# Impact of 3D radiative transfer on airborne NO2 imaging remote sensing over cities with buildings

Marc Schwaerzel et al. 2021

### Response to the Reviewer's Comments

We thank Reviewer 2 for his/her positive comments, critical assessment and useful points to improve the quality of our paper. In the following we address his/her concerns point by point. Changes in the paper are shown in blue. We hope we clarified all concerns and that the revised manuscript has improved.

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### Reviewer 2

**Reviewer Point P 2.1** — This paper looks to address the 3-d radiative transfer effects of urban landscapes on NO2 retrievals. The authors use monte carlo simulations from MYSTIC for a simplified urban landscape in Zurich to examine the impacts of buildings AMF calculations (so called 3D-box AMF). This is a very interesting study with significant implications to airborne retrievals. The only part the authors don't seem to address is how they would account for such 3-d effects in actual airborne retrievals. Many of the assumptions they make in this study would likely not be applicable to real world retrievals. Maybe this will come in a later paper, but it would make the paper stronger to explain how this could be translated into actual retrievals.

**Reply**: We understand the reviewer's point on the lack of information concerning a real application. We have added a subsection discussing the application to real data. This matter, will be the core of a further study, where we will apply 3D-box AMFs to real APEX data.

> The codes developed for this study can also be applied to real observations, for example, to the campaigns conducted with APEX imaging spectrometer. A major challenge is to obtain the required input data. 3D building data are available for many cities, but albedos for ground, roof and walls are generally not available. In addition, realistic 3D $NO_2$ fields from a building-resolving dispersion model are required to compute the total AMFs, which requires high-resolution emission inventories and additional model development, because most building-resolving models are not optimized for providing realistic vertical distributions of trace gases or cannot not be applied to a full city at high resolution (Berchet et al., 2017).

To minimize 3D effects when using 1D-layer AMFs, it would be recommendable to obtain the airborne spectrometer measurement around local noon when the SZA is lowest and avoid large viewing zenith angles. However, around noon turbulent atmospheric mixing will be strong and the $NO_2$ distributions would be smoothed as well.

The computation of 3D-box AMFs with buildings is computationally quite expensive, but still manageable for current airborne campaigns. For example, the computation of the 3D-box AMF field for a single APEX pixel (e.g. on Fig. 6f) takes about 280 s on a single core of our Linux machine (Intel(R) Xeon(R) W-2175 CPU @ 2.50GHz). Processing a full campaign consisting of about 100'000 pixels takes about 23 days using all 14 cores on the system. However, simulating AMFs for an APEX campaign would not require simulation for a 1 km x 1 km domain. Nonetheless, computing 3D-box AMFs is significantly more expensive than computing 1D-layer AMFs and reducing computation time, for example, by finding suitable parametrizations using machine learning, would make it possible to calculate the 3D-box AMFs on smaller hardware, to larger campaigns or to run simulations with more details and at higher spatial resolution.

**Reviewer Point P 2.2** — The authors note that 50% of the NO2 sensitivity is from outside the ground pixel for a nadir viewing geometry. They also note that the urban canopy module in MYSTIC currently only supports Lambertian reflections. Could the authors elaborate on how the Lambertian assumption would effect their results? Would it be a safe assumption that accounting for specular reflection you would have less light scattering in from outside the ground pixel?

**Reply**: The sensitivity to neighboring pixels depends strongly on the reflectance properties of the neighboring pixels. Considering non-Lambertian reflection would increase the complexity of the analysis. If all neighboring pixels are specular reflecting, multiple scattering is required for photons to reach the instrument (except if the direct light path crosses the light-of-sight of the instrument), while only single scattering is required for Lambertian surfaces. As a result, sensitivity would decrease for specular reflection. For real application, surface reflectance would be best described by BRDF functions. We added the following line in the manuscript:

For an even more realistic description of the surface reflectance for real applications, the BRDF reflection function would be a well suited method.

**Reviewer Point P 2.3** — The simple assumptions about albedo seem to not be very realistic. It would be nice to do simulations with more reasonable albedos or at least provide some discussion on the possible errors from making these assumptions about the albedo.

**Reply**: We agree that albedo is important and has a big impact on AMFs. The albedos used in this study were taken from APEX measurements over our study area. While real albedos have some variations, the used values (0.1 and 0.2 for roofs/walls and 0.1 for ground) are typical for this area of the city. However, it is true that albedos can vary for different areas and cities. We added the following paragraph in the conclusions to discuss this in more details:

> Generalizing our results to others cities is challenging, because many relevant parameters such as building shapes, surface reflectances and a priori $NO_2$ distribution vary strongly between different cities. In our case study, we used a surface reflectance of 0.1, which is a realistic value for Zurich but not necessarily for other cities. In general, a higher surface reflectance of the observed ground pixel implies less atmospheric scattering and a higher sensitivity of the instrument to the main optical path and higher albedo of neighbouring pixels increases the sensitivity to this neighbouring pixel.

**Reviewer Point P 2.4** — Pg 1 Ln 18. "by fuel combustion by traffic, heating systems...", suggest changing to "by fuel combustion, traffic, heating systems..."

**Reply**: We implemented the suggested change.

**Reviewer Point P 2.5** — Pg 2 Ln 53. Please spell out MYSTIC completely, the Monte carlo code for the phYSically correct Tracing of photons In Cloud atmospheres

**Reply**: We spell out MYSTIC completely now.

**Reviewer Point P 2.6** — Pg 8 Ln 186 "The reflectance was set to 0.1", please clarify that you are referring to surface reflectance, not top of atmosphere reflectance

**Reply**: We added "surface" before reflectance.

**Reviewer Point P 2.7** — Pg 15, Fig 10 It is curious that the building in the bottom right of the figure shows now shadowing effects despite the sun being to the west. Can you explain why this building is not effect by shadows effects. Even if it was in the shadow of the building to the west, one would still expect and impact on SCDs.

**Reply**: Excellent observation. We verified the simulation inputs and it appears that the building was missing, because we selected only buildings whose centroids are within the domain, whereas all buildings were included in the drawing of building contours. We run the simulation again including the building. Figure 10 was updated.

**Reviewer Point P 2.8** — Pg 15 Line 316 "with 19% and 24% for simulations without aerosols and without and with buildings, respectively". This statement is a bit confusing. I suspect you mean 19% from outside the optical path with no aerosol/no building and 24% from outside the optical path with no aerosol/with building, but it is not clear

**Reply**: Yes you are right. We clarified the sentence as following:

> Only a small but not negligible amount of photons are from outside the main optical path, with 19% for a simulation without aerosols and without buildings and 24% for a simulation without aerosols and with buildings.

**Reviewer Point P 2.9** — Pg 15 Line 317 should be "The effect becomes more.."

**Reply**: We corrected the typo.

## References

Berchet, A., Zink, K., Muller, C., Oettl, D., Brunner, J., Emmenegger, L., and Brunner, D.: A cost-effective method for simulating city-wide air flow and pollutant dispersion at building resolving scale, Atmospheric Environment, 158, 181–196, https://doi.org/https://doi.org/10.1016/j.atmosenv.2017.03.030, 2017.