (2002) estimated that 60-80 % of the CO amount in the Mediterranean had originated from fossil fuel combustion in Western and Eastern Europe during the Mediterranean Intensive Oxidant Study (MINOS), performed in the summer of 2001.

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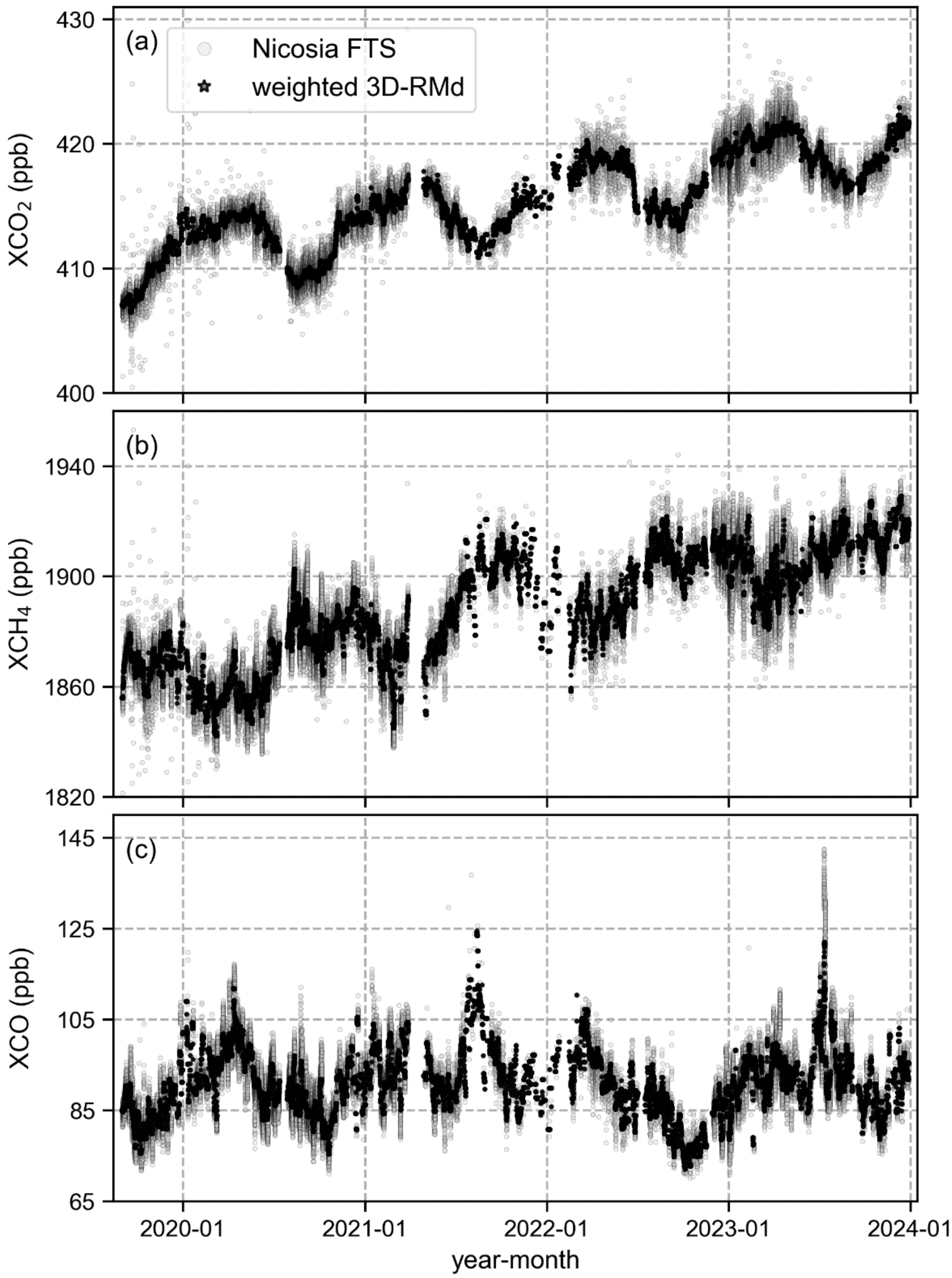

Figure 3: The total columns of carbon dioxide (X_{CO_2}, (a)), methane (X_{CH_4}, (b)) and carbon monoxide (X_{CO}, (c)) from TCCON Nicosia. Grey markers represent FTS measurements, and black stars represent a 3-day running median, calculated from hourly means weighted by the squared inverse measurement error.

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3.3 TCCON Nicosia and AirCore comparison

This section describes a quantitative comparison between TCCON Nicosia public.X_{gas} data and AirCore-derived total column quantities (AC.X_{gas}), aiming to evaluate the GGG2020 retrievals at Nicosia relative to the specific WMO-tied measurements (the Cyprus AirCores, June 2020).

3.3.1 AirCore profiles

Figure 4 shows the in situ profiles obtained by the three AirCores sampled between 19 and 30 June 2020. These profiles reveal that the mole fraction of CO_2 has a relatively uniform vertical distribution with variations at the order of ~ 4 % between the surface and 20 km altitude. In contrast, CH_4 shows a mole fraction reduction of approximately 40% above 20 km altitude and CO of around 80 % over the same altitude range, compared to the ground.
During the flights of the June 29 and 30, a significant enhancement (+30 ppb) in the CO profiles (see Fig. 4c, grey and light-grey) was observed between the 12 – 17 km altitudes, along with smaller but still noticeable increases in CH_4 and CO_2 within the same altitude range. A HYSPLIT back-trajectory analysis (see Fig. S4 in supplement) was used to trace back the origin of air masses at these altitudes. These air masses were shown to originate from Southeast Asia and were transported to the Eastern Mediterranean via the Asian Summer Monsoon Anticyclone (ASMA) (Basha et al., 2020; Pan et al., 2016; Park et al., 2007; Santee et al., 2017). This annual meteorological phenomenon occurs annually, typically between 50° – 120° E, and is strongest near the Northern Hemisphere sub-tropical latitudes (Yihui and Chan, 2005). Under specific climatological conditions such as the approach of the Azores high on the western end of the Mediterranean causing a westward shift of the Monsoon low (Yadav, 2021), this phenomenon can affect the air quality of the Eastern Mediterranean region typically from the end of June to mid-August (Lawrence and Lelieveld, 2010; Lelieveld et al., 2001, 2002, 2018; Scheeren et al., 2003; Tyrlis et al., 2013).

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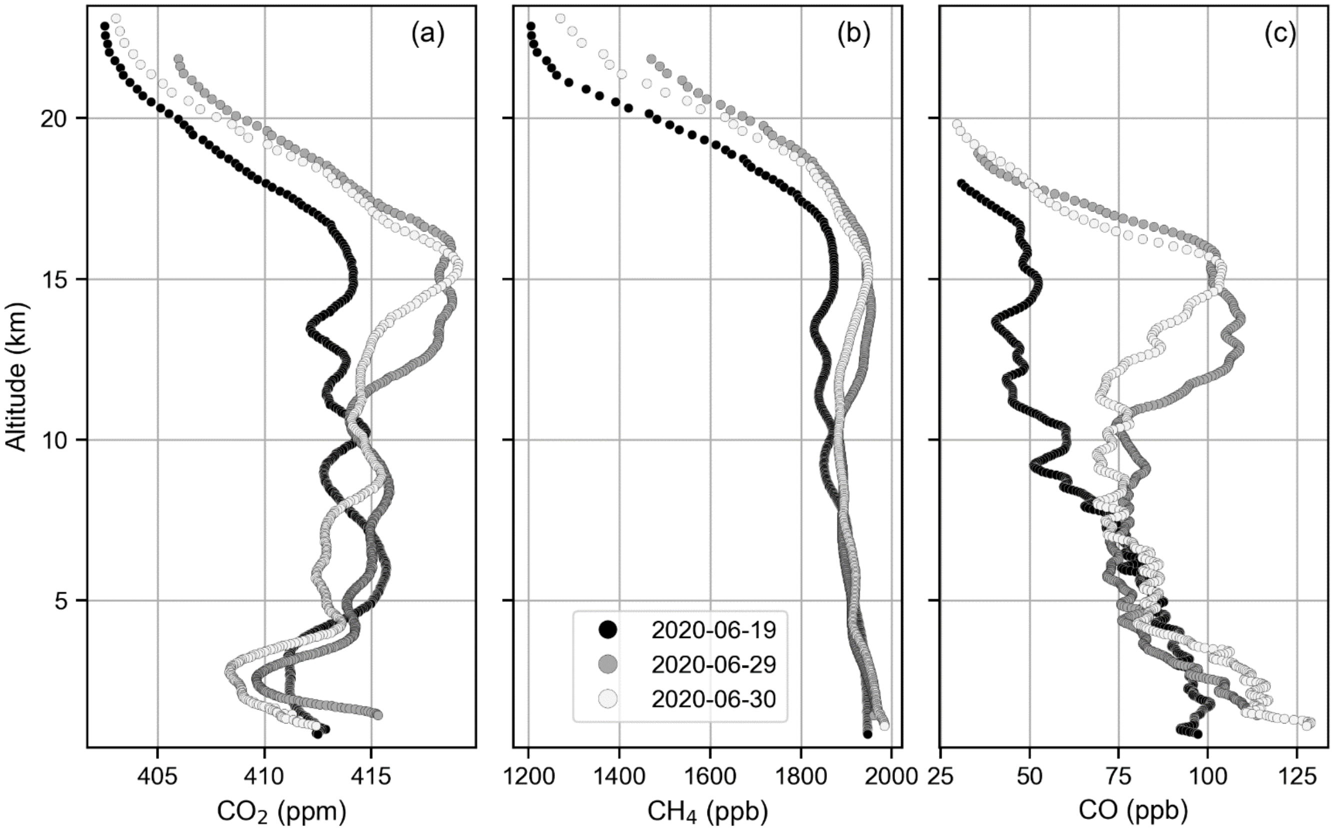

Figure 4: The Nicosia, Cyprus AirCores; flights on June 19, 29, and 30 June 2020 in black, grey, and light grey, respectively. (a) Carbon dioxide, (b) methane and (c) carbon monoxide vertical profile. We apply an upper cutoff between 18 and 20 km altitude on the carbon monoxide CO profiles to remove non-real enhancements due to stratospheric ozone reactions inside the AirCore tubing.

3.3.2 TCCON Nicosia Vs AirCore-derived data

TCCON Nicosia official data, public.X_{gas}, are compared with total column-integrated in situ measurements, AC.X_{gas}, to evaluate the consistency of TCCON Nicosia observations with its own (site specific) AirCores, in a visual-only comparison. Figure 5 shows the Nicosia AC.X_{gas} in blue diamonds along with GGG2020 retrieved data, both standard (public.X_{gas}, grey circles) and custom retrievals (custom.X_{gas}, red stars). The custom.X_{gas} data (see Sect. 2.2) help assess the influence of trace gas prior profiles, used in simulating the NIR spectra, on TCCON retrievals. Consequently, any remaining differences may be date- (flight-), or site-specific originating from uncertainties in spectroscopy or instrument-related errors (see Sect. 9 and Fig. 23 of Laughner et al., 2024).

Table 2 summarizes these results for each gas species and flight. It shows the flight medians for both the public and custom retrieved X_{gas} data, the integrated in situ X_{gas} (AC.X_{gas}). These results show that the TCCON and the in situ AC.X_{gas} agree within their calculated uncertainties range.

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Since we quantify each error source separately (see Sect. S2.6 in supplementary material), we find that stratospheric error due to the un-sampled stratosphere, is typically the largest contributor to $AC.X_{CH_4}$ uncertainties (see Table S4, supplement). This is expected for methane, given its sharp decrease in the stratosphere. For $AC.X_{CH_4}$, the AC measurement error is the second most significant source and depends on the instrumentation – specifically, the AC sampler's resolution and the gas analyzer's precision.

For the $AC.X_{CO}$, the AC measurement error is the dominant source of uncertainty. This is primarily due to the gas analyzer's low precision for CO measurements, the low resolution of this specific AC sampler compared to a high-resolution AC (Membrive et al., 2017) and the stronger diffusion of carbon monoxide inside the AC tubing (Massman, 1998).

It is important to highlight that the GGG2020 X_{CO} product, as discussed by Laughner et al. (2024), is not tied to a reference scale. Instead, its difference is assessed against in situ-derived data.

Laughner et al. (2024) in their Fig. 16 (e) show that, even though the X_{CO} network mean difference across all the TCCON/in situ comparisons is small (~0.85 %), there is substantial variability in the TCCON/in situ X_{CO} agreement, with individual measurements often exhibiting large uncertainties, with differences with respect to the in situ data up to ~30 %.

Differences between X_{gas} and $AC.X_{gas}$ can arise from 1) gas prior assumptions in the retrievals and 2) mismatches in air mass sampling. Concerning 1), 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). Concerning 2), the AC lands at a different location from the launch, and it measures starting at the highest altitude towards the ground, sampling a gas profile that is neither vertical nor coincident with the line of sight of the spectrometer (see Fig. S3 in supplement). Therefore, discrepancies between the AirCore trajectory and the FTS line of sight may contribute to observed differences. For instance, if the AirCore follows a west-to-east trajectory along a gas concentration gradient while the FTS observes along a north-to-south line of sight, spatial variations in sampled air masses can lead to differences.

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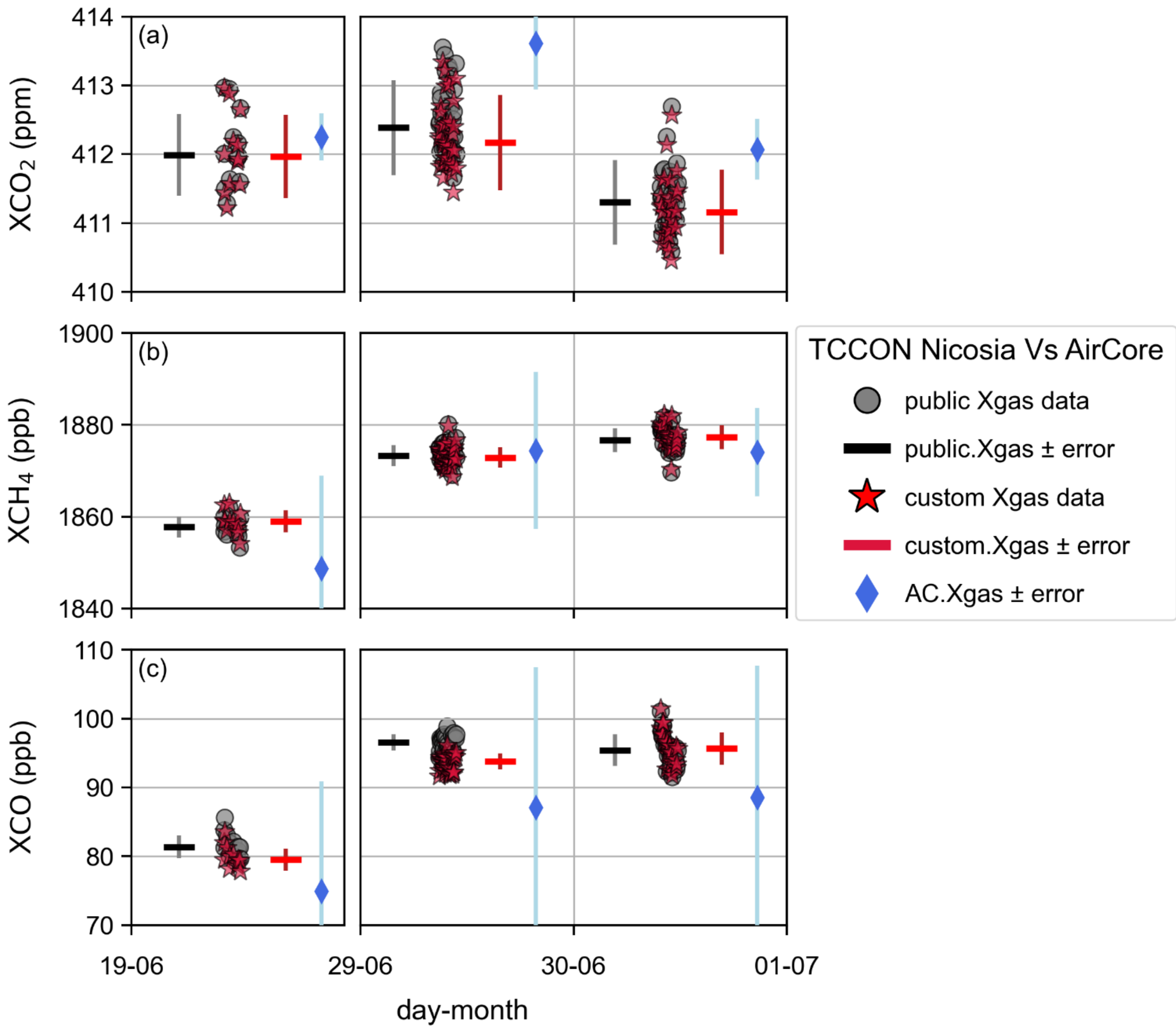

Figure 5: Comparison of the Nicosia FTS data (public.X_{gas} ± error, black dash) with the integrated in situ profiles (AC.X_{gas} ± error, blue diamonds). AirCore flights took place on the June, 19, 29 and 30 June 2020. For each gas, individual public data from the
375 **standard GGG2020 retrievals are shown as grey circles, while the black dash represents the median (public.X_{gas} ± error). Using the AirCore assembled profiles as trace gas priors in GGG2020, the custom retrieved data (custom X_{gas}) are depicted by red stars, with the corresponding median as a red dash (custom.X_{gas} ± error). The public and custom X_{gas} error includes the random error caused by measurement variability and differences caused by a not ideal X_{luft}. The AC.X_{gas} error (blue error bars) includes AC measurement uncertainty, stratospheric and ground error. For more details on the error analysis, refer to Sect. B6 in the supplementary material.**
380 **Please note that some error bars in AC.X_{gas} extend outside the y-axis limits.**

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Table 2: Retrieved and calculated X_{gas} quantities. The public.Xgas (official Nicosia data) flight median ± error value is compared to the AirCore derived comparison quantity (AC.X_{gas} ± error). The custom retrieved Nicosia data (custom.X_{gas} ± error) (see Sect. 2.2 and B5 in supplement) are also shown here for comparison. The error values for all X_{gas} products are discussed and calculated in Sect. B6 in the supplementary material. Values are rounded to the nearest decimal.

Flight Number	1	2	3
		Quantity ± error	
AC. X_{CO_2} (ppm)	412.25 ± 0.35	413.61 ± 0.80	412.07 ± 0.45
custom.X_{CO_2} (ppm)	411.96 ± 0.61	412.17 ± 0.69	411.16 ± 0.62
public.X_{CO_2} (ppm)	411.99 ± 0.60	412.39 ± 0.69	411.30 ± 0.61
AC.X_{CH_4} (ppb)	1848.7 ± 20.8	1874.4 ± 28.8	1874.1 ± 10.4
custom.X_{CH_4} (ppb)	1859.0 ± 2.4	1872.9 ± 2.8	1877.3 ± 2.6
public.X_{CH_4}	1857.8 ± 2.2	1873.3 ± 2.3	1876.7 ± 2.6
AC.X_{CO} (ppb)	74.9 ± 17.1	87.1 ± 20.7	88.5 ± 19.5
custom.X_{CO} (ppb)	79.5 ± 1.6	93.8 ± 1.1	95.7 ± 2.4
public.X_{CO}	81.4 ± 1.6	96.6 ± 1.2	95.4 ± 2.3

4. Conclusions and Outlook

The establishment of the ground-based FTS station in Nicosia, Cyprus – operational since September 2019 – represents a significant advancement in GHG monitoring for the Eastern Mediterranean and Middle East (EMME) region. This station is unique due to its geographical location at the crossroads of Europe, Asia, and Africa, providing critical observations in a climate-vulnerable region with complex atmospheric dynamics. The TCCON Nicosia setup includes two complementary measurement systems:

1. NIR solar absorption measurements (TCCON), providing total column observations of GHG, i.e. X_{CO_2}, X_{CH_4}, X_{CO}, X_{N_2O}, X_{HF}, X_{H_2O} and X_{HDO} since 2019. Future efforts will focus on extending X_{gas} time series and continuously updating the public dataset. This will support long-term monitoring of seasonal and interannual trends and their relationship to climate variability in the EMME region.

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2. MIR observations (NDACC-compatible), measuring additional trace gases, including HCHO, OCS, NO_2 and C_2H_6, since 2023. Future research will investigate these species, which can provide valuable insights into atmospheric chemistry, pollutant transport, and interactions with biogenic and anthropogenic sources.

The combination of these techniques enhances the station's long-term atmospheric monitoring capabilities and enables multi-species analyses. Additionally, Nicosia's consistently clear skies facilitate high data coverage (>70%), allowing future studies to gain detailed insights into seasonal cycles, diel variations, and special atmospheric events such as pollution episodes and long-range transport. This will improve our understanding of short-term variability and source attribution.

Independent evaluation through WMO-traceable AirCore observations confirms agreement of in situ with TCCON measurements within their uncertainties. However, with only three AirCore profiles available at Nicosia, further measurements – sampling with a high-resolution AirCore device to reduce uncertainties – at different time periods are needed to robustly assess the representativeness of these measurements.

The establishment of a ground-level GHG site on Cyprus's west coast (Ineia), compliant with ICOS recommendations, will provide valuable complementary measurements. The synergy between TCCON Nicosia total column data and Ineia in situ surface observations will offer a more comprehensive assessment of the atmospheric boundary layer and regional carbon budgets.

Future work will integrate TCCON Nicosia observations with atmospheric models to refine estimates of regional sources and sinks. This integration will provide insights to guide both regional and global climate policies aimed at reducing GHG concentrations.

In summary, the TCCON Nicosia station is a critical observational platform for monitoring GHGs in the EMME region. Its expanding measurement capabilities, ongoing improvements in data quality, and potential collaboration with in situ networks like ICOS will continue to provide valuable datasets supporting climate science and policy-driven mitigation efforts on both regional and global scales.

Code availability

The python code and ancillary data used for the AirCore analysis results presented in this paper are available online at: https://doi.org/10.5281/zenodo.15085720, last access 26 March 2025.

Data availability

The Nicosia TCCON data can be accessed at https://data.caltech.edu/records/9kdk2-c5881, last access 5 December 2024.

The Cyprus AirCore data can be accessed at: https://zenodo.org/records/13132338, last access 5 December 2024.

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The in situ ground data at the Nicosia location can be accessed at: https://doi.org/10.5281/zenodo.7788482, last access 5 December 2024.

Supplement

The supplement related to this article is available online at: https://doi.org/10.5281/zenodo.15085720, last access 26 March 2025.

Author contributions

CR: Conceptualization, data curation, formal analysis, software, visualization, writing – original draft preparation, review & editing. CP: Data curation, formal analysis. PQ: Nicosia AirCore data sampling & analysis, software. TL: Nicosia AirCore profiles calculation, software. JL: Formal analysis, data curation, software, writing – review & editing. MD: Software, writing – review & editing. MP: Data curation, writing – review & editing. MR: Resources and AirCore profiles calculation. EB: Supervision, writing – review & editing. MB: Supervision, writing – review & editing. JN: Supervision, resources and funding acquisition, writing – review & editing. TW: Conceptualization, supervision, resources and funding acquisition, writing – review & editing. JP: Supervision, writing – review & editing. JS: Supervision, resources and funding acquisition, writing – review & editing. MV: Supervision, conceptualization, writing – review & editing.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Atmospheric Measurement Techniques.

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