Response to interactive comments from Referee #1

We gratefully thank the reviewer for the careful reading of our manuscript and for the very constructive comments. Below the reviewer's comments are given in italic bold font. Our responses to the comments and how the comments have been addressed in the manuscript are shown in roman font.

It would be good to have a short discussion of what the expected effect of aerosols is on the discussed 3d effects which here are discussed in a Rayleigh atmosphere.

Without cloud, the effect of aerosol on trace gas retrieval is already complex. Thus, it hard to give the effect of aerosols on the 3D cloud effects, and it's rarely discussed in the literature. I have added a discussion in the introduction:

"The impact of aerosol on the trace gas retrieval is quite complex, which depends on many factors (Leitão et al., 2010), and it will become more complicated when 3D clouds are included. On the other hands, the effects of aerosols are very similar to the considerations made for clouds, and the aerosols are treated as clouds in some studies (Chimot et al., 2016). In this work, aerosols are not included."

Page 2, last line: This sentence is a bit unclear as spatial heterogeneity will also be relevant in clear sky scenes and several effects are addressed at the same time here. Please separate into two (or more) sentences.

The sentence has been rephrased to:

"In current atmospheric trace gas retrieval schemes from space sensors, clouds are treated in a simplistic way ignoring 3D structures and cloud shadows. The impact of 3D features like spatial heterogeneity and structured cloud boundaries increase when the spatial resolution of the instruments approaches the dimensions of cloud features."

Page 3, line 14 / 15: It would be nice to have a very brief indication also of what Várnai et al. found in their work.

We have included the following sentence: "the results indicate that the 3D radiative processes contribute to near-cloud reflectance enhancements, especially within 1 km from clouds."

Page 9, line 21: I think it would be good to iterate here that only one aspect of possible errors introduced by cloud correction is covered. Perfect knowledge of all parameters is assumed and in particular, the NO_2 profile is assumed to be the same inside and outside of the cloud.

We have included: "In this study, the calculation of NO2 AMF uses the perfect knowledge of all parameters, and in particular, the NO_2 profile is assumed to be the same inside and outside of the cloud. The only source of the error in the NO2 retrieval is introduced by cloud correction."

Figure 2: I think that this display is somewhat misleading – I was tempted to see points close to the 1:1 line as "good" points while in reality, they are just points for which both cloud retrievals perform similarly. The main point of the discussion here is how large errors are and I think histograms of relative errors would be more appropriate.

The figure is to show not only the bias the NO2 AMF retrieval due to the simplified cloud correction, and also comparison of the bias using different cloud products. It's difficult to display the latter when we use the histograms of the errors. We have added a group of figures in the appendix to show the examples of cloud and NO2 AMF retrieval for 1D clouds.

Figure 10: It would be nice to have the same x-axis in both plots to allow direct comparison

Correction made as suggested.

Section 4.1.1 It would be interesting to add a short discussion of what you think about the surface albedo fitting implemented in the current TROPOMI lv2 product where the surface albedo is determined from radiance in case it is lower than the climatological value for a scene.

We have made a statement:

"This correction can extend to the satellite measurements where the fitted surface albedo from the radiance is lower than the climatological value, and this may reduce the retrieval error due to surface albedo in certain situations. However, surface albedo at the UV-visible band is usually small. The NO_2 AMF calculation is very sensitive to surface albedo, especially for low surface albedo and polluted regions(Boersma et al., 2004). Such as the cases mentioned above cause significant error in the NO_2 retrieval."

Cases where the retrieved albedo is 0 appear to be problematic – can you discuss this a bit more? Is that because the atmosphere is illuminated less than it would without cloud which reduces the backscattered intensity but does not change the layer AMF in the same way as a small albedo?

In clear scene, the satellite measured radiance is the sum of backscattered radiance from the atmosphere and reflected radiance from the Earth's surface. Thus, we give an explanation:

"This means that the cloud leads to less photons through cloud into the shadow and back to the satellite, and this reduction is larger than the reflected radiance from the Earth's surface in corresponding clear scene."

The application to TROPOMI data is based on the assumption that NO_2 retrievals should yield the same column in cloudy and clear regions as well as in the cloud shadow. However, considering the reduced actinic flux in the cloud shadow (and the increased values inside the cloud), shouldn't we actually see differences?

This question is related to the impact of horizontal variation of the NO2 concentration, and this can be checked with the 3D box-AMF.

In general, the 3D effects will be larger/smaller when NO2 in cloud regions is higher/lower than NO2 in clear regions compared to the 3D effects for NO2 in cloud regions = NO2 in clear regions. On the other hand, the spatial scale of cloud shadow is comparable to the size of the TROPOMI pixels, and this effect may be small. This requires further investigation.

Bibliography

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Chimot, J., Vlemmix, T., Veefkind, J. P., de Haan, J. F., and Levelt, P. F.: Impact of aerosols on the OMI tropospheric NO2 retrievals over industrialized regions: How accurate is the aerosol correction of cloud-free scenes via a simple cloud model?, 9, https://doi.org/10.5194/amt-9-359-2016, 2016.

Leitão, J., Richter, A., Vrekoussis, M., Kokhanovsky, A., Zhang, Q. J., Beekmann, M., and Burrows, J. P.: On the improvement of NO2 satellite retrievals - Aerosol impact on the airmass factors, Atmospheric Measurement Techniques, 3, 475–493, https://doi.org/10.5194/amt-3-475-2010, 2010.