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 Frederik Tack for his positive comments, critical assessment and useful points to improve the quality of our paper. In the following we address his 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.

Reviewer 3

Reviewer Point P 3.1 — The studied 3D effects are indeed a very relevant problem in case of airborne/high resolution spaceborne trace gas retrievals over urban areas. A comment I had on the previous study of Schwaerzel et al., 2020 and also here is that I'm eager to see the impact on the VCD of using 3D BOX-AMFs (with/without building layer) instead of 1D layer-AMFs on a real-world airborne data set. Just as demonstrated with the synthetic data, a sample of an APEX data set acquired over Zurich could be used for this.

Reply: We agree that the application to real observations is important and we are currently in the process to apply 3D-box AMFs to real data from an APEX campaign over Zurich and eventually Munich. However, this step also requires additional work, for example, setting up city-scale dispersion models to have suitable 3D NO_2 fields. Since this additional work would make the manuscript substantially larger, we decided against adding it here.

Reviewer Point P 3.2 — I suggest to add a figure and description where you compute back the VCDs, e.g. based on the SCD-3D (considered that this is the typical smoothed NO2 field observed with an airborne imager) and the AMF-1D. This could demonstrate the impact of smoothing on the retrieved VCD (when compared to the 'true' simulated NO2 field of Fig. 2c) when not considering 3D effects. Same could be done by computing the VCD based on SCD-3D-UC and AMF-3D to demonstrate the impact of adding/neglecting the urban canopy. This would help the interpretation and avoid that a non-careful reader could have the impression that the 3D case leads to a more smoothed NO2 field when looking at the SCDs in Figure 6.

Reply: This is a good suggestion, we added a new section addressing the computation/retrieving of VCDs from (simulated) SCDs that include 3D effects and buildings. We added the following three figures showing VCD fields calculated from the

SCDs calculated with 3D-box AMFs with buildings. Additionally we added a figure showing the VCDs retrived from SCDs calculated with 3D-box AMFs without buildings to the supplement. Figure 1 compares VCDs calculated from the new assumed "true" SCD_{3D-UC} combined with AMFs from (left) 3D-box AMFs accounting for buildings (middle) 1D-layer AMFs and (right) 3D-box AMFs ignoring buildings.

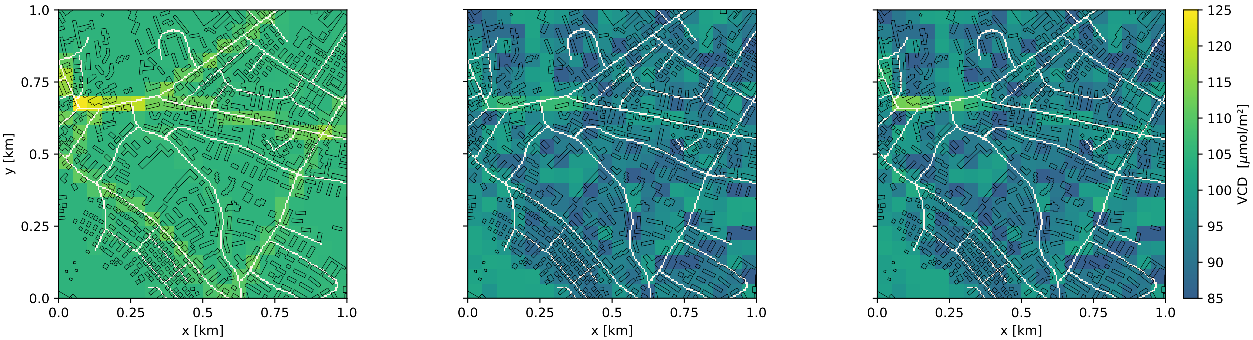

Figure 1. VCDs for a simulation with SAA of 90° with 3D-box AMFs simulation (left) with and (right) without buildings, and with (middle) 1D-layer AMFs.

In the main text we added a subsection containing the following text:

In imaging remote sensing, NO_2 VCDs are retrieved from SCDs using AMFs. Here SCD_{3D-UC} are considered as the "true" SCDs measured by an airborne imaging spectrometer and VCDs were calculated using either 1D-layer AMFs or 3D-box AMFs without buildings (Fig. 11). The VCDs computed with 1D-layer AMFs fails to correct for the spatial smoothing induced by the complex 3D optical path of the photons (Fig. 11b). In additions, the effects of buildings are not corrected resulting in additional noise introduced by shielding effect of the buildings and significantly lower VCDs with a field average of $90.1\,\mu\mathrm{mol\,m^{-2}}$ compared to the $108.4\,\mu\mathrm{mol\,m^{-2}}$ of the true VCDs. When VCDs are computed using 3D-box AMFs without buildings, the spatial smearing is corrected but the noise component and lower VCDs (mean: $91.4\,\mu\mathrm{mol\,m^{-2}}$) would remain in the retrieved VCDs.

Reviewer Point P 3.3 — This work is building further on an earlier work, i.e. Schwaerzel et al.(2020), and there is clearly an overlap. Please add here explicitly in which way this new study differentiates from the previous study. The full study is not only focusing on the addition of the urban canopy.

Reply: We clarified this point adding the following sentence:

The study builds on the work by Schwaerzel et al. (2020), where we highlighted the importance of 3D RT effects on trace gas remote sensing for ground-based and airborne instruments.

Reviewer Point P 3.4 — Although each building surface can have its own albedo, for reasons of simplicity everything is given the same albedo of 0.1 in the study discussed in 3.3. It is somewhat confusing as sometimes "building shadows" are mentioned in the discussion (pointing to a different albedo). However, I think the authors refer with 'building shadows" rather to areas of the surface that cannot be 'seen'or are 'shielded' due to building obstruction of the lightpath. If this is the case, I would suggest to be more careful with the use of "shadows"or "shadowing effects" in the further discussion and maybe mention it as a 'shielding' effect. I also would explicitly repeat the made assumptions on the albedo in Sect. 3.3.

Reply: The presence of building shadows does not change the albedo of a surface, because the albedo is a property independent of illumination conditions. We have used the term "building shadowing" where the ground pixel is located in the building shadow and, therefore, the direct optical path towards the sun is shielded by the building. However, we noticed that the term "shadowing" is used in BRDF products to describe ground pixels where objects cast shadows. Since this can lead to confusion, we have replaced the term "building shadowing" with "building shielding" in the manuscript.

Reviewer Point P 3.5 — Title: "Cities with buildings"sounds a bit weird. Maybe replace by "built-up areas"?

Reply: We understand your point, as we had the same discussions on the title internally but decided on using "cities with buildings" because it emphasises that buildings have not yet been taken into account in airborne NO_2 remote sensing.

Reviewer Point P 3.6 — p.2, l.28: You might consider adding the following reference : Vlemmix, T., Ge, X. (., de Goeij, B. T. G., van der Wal, L. F., Otter, G. C. J., Stammes, P., Wang, P., Merlaud, A., Schüttemeyer, D., Meier, A. C., Veefkind, J. P., and Levelt, P. F.: Retrieval of tropospheric NO2 columns over Berlin from high-resolution airborne observations with the spectrolite breadboard instrument, Atmos. Meas. Tech. Discuss. [preprint], https://doi.org/10.5194/amt-2017-257, in review, 2017.

Reply: We added the citation.

Reviewer Point P 3.7 — -p.4, l.105: Not clear what the difference is between 'material' and 'material type'. Please specify

Reply: We have rewritten the description of the NetCDF file as follows:

> The triangular mesh is stored in a NetCDF file readable by MYSTIC. An example file layout is shown in the supplement. The file contains the variable `vertices` (shape: $N_v \times 3$, type: double), which is a

list of x, y and z coordinates. A mesh of N_t triangles is build from these vertices using the `triangles` variable (shape: $N_t \times 3$, type: int) by storing the indices of the 3 vertices that create the triangles. The variable `materials_of_triangles` (shape: N_t, type: int) is used to assign each triangle the index of a material type. The material types are defined using the variables `material_type` (shape: N_m, type: string), `material_albedo` (shape: N_m, type: double) and `temperature_of_triangle` (shape: N_m, type: double) to assign a name, albedo and temperature to each material.

Reviewer Point P 3.8 — p.5, l.125: Albedo typically has a strong impact on the AMF. Since the focus of this study is on adding the urban canopy (and its impact), it would be useful for further studies to do a sensitivity test to show the impact on the AMF of different typical roof types (even if the focus of the study here is not specifically on the building albedo).

Reply: We agree that conducting sensitivity studies for varying roof albedos (and other parameters) would be interesting further studies. We partially showed the effect magnitude of a different type of albedo in the supplement for a roof albedo of 0.2. However, we would like to keep the examples simple here to introduce the general concept and leave detailed sensitivity studies for later work.

Reviewer Point P 3.9 — p.7, l.155: I assume this is done for each along-track pixel?

Reply: Yes, each along-track pixel is an average of 10 discrete steps of 5 m (i.e. 10 instrument positions).

Reviewer Point P 3.10 — p.9, l.205: "The slight increase in the column AMFs in the right is induced by scattering events in the right side of the domain appearing on the left of the domain due to circular boundaries"This effect is not well understood.

Reply: Since MYSTIC uses circular boundary conditions, photons leaving the model domain on the left will enter the domain on the right. As a result, column AMFs on the right side of the ground pixel can be increased when the main optical passes overhead in the upper atmosphere for small domains and large SZAs. This model artefact was visible in an early version of the figure. In the current version the artefact cannot be seen anymore, because we only integrate up to 0.4 km. We removed the sentence in the revised version to avoid confusion.

Reviewer Point P 3.11 — p.11, l.251: AMFs calculated with 3D-box AMFs but without buildings (Figure 6b) are lower over the roads and slightly larger just aside the roads." -> it would help the reader to repeat why this is the case.

Reply: We extended the sentence with the following:

> , because the 3D-optical path crosses neighbouring columns with decreased or increased concentrations, respectively.

Reviewer Point P 3.12 — p.12, l. 268: "Not including the urban canopy would therefore underestimate VCDs by 12%..."I first thought to elaborate a bit on this in the conclusion. However, I think it is difficult to generalize, depending on the complexity of the urban canopy and also due to the fact that the bulk of the NO2 can be in elevated layers in real-world conditions which would reduce the impact of adding the UC.

Reply: We agree that a generalisation is difficult because it depends on various factors (urban canopy structure, reflectances, 3D NO_2 distribution). We briefly discuss the limitation of our scenario in the conclusions.

> 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 3.13 — p.15, 322: "When buildings are included, NO2 SCDs are generally lower due to the shadows of building" As you assume a same surface reflectance in the study I assume this is rather due to the blocking of the lighpath?

Reply: Yes (see our reply to point 3.4).

Reviewer Point P 3.14 — Conclusions: Some suggestions would be helpful for future airborne/spaceborne missions and/or instrument design to reduce 3D effects over urban areas, e.g. to operate close to local noon and maybe operate with small VZA, or to put some thresholds on SZA and VZA? The latter is of course a trade-off with the amount of data than can be acquired during an overpass.

Reply: Yes, this is a relevant point. We added a new section 3.4 where we discuss application to real observations and give some recommendations for future campaigns.

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.

Reviewer Point P 3.15 — p.2, l.31: to -> towards the instrument-

Reply: We corrected this point.

Reviewer Point P 3.16 — p.2,l.40: is NO2 maps -> is that NO2 maps-

Reply: We corrected this point.

Reviewer Point P 3.17 — p.7,l.180: Fig.2c -> Fig. 2c

Reply: We corrected this point.

Reviewer Point P 3.18 — p.7,l.180: Fig.2c -> Fig. 2c (Note as well that references to figures are not always consistent throughout the manuscript. Sometimes written as Figure 1, sometimes as Fig. 1)

Reply: Thank you, we replaced all "Figure" located in the middle of a sentence by "Fig." as required by the AMT style guideline.

Reviewer Point P 3.19 — -p.15, 314: in the direction of -p.16, 326: Two times “have”

Reply: We corrected these mistake.

Reviewer Point P 3.20 — -Fig. 8: This caption is not self-explanatory. Also in the text the figure is not clearly explained.

Reply: We clarified the reference to the figure in the text and modified the caption as following:

Sketch of two main optical paths for an airborne spectrometer pointing at (1) a road in grey and (2) at a pixel aside the road.

Reviewer Point P 3.21 — -Please have a close look at the supplement to correct for typos, e.g. p.2, l. 55: should be ‘emission’; add space between 15 and [;‘this’parameters ‘these’parameters, etc

Reply: We have revised the language and grammar in the supplement and changed "immission" to "concentration" as we refer to a measurable concentration and emissions here.

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.

Schwaerzel, M., Emde, C., Brunner, D., Morales, R., Wagner, T., Berne, A., Buchmann, B., and Kuhlmann, G.: Three-dimensional radiative transfer effects on airborne and ground-based trace gas remote sensing, Atmospheric Measurement Techniques, 13, 4277–4293, https://doi.org/https://doi.org/10.5194/amt-13-4277-2020, 2020.