Referee (#1)

The authors would like to thank Referee #1 for his/her thoughtful and helpful comments and suggestions. Below are the comments by Referee #1 in blue and our response in black. Any modification made to the text of the manuscript has been highlighted within a green box. The line numbers correspond to the version of the manuscript available for online discussion.

Comment 1

This is basically a theoretical sensitivity study focusing on surface reflectance. Some additional analysis of what to expect in a real retrieval (e.g., Zhou et al., 2010; Lin et al., 2015) and applications (which combine pixels with forward reflecting and pixels with backward reflecting) would be nice. I expect that adding forward and backward scenes together reduce the net effect of surface reflectance on both cloud and NO_2.

Doing a retrieval accounting for the surface BRDF in all the steps is not possible at this stage, as it would require the development of two (cloud and trace gas) retrievals explicitly accounting for surface anisotropy effects, as well as the addition of a model to account for BRDF effects over water. One of the main motivations for our theoretical study was to quantify the effects over land and to confirm that it is strictly necessary to coherently account for surface BRDF both in trace gas and cloud retrievals.

Sections 4.2 and 5.2 describe pseudo-applications, where both forward and backward pixels are considered with the exact same geometry that we encounter in one month of measurements. The spatially averaged result is an increase in the AMF of 6% and 9% over Amazon and France respectively when accounting for surface BRDF effects. As shown by Fig. 11(c, d), averaging over both forward and backward scattering scenes might reduce the net effect for some pixels but not for all of them.

Comment 2

Whether (and how) the effects on Ceff and Mcr act together or compensate each other to affect NO2 AMF is dependent on cloud pressure (CP). In this study, CP is assumed at 850 hPa, which for polluted situations means that most NO2 is below cloud, that Mcd is much smaller than Mcr, and thus that the effects through Ceff and Mcr are complementing each other. A higher CP could lead to Mcd larger than Mcr and thus compensating effects (on NO2 AMF) through Ceff and Mcr. Please comment.

This is a very good point that was not addressed in the manuscript. We have chosen 850 hPa after analysing cloud pressure distributions over Amazonia in March 2008. The distribution for this particular month shows that for low cloud fractions, clouds between 900-800 hPa are more frequent than clouds with pressures between 1000-900 hPa (15% vs. 8%). Over land areas other than Amazonia, this percentage is more similar (22% vs. 19%). A preliminary analysis done with a directional surface LER derived from GOME-2 shows that accounting for surface reflectance anisotropy effects tends to reduce cloud pressures by 40 hPa on average (with differences up to 120 hPa).

We have repeated the analysis in Sect. 5.1 (surface BRDF effects on tropospheric NO_2 air mass factors) using different cloud pressures (from 800 to 978 hPa).

Figure AC1 shows surface BRDF effects on total tropospheric AMF for decreasing cloud pressure, for a cloud fraction of 0.1. For cloud pressures higher than the 850 hPa assumed in the manuscript, the contribution from surface BRDF effects to the change in M from the change in cloud fractions becomes smaller. There is a cloud pressure (in Fig. AC1 between 900 and 950 hPa) for which the effects on M_{cr} and on cloud fraction compensate each other. For an even higher cloud pressure (e.g. 978 hPa), M_{cd} is larger than M_{cr} and the sign of the effect changes. In the backward scattering we have lower BRDF AMFs and in the forward scattering higher BRDF AMFs. In the unpolluted situations the differences also become larger for higher cloud pressures.

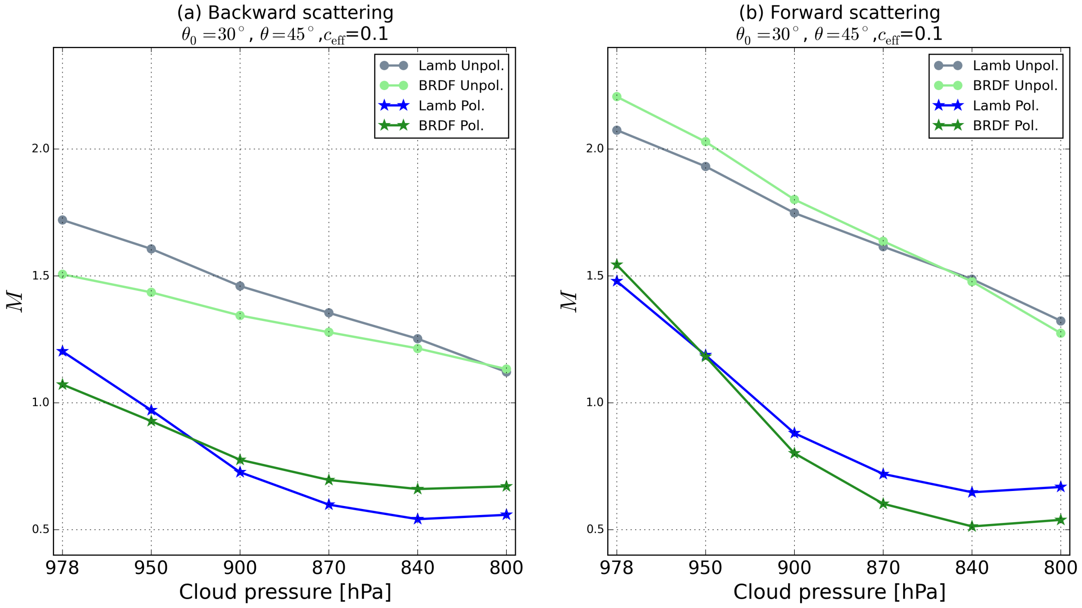


Figure AC1: Total tropospheric NO_2 AMF as a function of cloud pressure in the (a) backward scattering direction and (b) forward scattering direction computed with surface BRDF (green) and a Lambertian surface (blue), for (θ, θ_0) = (45°, 30°), for a moderately polluted (stars) and unpolluted (circles) troposphere. BRDF parameters are (fiso, fvol, fgeo) = (0.04, 0.03, 0.008) and Aws = 0.036 for the Lambertian surface.

We have included Fig. AC1 in the supplementary material, and we have added a paragraph based on the discussion above (P20, L6):

The differences between BRDF and Lambertian AMF for different cloud pressures are shown in Fig. S6 in the supplementary material. A preliminary analysis done with a directional surface LER derived from GOME-2 shows that accounting for surface reflectance anisotropy effects reduces the cloud pressure by 40 hPa on average (with differences up to 120 hPa). This means that high cloud fractions will occur less often and therefore the results shown for 850 hPa are representative of the surface BRDF effects on AMFs.

Comment 3

Sects. 4 and 5 – Do you assume Henyey-Greenstein clouds in the forward model (Eq. 8) and then assume Lambertian clouds in the reverse model (i.e., in the cloud and NO2 retrievals)? What else are different between the forward and reverse models?

The assumption of the Henyey-Greenstein (HG) cloud is used to simulate top-of-atmosphere radiances with DAK that resemble as much as possible what the satellite would measure (R_{meas}) in a realistic cloudy scene. We then indeed assume Lambertian clouds in the reverse model. In other words, the forward model to simulate TOA radiances assumes surface reflectance to be anisotropic, and includes a HG cloud, and the reverse model assumes the cloud reflection to be Lambertian. The assumption of a Lambertian cloud is what is currently done in the operational cloud retrievals at KNMI (O2-O2, FRESCO+).

We have modified the sentence that refers to this in the manuscript (P15, L6):

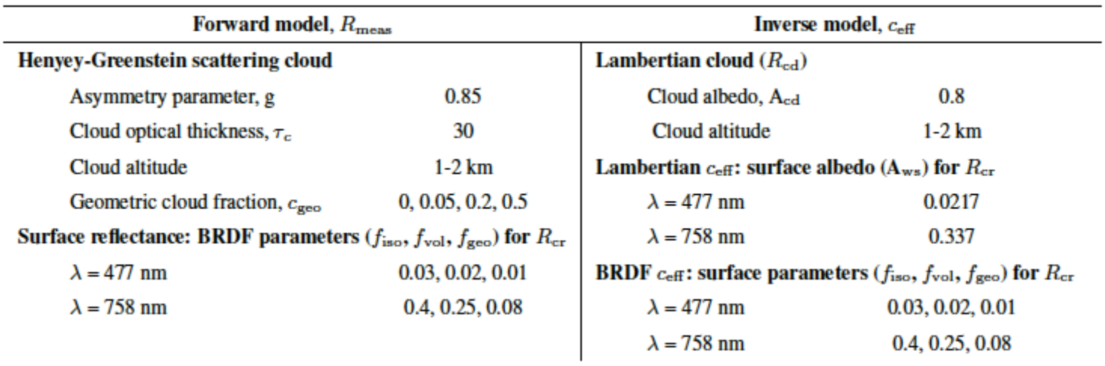
"…we use the forward model DAK to approximate R_{meas} simulating the TOA reflectance for a scene with a Henyey-Greenstein cloud and surface reflectance anisotropy."

Is cloud pressure the same between forward and reverse models?

In our case, the Lambertian cloud is located at the same pressure level as the Henyey-Greenstein cloud (1-2 km). By setting the clouds at the same altitude, we isolated the surface BRDF effects on cloud fraction only, as we do not consider potential effects on cloud pressure.

We have modified Table 1 to include this information and clarify the settings of the forward model and inverse simulations.

Table 1. Settings for Lambertian and BRDF c_{eff} simulations in Sect. 4.1. Inverse model for Lambertian c_{eff} reproduces current O_2-O_2 and FRESCO+ retrievals, with Lambertian surface and Lambertian cloud. Inverse model for BRDF c_{eff} reproduces the retrieval accounting for surface BRDF effects.



Forward model, R_{meas}		Inverse model, c_{eff}	
Henyey-Greenstein scattering cloud		**Lambertian cloud (R_{cd})**	
Asymmetry parameter, g	0.85	Cloud albedo, A_{cd}	0.8
Cloud optical thickness, τ_c	30	Cloud altitude	1-2 km
Cloud altitude	1-2 km	**Lambertian c_{eff}: surface albedo (A_{ws}) for R_{cr}**	
Geometric cloud fraction, c_{geo}	0, 0.05, 0.2, 0.5	$\lambda = 477$ nm	0.0217
Surface reflectance: BRDF parameters ($f_{\mathrm{iso}}, f_{\mathrm{vol}}, f_{\mathrm{geo}}$) for R_{cr}		$\lambda = 758$ nm	0.337
$\lambda = 477$ nm	0.03, 0.02, 0.01	**BRDF c_{eff}: surface parameters ($f_{\mathrm{iso}}, f_{\mathrm{vol}}, f_{\mathrm{geo}}$) for R_{cr}**	
$\lambda = 758$ nm	0.4, 0.25, 0.08	$\lambda = 477$ nm	0.03, 0.02, 0.01
		$\lambda = 758$ nm	0.4, 0.25, 0.08

We have added a sentence in the text (P15, L18):

The Lambertian cloud is located at the same pressure level as the Henyey-Greenstein cloud so we can isolate surface BRDF effects on cloud fraction only (see settings in Table 1).

It is not clear how the difference between Ceff and Cgeo is derived. Also, where is the Cgeo from (e.g., in Fig. 8)?

In cloud retrievals, the difference between geometric and effective cloud fraction, as explained in Stammes et al. (2008):
"The effective cloud fraction is the amount of Lambertian cloud with albedo Ac that one has to add to the clear pixel to explain the observed reflectance. The geometric cloud fraction is the part of the pixel that is covered by the "true" cloud. The effective cloud fraction is the radiometrically equivalent cloud fraction, which in combination with the assumed cloud albedo yields a TOA reflectance that agrees with the observed reflectance."

In Sect. 4.2 (Fig. 8), in order to apply Eq. 8, we used a C_{geo} distribution with an area-wide average of 0.33 distributed randomly for East and West measurements (Fig. 8a, d). Together with the Henyey-Greenstein cloud simulation, we applied Eq. 8 to obtain R_{meas} using those C_{geo} values. Finally, we apply Eq. 9 to obtain the effective cloud fraction (C_{eff}) (with Lambertian and BRDF assumptions, Fig. 8 b,e,c,f).

We have slightly modified the text that explains this (P17, L5):

To simulate measured reflectance, we assume a geometric cloud fraction distribution with an area-wide average of $C_{\mathrm{geo}} = 0.33$. Figure 8a,d show the C_{geo} distribution for East and West measurements respectively.

Comment 4
P3, L20 – clarify "clear-sky"

Clear-sky means that they only selected scenes where cloud fraction was very low or strictly zero (Noguchi et al., 2014). We modify the sentence:

"They analyzed clear-sky scenes (i.e. no clouds present) or scenes with very low cloud fractions (i.e. lower than 0.2), ..."

Comment 5
P12, L7 – could you comment on the large difference near the hot-spot region between LIDORT and DAK/SCIATRAN?

We did not address this issue in the manuscript as the only purpose of the comparison with LIDORT and SCIATRAN was to validate our surface BRDF implementation in DAK. The reason for the difference between LIDORT and DAK, SCIATRAN is that there is no hot-spot correction in the simulations by LIDORT (H. Yu, personal communication).

Comment 6

Sect. 5.1 – why not use the retrieved Ceff_BRDF, rather than assuming Ceff_BRDF = 0.1 ± 0.05?

In Sect. 5.1 we use a fixed change in the cloud fraction to understand how the change in cloud fraction due to surface BRDF affects forward and backscatter measurements separately. The choice of 0.1 ± 0.05 is our best approximation of what would happen if we develop a completely new revised cloud algorithm based our analysis in Sect. 4. In Sect. 5.2, we use the calculated Ceff_BRDF from section 4.2 (shown in Fig. 8) and not the fixed change of ± 0.05.

We modify the text to make it clear (P20, L12):

We apply Lambertian and BRDF C_{eff} distributions from Sect. 4.2 (as in Fig. 8). This way we account for the calculated surface BRDF effects in cloud fraction instead of the average change of 0.05 assumed in the sensitivity analysis in Sect. 5.1.

Comment 7

Table 2 –please provide a complete set of ancillary parameters such Ps, T profile, etc.

Atmospheric profile corresponds to the mid latitude standard atmosphere (Anderson et al., 1986). We extend Table 2 with this information. Fig. AC2 shows the NO_2 profiles that were used for the moderated polluted and unpolluted simulations in Sect. 4. These profiles correspond to $N_{v,trop} = 4 \cdot 10^{15}$ molec/cm^2 and $N_{v,trop} = 0.2 \cdot 10^{15}$molec/cm^2.

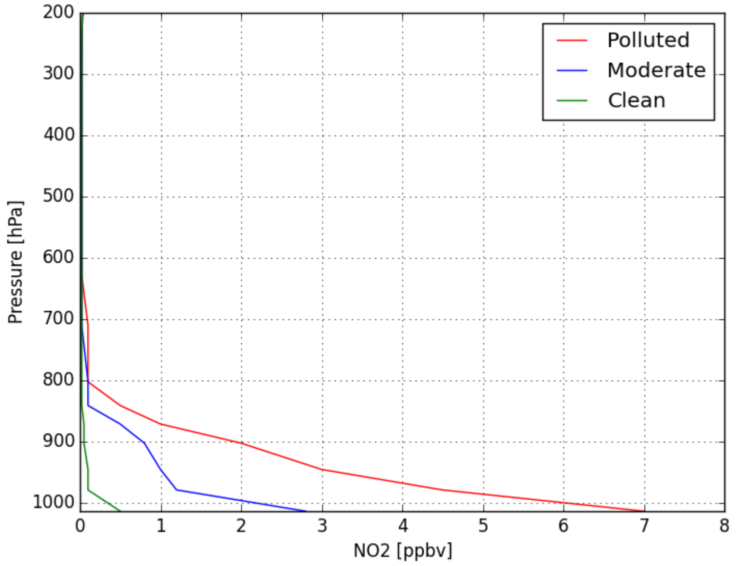


Figure AC2: Clean, moderate and polluted profiles used in the study.

References

Anderson, G. P., Clough, S. A., Kneizys, F. X., Chetwynd, J. H., and Shettle, E. P.: AFGL Atmospheric Constituent Profiles (0– 120 km), Environ. Res. Papers, Optical Physics Division, Air Force Geophysics Laboratory Hanscom AFB, MA, 43 pp., http://nla.gov.au/nla.cat-vn4005592, 1986.

Noguchi, K., Richter, A., Rozanov, V., Rozanov, A., Burrows, J. P., Irie, H., and Kita, K.: Effect of surface BRDF of various land cover types on geostationary observations of tropospheric NO2, Atmos. Meas. Tech., 7, 3497–3508, https://doi.org/10.5194/amt-7-3497-2014, 2014.