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.

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Response to interactive comments from Referee #2

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.

The quantities directly affected by 3d cloud effects would be the retrieved cloud fraction and cloud height.

These quantities are generally used for calculating NO_2 AMFs, and, as far as I understand, this should not be changed according to the authors.

But then it is essential to first check how far the cloud retrievals are affected by 3D effects before analysing the effects on trace gases.

For instance, a cloud shadow causes lower reflectance. This might actually be dealt with in the existing algorithms if negative cloud fractions would be allowed. This way it might be actually quite simple to account for cloud shadow effects without introducing new concepts/quantities like CSF.

Also other 3d effects (clouds in neighboring pixels) will affect the cloud fraction and cloud height retrieved based on IPA. It would be interesting to see to which extent these "wrong" CF/CH parameters do the NO_2 AMF correction intrinsically (such as aerosol effects being partly accounted for by the cloud algorithms yielding higher CF and lower CH than "reality").

In this study, the 3D effects of NO_2 retrieval are discussed based on the classic NO_2 retrieval approach, which applied the cloud correction to the AMF calculation only for partly cloudy scene (the retrieved cloud fraction is larger than 0), otherwise, the scene is treated as cloud-free. The approach mentioned in the reviewer's comment, which uses the unrealistic cloud properties (negative CF), is not the standard approach. In addition, the cloud fractions are confined to [0,1] in the current TROPOMI cloud products (Loyola et al., 2018; van Geffen et al., 2021).

On the other hand, this approach can be added in the "Mitigation" part, which is one of possible way to improve the current NO_2 AMF calculation in the cloud shadow, called "AMF using extended cloud retrievals".

I would thus like the authors to add an analysis of 3D effects on the cloud products first. The further mitigation strategy might be different if 3D effects could already be accounted for by e.g. negative cloud fractions. In any case, the mitigation strategies cannot be discussed without knowledge on the effect of 3D cloud structures on the standard cloud products themselves.

We do not agree to add “an analysis of 3D effects on cloud products”, since the main focus in the study is analysing the 3D effects on the NO_2 retrieval, and the cloud products used for cloud correction in the NO_2 retrieval are based on a simple cloud mode and obtain the effective cloud properties (CF, CH). The accuracy of cloud retrieval does not link to the accuracy of cloud correction, especially for the nearly cloud free scene, which is the main concern for the NO_2 retrieval.

We add a series of Figures (Figure 1) in Appendix to give the examples of cloud and NO_2 retrieval for 1D cloud cases, which show that the FRESCO retrieval usually is closer to the true cloud height, but the NO_2 AMFs using the O_2-O_2 cloud correction often show better agreement with the true AMF, especially for the high cloud cases. Thus, we believe that the analysis of 3D effects on cloud products is not a relevant topic in this paper. In addition, an example of extended cloud retrievals in the cloud shadow is included in the section “AMF using extended cloud retrievals”.

Minor comments:

Page 1, Line 2: "generally implement Lambertian cloud models": This is not true, see for instance OCRA/ROCINN.

The sentence has been rephrased to: “generally implement a simple cloud model”

Page 1, Line 3: "photon path length corrections": to my understanding, the cloud algorithms interprete the measured O2 or O4 absorption in terms of a cloud height. This should be stated here.

This has been stated after:

The latter relies on measurements of the oxygen collision pair (O_2-O_2) absorption at 477 nm or on the oxygen A-band around 760 nm to determine an effective cloud height.

Page 2, line 6: "amount of the trace gas along the average path": this sounds like the average path could be calculated and then linked to the amount of trace gas. It is rather the average absorption along light paths.

This has been rephrased to: “the integrated trace gas concentration along the light path”

Page 2, line 19: "A simplified Lambertian cloud model is generally used": This is not true, see for instance OCRA/ROCINN.

The sentence has been rephrased to:

“A simple cloud model is generally used, which treats cloud as a Lambertian surface or a scattering layer, relying on the concepts of cloud fraction, cloud top albedo and cloud top pressure(Acarreta et al., 2004; Loyola et al., 2018; Wang et al., 2008).”

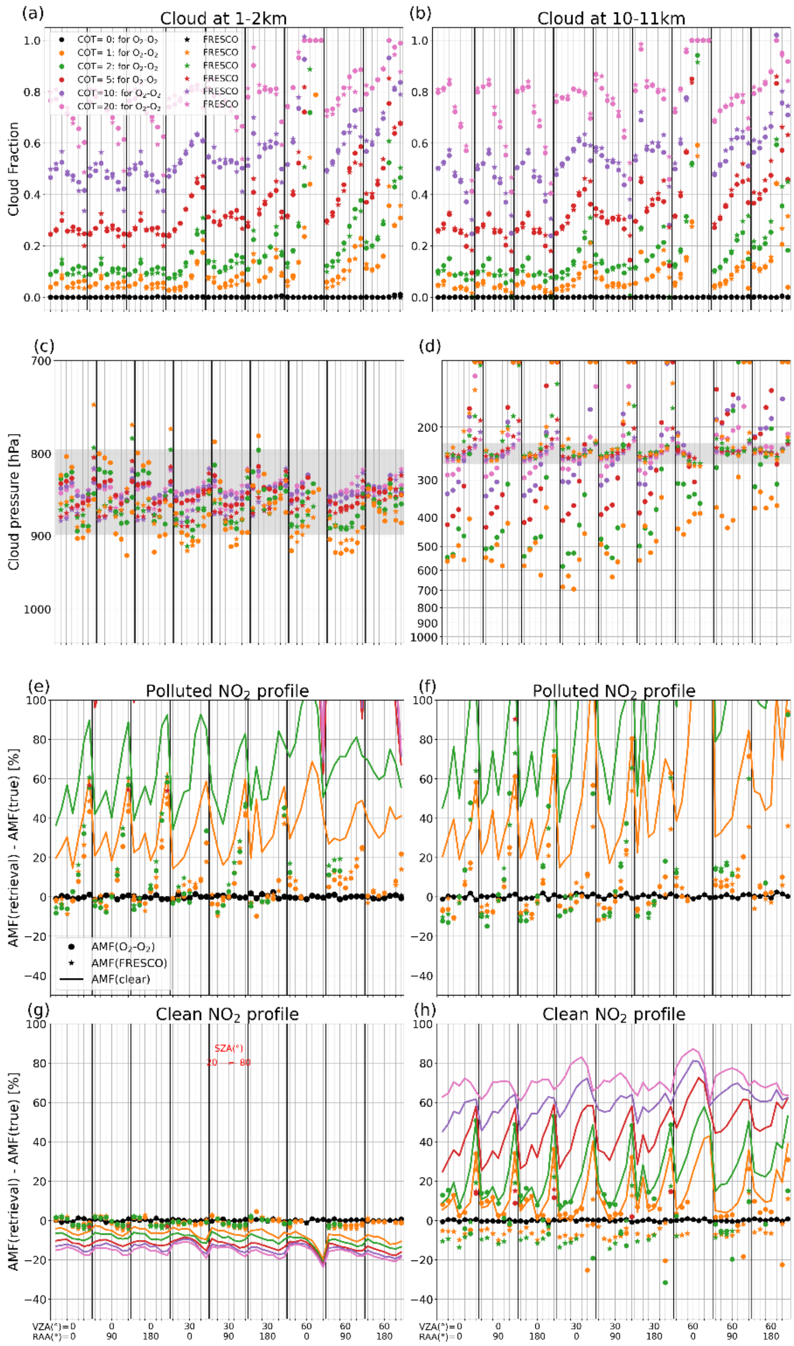

Figure 1: Examples of cloud and NO_2 retrieval for 1D cloud scenes, discussed in Section 2.5, with 1-2 km (left) and 10-11 km (right) cloud height. (a) and (b) show O_2-O_2 and FRESCO cloud fraction retrievals, (c) and (d) are the cloud pressure retrieval from O_2-O_2 and FRESCO cloud algorithms, the grey regions indicate the true cloud layer. (e)-(h) compare the bias of the NO_2 AMF retrievals using cloud correction based on O_2-O_2 and FRESCO cloud products, as well as the retrieval without cloud correction, for polluted (e)/(f) and clean (g)/(h) condition. The cloud correction is applied when the pixels with CF_w less than 50%. The x-axis represents the cases with different geometries. A variety of colors represent the cases with different cloud optical thickness.

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Response to interactive comments from Editor #1

Reading the reply to Referee #2, I had the impression that only the classical Lambertian cloud model (CRB) retrieval will be discussed in "AMF using extended cloud retrievals". I strongly recommend to include in this section also a discussion of AMF calculations using the more realistic cloud-as-layer (CAL) model as it is done in Liu et al., 2021: https://doi.org/10.5194/amt-14-7297-2021

NO_2 retrieval corrected by the cloud retrieval based on CAL model is added in the "AMF using extended cloud retrievals" part. Instead of OCRA/ROCINN cloud algorithm, a simple cloud retrieval approach is presented, which assumes the cloudy scenes are 100% covered by a uniform layer of water cloud with 1 km geometrical thickness. The cloud single scattering albedo sets as 1 and the asymmetry parameter is 0.85, these values are consistent with those used in the cloud and NO_2 retrieval (Liu et al., 2020, 2021). This approach retrieves cloud top pressure and optical thickness based on the measured reflectance at 460 nm and O_2-O_2 SCD or three 1-nm (758–759 nm, 760–761 nm and 765–766 nm) averaged radiances around O_2-A band.