Response to Anonymous Referee #2 for EGUSPHERE-2025-4157 (ACROPOLIS: Munich Urban CO_2 Sensor Network)

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Anonymous Referee #2

General Comment

This paper reports the initial results of establishing a CO_2 observation network using the low-cost NDIR-based Vaisala GMP343 sensors at 17 sites across the city of Munich.

The study focuses on two main aspects: (1) how the accuracy of the sensors used in the network was improved, and (2) how the system was applied to capture high-resolution spatial and temporal CO_2 variability within the city.

For the first aspect—sensor accuracy—the study compares the sensitivity of the Vaisala GMP343 sensors to three environmental variables (humidity, pressure, and temperature) against a Picarro reference instrument. Among these variables, temperature had the greatest impact on the NDIR sensors. In the second-generation network, an additional temperature stabilization enclosure was introduced to address this issue. As a result, the RMSE decreased from a maximum of 2.6 ppm in the first-generation system to less than 1 ppm in the second generation, achieving the target accuracy. In summary, the study aimed to enhance NDIR sensor accuracy primarily by controlling the temperature factor.

For the second aspect, the monitoring sites were categorized into three zones—urban, suburban, and rural—to examine spatial variability in CO_2 concentrations. At one specific site (MAIR), a Hampel filter was applied to remove the influence of nearby ventilation outlets. Although the filter effectively removed some peaks, it was not entirely successful in eliminating all local pollution signals. The study found that the classified zones showed clear diurnal and seasonal differences: during summer, rural and suburban sites exhibited greater diurnal variability than urban sites due to photosynthetic activity. This pattern persisted in winter, though the diurnal amplitude was considerably smaller.

Overall, the study is well conducted, but several areas require revision or clarification before publication. Please refer to the comments below:

Response:

We sincerely thank the reviewer for the positive and encouraging feedback, as well as for the time and effort dedicated to reviewing our manuscript. We address the individual comments point by point below.

(1) **(Page 6, Line 123)** *The paper states that the intake line was extended up to 50 m, with a flow rate of about 0.5 LPM. Is this flow rate sufficient for such a long sampling line? Please provide a proper justification or reference.*

Response:

We thank the reviewer for this valuable comment and fully agree that the choice of tubing diameter and flow rate is critical to ensure representative air sampling, particularly when longer intake lines are used. To verify that a 50 m sampling line is suitable for our system, all stations were operated with 50 m of tubing during the 2024 site-by-site evaluation campaign to simulate the most demanding deployment conditions. The site-by-site results confirmed that this configuration is appropriate, as no significant deviations or artifacts were observed compared to the reference measurements.

To further substantiate this, we quantified the flow characteristics for the 50 m of $1/4''$ (Outside Diameter (OD): 6.35 mm, Internal Diameter (ID): 4.3 mm) SERTOflex tubing at a flow rate of 0.5 L/min. The corresponding Reynolds number is approximately 160, confirming laminar flow. Under these conditions, the residence time is about 1.45 min, which is acceptable given that we are interested in hourly averaged data rather than high-frequency measurements. The calculated pressure drop of 0.09 hPa is negligible compared to the approximately 15 hPa drop caused by the 2 µm inlet filter.

In practice, the installed tubing lengths are, depending on local conditions on the rooftops, between 10 and 20 m, resulting in residence times of only 17–34 s. We updated the manuscript to include the additional information presented here.

Addition to the manuscript: (Page 6, After Line 125)

The choice of tubing diameter and flow rate is important to ensure representative air sampling, particularly when longer intake lines are used. In our configuration, ambient air is drawn through 50 m of $1/4''$ (Outside Diameter (OD): 6.35 mm, Internal Diameter (ID): 4.3 mm) SERTOflex tubing at a flow rate of 0.5 L/min. To verify the suitability of this setup, we calculated the Reynolds number, residence time, and pressure drop (See Appendix Appendix F). The corresponding Reynolds number of approximately 160 confirms laminar flow. Under these conditions, the residence time is about 1.45 min, which is acceptable given that the network provides hourly averaged data rather than high-frequency observations. The calculated pressure drop of 0.09 hPa is negligible compared to the approximately 15 hPa pressure drop introduced by the 2 µm inlet filter.

In practice, the installed tubing lengths vary depending on local rooftop conditions and typically range between 10–20 m, resulting in residence times of only 17–34 s.

(2) **(Page 9, Line 215)** *Calibration was performed only at two points—400* ppm *and 520* ppm*—for slope/intercept correction. Can linearity across a wide and long-term concentration range (350–600* ppm*) be ensured with only two calibration points? Since actual* CO_2 *levels in different urban zones may fall outside this range, would additional multi-point calibration or slope tracking be necessary?*

Response:

We appreciate the reviewer's thoughtful comment regarding the number of calibration points. We agree that including additional calibration points could further enhance the robustness of the calibration across a broader concentration range. However, implementing multi-point calibration increases both the operational complexity and the overall cost of the system, which would reduce the scalability and long-term maintainability of the network. One of the main design goals of ACROPOLIS was to achieve a balance between accuracy, simplicity, and deployability across multiple urban sites. As our study focuses on the well-mixed urban background signal rather than strong local point sources, the chosen calibration points at 400 ppm and 520 ppm were selected to effectively cover the expected range of ambient CO_2 concentrations in the studied environment. To substantiate this choice, we analyzed the distribution of measured CO_2 concentrations across all urban ACROPOLIS sites in Munich for the period from January 2024 to October 2025 (see Figure 1). The resulting histogram confirms that the vast majority of CO_2 observations fall within the 400–520 ppm range, with only a small fraction of data points outside this interval. Moreover, as illustrated by the scatter plot in Appendix A of the manuscript, the applied two-point calibration yields a stable and accurate correction even for measurements slightly beyond the selected range. These results demonstrate that the adopted two-point calibration strategy provides sufficient linearity and accuracy for the intended application while maintaining the scalability required for a scaleable, city-wide sensor network.

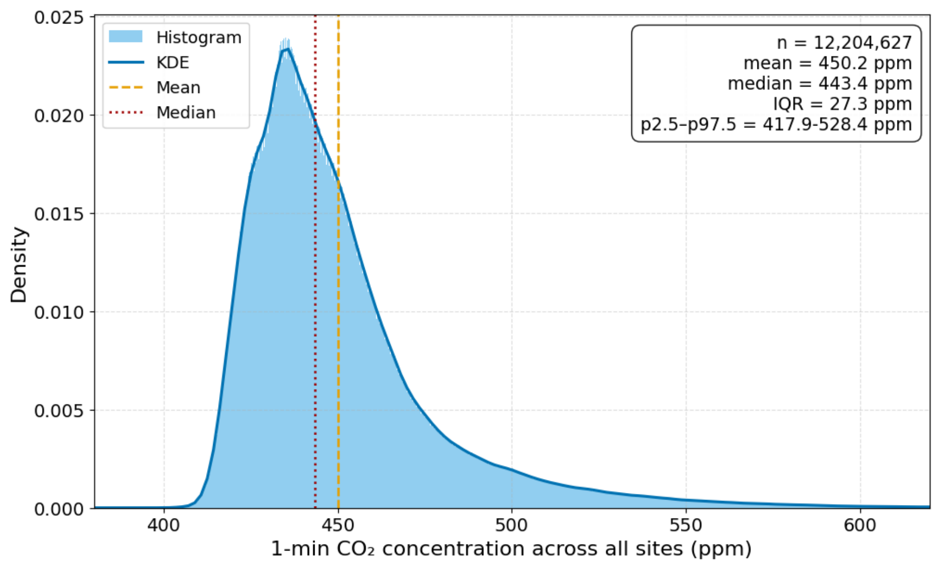

Figure 1. Distribution of over 12 Million CO_2 concentrations measurement across all urban ACROPOLIS sites in Munich for data from January 2024 until October 2025. The vertical dashed lines indicate the mean and median. Interquantile range (IQR), kernel density estimate (KDE), and 2.5% and 97.5% percentiles are shown.

Addition to the manuscript: (Page 37) Added Figure 1 as Appendix G.

(3) **(Page 9, Line 203)** *The use of the Wagner equation to calculate water vapor saturation pressure for deriving dry mole fractions seems appropriate. However, since the water vapor data came from an external instrument, that instrument itself likely has some uncertainty. Would this not affect the accuracy of the dry* CO_2 *mole fraction? Please discuss this potential limitation.*

Response:

We thank the the reviewer and agree that uncertainties in humidity measurements can influence the correction from wet to dry CO_2 mole fractions. To assess this, we evaluated the expected impact of the SHT45 humidity sensor's specified accuracy (± 1 % RH) under representative environmental conditions. Using the Wagner equation, the resulting effect on the dry CO_2 mole fraction is approximately 0.04 ppm under cool and dry conditions (5 °C, 10 % RH), and approximately 0.20 ppm under warm and humid conditions (30 °C, 80 % RH). In all cases, this influence is minor compared to our target performance. Moreover, each system undergoes a bias correction with dry reference gas during calibration, which further minimizes any residual offset.

Based on the 2024 site-by-site evaluation campaign, we confirmed that the overall uncertainty of the dry CO_2 measurements meets our target performance when compared to the Picarro reference, indicating that the humidity correction does not introduce significant additional uncertainty.

We therefore conclude that the contribution of humidity measurement uncertainty to the calculated dry CO_2 values is acceptable for our application.

Addition to the manuscript: (Page 10, After Line 223)
Uncertainties in the humidity measurements can influence the correction from wet to dry CO_2 mole fractions. To quantify this effect, we evaluated the impact of the SHT45 humidity sensor's specified accuracy (± 1 % RH) under representative environmental conditions. Using the Wagner equation, the resulting uncertainty in the dry CO_2 mole fraction is approximately 0.04 ppm under cool and dry conditions (5 °C, 10 % RH) and about 0.20 ppm under warm and humid conditions (30 °C, 80 % RH). Across all relevant conditions, this effect remains negligible compared to the overall target precision of the system.

(4) **(Page 10, Line 230)** *Using a long analysis window may risk classifying short-term traffic plume signals as "outliers." However, such short-term and abrupt fluctuations are key features of urban* CO_2 *dynamics. Applying too long a window could remove meaningful short-term events as noise. Please provide additional justification or discussion on this issue.*

Response:

We thank the reviewer for raising this important point and agree that different use cases of urban CO_2 measurements require different approaches regarding temporal resolution and the treatment of local contamination. The chosen window size for the Hampel filter is intentional, as our objective is to extract well-mixed urban background signals while filtering out short-term plumes.

Our sensors are installed at rooftop level, typically surrounded by buildings with combustion-based point sources. While we try our best to select locations to minimize direct contamination, avoiding local influences entirely in dense urban environments is inherently difficult.

We would like to clarify that our implementation of the Hampel filter does not remove any data. Instead, it provides a flag indicating potential contamination events. We do this by comparing the output of the hampel filter with the original signal and flagging differences. This allows users with different scientific objectives, for instance studies focusing on short term plumes to apply their own filtering strategies using the published dataset. We have clarified this point in the revised manuscript.

Addition to the manuscript: (Page 11, After Line 246)
In our implementation, no data points are removed. Potential contamination events are identified by comparing the Hampel filter output with the original signal and flagging deviations directly on the original time series. This approach allows users with different scientific objectives, for example those focusing on short-term plumes, to apply their own filtering or thresholding strategies using the published dataset.

(5) **(Page 21, Figure 10, Lines 416-427)** *To control excessive local pollution, the study applied the Hampel filter used in previous studies. While this method effectively removes extremely high peaks, it does not fully eliminate local contamination. The paper notes that the filter captured the ventilation effects but did not perform particularly well. Moreover, since this station is used as a background site, placing the sensor so close to a ventilation outlet seems questionable. Please provide further explanation or justification for this site configuration.*

Response:

We thank the reviewer for this constructive comment. At the beginning of the network deployment, limited guidance was available on what constitutes an optimal site configuration for urban CO_2 monitoring. Identifying rooftop hosts willing to provide space and electrical access free of charge proved challenging, and site selection therefore required some degree of compromise. We considered it valuable to include a diverse range of sites to better understand how varying local conditions influence measurement quality and concluded to deploy it rather than keeping it in our lab.

For the specific site mentioned, the air inlet was installed upstream of the prevailing wind direction relative to the nearby ventilation outlet. Under typical south-westerly winds and higher wind speeds, the inlet is expected to remain outside the plume, ensuring that background conditions are captured reliably. The potential contamination source operates only during the heating season and thus has limited temporal impact on the overall dataset.

We are happy to report that in September 2025 the administration of Maisach supported us to relocate the station to the building on the other side of the street, improving the site configuration.