Response to Reviewer #1

We thank the reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions. Our point-by-point responses are provided below, with reviewer comments shown in blue and our replies in black.

The paper of Mijling et al. presents ground-based measurements of NO2 in a poorly sampled region in Africa with a low cost but reliable technique. The study is well conducted, the dataset and findings are relevant for the research as well as for the local community, and the paper is pleasant to read, so I highly recommend publication after the authors have considered the remarks below.

My only major comment on the content is the strong statement in the abstract 'TROPOMI underestimates the tropospheric NO2 column densities by a factor of roughly 2.5...'. The parametrization method to reach this 2.5 number is clearly described and seems reasonable, but there s no validation of it. It seems to me that this could have been done with MaxDOAS at European sites. Did the authors consider doing that? I would simply add something like 'Using a parametrization method based on our ground-based measurements and TROPOMI' at the beginning of the sentence to improve this point. The formulation on the conclusion reads good on the other hand.

We refined our statement on the underestimation of TROPOMI by revising the end of the abstract to "*Using a parametrization method based on ground-based measurements and TROPOMI retrievals, we find that TROPOMI underestimates tropospheric* NO_2 *column densities by roughly a factor of 2.5 in March 2025. (…).*"

We agree that the proposed parametrization method would gain confidence if properly validated. This could be done using MAX-DOAS measurements in Europe, as suggested. We feel that conducting such a thorough validation study is beyond the scope of the current paper, as it would divert focus from our main findings, but we plan to consider this in future investigations.

Beside that, I have mainly minor comments.

L.61: 'To the best of our knowledge, there are currently no operational AQMs openly reporting NO2 measurements in Sub-Saharan Africa (OpenAQ, 2025).' What about South-Africa? (https://saaqis.environment.gov.za/)

Thank you for this suggestion. We are aware that South Africa operates an active monitoring network. From Gwaze & Mashele (2018), we understand that there are 130 fully automated air quality monitoring stations in South Africa, some of which measure NO_2. However, the data does not appear to be openly accessible. We attempted to access the website on several occasions between 6 and 16 March 2026 without success. Although the website includes a login option, it is unclear how new users can register. In addition, the data shown in the Dynamic Tables do not indicate from which monitoring station the data is derived. We therefore decided to leave our statement unchanged.

In the intro, the authors could add that Palmes tube were used in citizen science projects in Europe, for instance in Antwerp with the curieuzeneuzen project, the data were used in scientific publication e.g.

D. Voordeckers, F.J.R. Meysman, P. Billen, T. Tytgat, M. Van Acker, The impact of street canyon morphology and traffic volume on NO2 values in the street canyons of Antwerp, Building and Environment, Volume 197, 2021, 107825, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2021.107825.

We agree that including this reference highlights how Palmes tubes meaningfully fill gaps in otherwise undersampled areas. We have therefore added: "*PDTs have also been used in citizen science monitoring campaigns across Europe, for example to measure local air quality and evaluate the street canyon effect in the city of Antwerp, Belgium (Voordeckers et al., 2021)*"

Also, the validation of TROPOMI in Kinshasa from Yombo et al. could be added as there are not many of such works in this region

Yombo Phaka, R., Merlaud, A., Pinardi, G., Friedrich, M. M., Van Roozendael, M., Müller, J.-F., Stavrakou, T., De Smedt, I., Hendrick, F., Dimitropoulou, E., Bopili Mbotia Lepiba, R., Phuku Phuati, E., Djibi, B. L., Jacobs, L., Fayt, C., Mbungu Tsumbu, J.-P., and Mahieu, E.: Ground-based Multi-AXis Differential Optical Absorption Spectroscopy (MAX-DOAS) observations of NO2 and H2CO at Kinshasa and comparisons with TROPOMI observations, Atmos. Meas. Tech., 16, 5029–5050, https://doi.org/10.5194/amt-16-5029-2023, 2023.

We agree with the reviewer that the work of Yombo et al. is relevant for our study, as it shows that the NO_2 retrieval product must be handled with care for African cities. We have added in the Introduction: "*In one of the few validation studies for sub-Saharan tropical cities, Yombo Phaka et al. (2023) show that incorrect a priori profile information in the TROPOMI retrievals leads to significant underestimation of the NO_2 column densities over Kinshasa.*"

On all the maps of Kumasi, I would add the North direction.

North direction added to Figure 7 and Figure 9.

L.91 and 94 Nitrate -> Nitrite?

Corrected

L.189 'true column density' -> I would remove 'true', reads tautological.

Done

Why is it 'campaign' in L.217 and 'campaigns' in L. 218, and again without s in L 237?

Plural changed to singular.

L.239 'Mounting height is approximately 2 meters (see Fig. 4).'-> already stated above, L.228

Removed

L 296 'contribute less significantly to ambient NO2 levels in these areas' -> less than what?

Clarified to "suggesting that industrial emissions are not a major contributor to ambient NO_2 levels in these areas".

Fig 9: unclear what the map on the right adds. The roads could be added to the column map and the right map deleted.

We prefer to keep the right panel as is. In addition to providing orientation by showing the road network, it distinguishes built-up areas (associated with NO_x emissions) from unbuilt areas (associated with lower emissions). This information would become cluttered if the left panel were overlaid semi-transparently.

L.338 'Elevated NO2 levels in upwind regions are not readily apparent in surface measurements, although they might be detectable with a more extend ground-based monitoring network that includes more urban background stations' -> I dont follow, did you mean 'downwind'?

Corrected to "*The elevated NO_2 levels found in downwind regions are not readily apparent in the surface measurements, (…)*".

L. 381 'coarse a priori NO2 profiles from TM5-MP'-> what about the realism of the profile, even at low spatial resolution in Africa? Again it would be good to refer to Yombo et al here since they studied the profile effect.

We decided not to included this reference here in order to avoid interrupting the flow of text, but instead add it to the Discussion and Conclusion section. Here we included the sentence: "*This confirms earlier studies by Yombo Phaka et al. (2023), showing the large impact of the a priori profiles on NO2 retrievals over sub-Saharan tropical cities.*"

L 453 'we apply a factor of 0.69 is applied' -> I suggest the active voice

Passive voice removed.

Reference

Gwaze, P., & Mashele, S. H. (2018). South African Air Quality Information System (SAAQIS) mobile application tool: bringing real time state of air quality to South Africans. Clean Air Journal, 28(1). https://doi.org/10.17159/2410-972X/2018/v28n1a1

Response to Reviewer #2

We thank the reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions. Our point-by-point responses are provided below, with reviewer comments shown in blue and our replies in black.

The publication describes the setup of a low-cost measurement network of NO_2 passive samplers in the city of Kumasi, Ghana. Air pollution is a growing concern in African cities, but observations are extremely scarce, almost non-existing. Even if this study is limited to one constituent (NO_2), it makes an important contribution to improve our knowledge of air pollution levels in this under-sampled part of the world. The study is also a great example of knowledge transfer, capacity building, and engagement with local scientists.

Since low-cost air quality sensors continue to suffer from issues such as drifts and cross-sensitivity, passive sampling is a valid alternative. It doesn't rely on expensive instruments but nevertheless requires a reasonably well-equipped laboratory and trained staff. The study demonstrates that operating such a network is feasible with the limited resources available at a University in Africa.

The manuscript is overall very well written and the results are presented in a thorough and relevant manner. The analysis of duplo samples and the comparisons between remote and local lab indicate that the measurements are of reasonably good quality. The comparisons with TROPOMI satellite observations and the analysis of surface-to-column ratios are interesting and relevant.

I thus have only a few minor points.

Where will the local laboratory obtain the chemical reagents and solutions (HCl, TEA, NEDA, sulphanilamide, $NaNO_2$) in the future? Are these materials all available in Ghana? Please comment.

This is indeed a relevant point. We have added to Section 2.3: "*A 10 g bottle of N-(1-naphthyl) ethylenediamine dihydrochloride (NEDA) was imported to Ghana; which is sufficient for extended use. All other chemicals could be sourced locally.*"

While a simple design of tube holders is clearly a necessity, the current design doesn't seem ideal as it provides no protection against rain, radiation and wind. It is common practice to mount diffusion tubes with some sort of shelter. Although this makes the design slightly more complicated, it should probably be feasible and certainly recommended. This comment links to another comment below regarding potential measurement biases, which depend on the way the tubes are exposed.

We share the reviewer's concerns and adapted Section 3.1 on precision and biases by replacing the last paragraph with "*Consistent exposure across sites was ensured by mounting all diffusion tubes on free-standing poles using identical holders. Nevertheless, the simple design of the tube holders provides little protection against radiation and wind. In particular, wind-induced turbulence can shorten the effective diffusion path and increase the uptake rate. Heal et al. (2019) identify wind as the largest contributor to bias, potentially leading to overestimations of several tens of percent. In addition, local temperature differences—such as between shaded and sun-exposed locations—may introduce site-specific bias. A better-designed mounting system that shields the tubes from wind and radiation should help reduce this bias in future measurements.*"

I am also a bit worried about tube handling: The time differences between preparation and deployment and between deployment and analysis of the tubes was a few weeks in case of the remote-lab tubes. I was wondering where the tubes were stored during this time, e.g. whether they were put into a fridge, which is recommended e.g. in the practical guidelines for the UK " Diffusion Tubes for Ambient NO 2 Monitoring: Practical Guidance" (/https://uk-air.defra.gov.uk/reports/cat05/0802141004_NO2_WG_PracticalGuidance_Issue1a.pdf).
They should be stored in a fridge or at least in a cool, dark place both pre-exposure and post-exposure to avoid degradation of the solvent. I understand that some of this can be accounted for by measuring blanks, but it is nevertheless recommended.

We added to section 2.5: "*Following the recommendations of Targa and Loader (2008), the tubes were stored in a dark and, as much as possible, cool location both before and after deployment*".

The result of the lab blank (Table 3) which, after preparation traveled from the laboratory in The Netherlands to Ghana and back, indicates that our tube handling introduced negligible offset. However, the 27-day period between preparation and analysis could indeed lead to a slight degradation, as noted in Section 3.3.

Comparison against an accredited lab is valuable but insufficient to guarantee a high quality of the measurements, because both the remote-lab and local-lab batches can be affected by the same biases caused by the way the tubes are exposed. An overview of potential sources of biases was given in Heal et al. (2019; https://www.mdpi.com/2073-4433/10/7/357). Another study on sources of biases is Vardoulakis et al. (2009; https://www.sciencedirect.com/science/article/pii/S1352231009001757). One important source of bias is ambient wind flow at the entrance of the tubes. In other tube designs, e.g. as described in a report for a Swiss network (https://www.ostluft.ch/fileadmin/ostluft/pdf/projekte/2021/BE_ReferenzbezugNO2-Passivsammler_GeK_20210527.pdf), there is therefore an additional wind protection element. Furthermore, remaining systematic differences to reference instruments were corrected for by a linear calibration function.

We elaborated on the possibility of biases in Section 5 (Discussion and conclusion) by adding *"It should be noted that the minimal tube holder design does not shield the tubes from solar radiation and wind, which are the dominant sources for potential (positive) biases (Heal et al., 2019). Therefore, future measurements should ideally be done in protective housings. Other sources of offset may arise from TEA degradation under longer exposure periods in tropical conditions.*"

I fully acknowledge that there was no reference instrument available, but I recommend considering this option for the future. The main point I would like to make is that the comparison with the reference lab does not fully account for all uncertainties, which needs to be acknowledged in the manuscript.

Reference equipment is indeed hardly available in Ghana. However, we have reached out to Afri-SET (African Sensor Evaluation and Training Centre for West Africa) at the University of Ghana in Accra. We are currently looking for funding to set up a validation campaign for the locally prepared and analysed Palmes tubes against NO2 reference equipment. We have added in Section 5: "*To better understand and correct biases in the Kumasi network, we plan to conduct validation measurements against local reference instruments.*"

It is stated several times that a longer exposure period of 4 weeks would improve precision. However, it should also be considered that a longer exposure might enhance biases, e.g. due to degradation of the solution.

This is now mentioned in Section 5: "*Other sources of offset may arise from TEA degradation under longer exposure periods in tropical conditions.*". To avoid redundancy, we removed the statement about the 4-week exposure period from the end of Section 3.3.

Further small points:

- Line 43: NOx are not only precursors of ozone but also of PM.

  Now mentioned by rewriting to "*NOx (nitrogen oxides) is not only a precursor of particulate matter, but also plays a key role in atmospheric photochemical reactions that produce tropospheric ozone (O3)*"

- Equation 1: The factors p_ref/p x T/T_ref seem to convert to standard pressure and temperature. It should thus be stated explicitly that C is the average concentration during the measurement at standard pressure and temperature.

  This has been changed in the description of Equation (1): "*Here, C is the average concentration of NO_2 during the measurement (in µg m^{-3}) at reference temperature T_{ref} (293 K) and reference pressure P_{ref} (1013 hPa).*"

- Line 196: Averaging kernels presented in Figure 11 are much larger than one.

  "*A value close to 1 implies (…)*" changed to "*Values larger than 1 imply (…)*"

- Line 228: Mounting at 2 m altitude doesn't seem to be a good idea as the tubes can easily be reached by anyone passing the location. In other networks a typical altitude is 3-4 m above ground to prevent damage by vandalism.

  

  The reviewer is right. In fact, the installation height was wrongly estimated by the authors, as can be seen in this photo. When the tube holders were mounted in the field, a stool was brought to stand on, in order to reach to an approximate height of 3.5 m. We changed the text accordingly.

- Line 241: Why only at 10 of the sites? Please comment.

  During the campaign, the focus was on validating the performance of diffusion tubes made from materials available in local markets (briefly discussed in Section 2.5). These locally made tubes did not perform as expected; in hindsight, using and recycling the unprepared tubes that were brought in proved to be the most reliable solution for continuous measurements in the local network. Based on this insight, it would have been indeed preferable to conduct side-by-side comparisons at all 20 sites.

- Line 479: As argued above, comparisons of duplo samples do not capture the full uncertainty. I would rather talk of precision here.

  "*uncertainty*" changed to "*precision*"; followed by discussion of potential sources of bias.

- Line 500: The average difference of 2 ug m^{-3} may not be significant. What is the standard error of this average?

  Based on the data in Table 5, we calculate the standard error of the average differences to be 1.87 ug/m^3. We clarified the interpretation by adding in Section 3.3: "*The uncertainty in the differences, however, is too large to claim a real bias*". We also removed a reference to this result in Section 5, as the apparent bias is not statistical meaningful and therefore not suitable as a conclusion.