

# 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<sub>2</sub> 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<sub>2</sub>), 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<sub>2</sub>) 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<sub>2</sub> Monitoring: Practical Guidance" ([https://uk-air.defra.gov.uk/reports/cat05/0802141004\\_NO2\\_WG\\_PracticalGuidance\\_Issue1a.pdf](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](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 NO<sub>2</sub> 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: NO<sub>x</sub> are not only precursors of ozone but also of PM.

Now mentioned by rewriting to “NO<sub>x</sub> (nitrogen oxides) is not only a precursor of particulate matter, but also plays a key role in atmospheric photochemical reactions that produce tropospheric ozone (O<sub>3</sub>)”

- Equation 1: The factors  $p_{ref}/p \times T/T_{ref}$  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<sub>2</sub> during the measurement (in  $\mu\text{g m}^{-3}$ ) 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  $2 \text{ ug m}^{-3}$  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  $1.87 \text{ ug/m}^3$ . 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 statistically meaningful and therefore not suitable as a conclusion.