

Response to reviewer #1

We thank the reviewer for his/her evaluation of our paper and useful comments that helped improve the manuscript. We appreciate reviewer's time and effort in reviewing the manuscript. Below are our responses to each comment. All reviewer's comments are in the standard font while the responses are in the italic font.

On behalf of the authors,

Alexander Vasilkov

Main points

(1)The start of the introduction, from l. 26 – l. 52 around Eqs. 1-3, seems detached from the remainder of the paper. The symbols and terms are different. The text and formulae are unclear. What is the link to the LER, which is used in the remainder of the paper?

In this section we provide basic definitions of the BRDF and related quantities (BSA and BRF) for informational purposes because there can be different definitions of those quantities in the literature. The BRDF as defined by Eq. 1 is parameterized in Section 3 using a linear combination of three RTLS kernel functions. The coefficients of those functions are then used in radiative transfer computations to calculate the LER with Eq. 6. Indeed, Equations 2 and 3 are not used in our computations. We give those definitions because those quantities are widely used in the literature (see e.g. Zhou et al., 2010; McLinden et al., 2014) and we would like to show a link of our approach to others. We have provided an extra sentence and a break in paragraph 1 of the introduction to make this clearer:

“Here, we give some basic definitions that have been used in the literature to provide context to our problem and for clarity as sometimes different definitions have been used for similar or the same quantities.”

- What is $I(\omega_r)$ in Eq. 1? Is that the same as I_m in Eq. 4? What is the relation to the top-of-atmosphere radiance as observed by OMI ?

$I(\omega_r)$ is not the same as I_m in Eq. 4. I_m is the top-of-atmosphere radiance as observed by OMI while $I(\omega_r)$ is the reflected radiance in the direction ω_r at the surface. $I(\omega_r)$ provides a boundary condition at the surface for calculation of the TOA radiance. We added in the text:

“ $I(\theta_i)$ is the radiance incident on the surface” and

“The reflected radiance $I(\theta_r)$ is calculated by integrating the product of BRDF and dF over all directions of the incident radiation. $I(\theta_r)$ provides a boundary condition at the surface for computations of the top-of-atmosphere radiance.”

Why do you use solid angle ω , whereas in the remainder of the paper you use θ and ϕ ? Explain θ_r , which is called θ in the remainder of the paper.

We use the solid angles to (1) simplify the equations and (2) follow the convention in the definition of BRDF. The denotations θ_i and θ_r are used in Eq. (1)-(3) only to distinguish the zenith angles of incident and reflected light. θ_r is the zenith angle of reflected light; the subscript “r” is omitted in the remainder of the paper for simplicity. We clarify that by adding the following immediately after Eq.2:

“where θ_r is the zenith angle of reflected light (subscript “r” is omitted in the remainder of the paper for simplicity)”

Why is F, mentioned below Eq. 1, not used in the equation?

We introduced the quantity F into Eq. 1, adding one more equality:

“BRDF=dI/dF=...”

- In Eq. 2 please give the integration limits. Below Eq. 2 it is apparently assumed that this particular Lambertian has an albedo of 1. But also for a less reflective Lambertian surface the relation can be used.

We added “where integration is carried out over the solid angle of 2π for the upper hemisphere”. Eq. 2 gives a general definition. The sentence below Eq. 2 considers a particular case of the perfect Lambertian surface that has albedo of 1. We have clarified this in a revised paper.

- Eq. 3: does BRF in this equation yields R_g in Eq. 4?

Yes, if a value of BRF is used as R_g in Eq. 4. In general, R_g can be a geometry-dependent or climatological LER.

(2) The interpretation of the scatter plots of retrieved cloud parameters from RRS and O2-O2 algorithms between the BRDF-dependent LER and climatology LER, especially the OCP, deserves more discussion. See Figs. 7 and 9. Apparently the RRS OCP is hardly depending on the surface BRDF, whereas the O2-O2 OCP is strongly depending on it. That is remarkable. It cannot be only explained by the decrease of Rayleigh scattering at 466 nm as compared to 354 nm, as stated in the paper. Another difference in both algorithms must be causing this. It is probably due to the fact that the RRS signal is not including all light paths that are relevant for the O2-O2 absorption (and NO2 absorption). Namely, the direct light path of direct sunlight reflected by the surface and arriving at the satellite is not included in the RRS signal, because there is no Rayleigh (Raman) scattering involved. But it is an important light path for the cloud-free part of the pixel. And this direct light path is also strongly contributing to O2-O2 (and NO2) absorption. So the RRS method is in first order insensitive to the surface and to its BRDF. Only

via the light paths Rayleigh + surface reflection, and surface reflection + Rayleigh can the RRS signal pick up surface BRDF effects. But that is a second-order effect. Please consider this cause in explaining the OCP behaviour of the RRS and O2-O2 algorithms.

We particularly thank the reviewer for this comment. We agree that the differences between the RRS and O2-O2 cloud algorithms deserve more discussion. Indeed, sensitivities of the OCP, derived from RRS and O2-O2, to surface reflectivity are different for the RRS and O2-O2 algorithms. This is because RRS first decreases with increase in surface reflectivity, and then it starts to slowly increase, while O2-O2 absorption increases monotonically. Also, the sensitivity to surface reflectivity depends upon the reflectivity itself. For high surface reflectivity, the reflected direct solar light significantly contributes to TOA radiance, and therefore causes the OCP differences related to the absence of RRS in direct solar light and the presence of O2-O2 absorption in direct solar light. However, for low surface reflectivity, this mechanism becomes less significant.

We replaced the last sentence in Section 5.2 by the following paragraph:

“The effect of replacing the climatological surface LER by the geometry-dependent LER is remarkably more pronounced for the O2-O2 OCP retrievals than for the RRS retrievals. This can be explained by two physical factors. Firstly, the Rayleigh optical depth of the atmosphere in the UV (the spectral window of the RRS cloud algorithm is 345 - 354 nm) is much higher than in the visible (the wavelength of the O2-O2 OCP retrieval is 477 nm). Higher scattering in the UV leads to a larger fraction of diffuse light illuminating the surface thus decreasing BRDF effects. In the visible, the smoothing effect of Rayleigh scattering is less than in the UV thus resulting in larger BRDF effects. Secondly, sensitivities of the OCP, derived from RRS and O2-O2, to surface reflectivity are different for the RRS and O2-O2 algorithms. The direct light path of direct sunlight reflected by the surface does not contribute to the RRS signal, because there is no Raman scattering involved. But this direct light path does contribute to O2-O2 absorption. That is why the RRS algorithm is generally less sensitive to the surface and to its BRDF for low cloud fractions. For high surface reflectivity, the reflected direct solar light significantly contributes to TOA radiance therefore causes the OCP differences related to the absence of RRS in direct solar light and the presence of O2-O2 absorption in direct solar light. However, for low surface reflectivity, this mechanism becomes less significant because the fraction of the reflected direct solar light in the TOA radiance is smaller.”

(3) Please add histograms of ECF and OCP for the orbits shown, and not only scatter plots, to see the difference between including and excluding BRDF effects, and the difference between RRS and O2-O2 algorithms.

We added histograms of ECF and OCP in Figs. 5, 7, 8, and 9. We also added the following in Section 5.1:

“Figure 5d shows normalized histograms of ECFs for $0.05 < ECF < 0.25$. The normalized histograms of ECF retrieved with climatological LER and ECF retrieved with BRDF are close to each other. This reflects small differences between the ECFs on average.”

and the following in Section 5.2:

“The histograms of OCP retrieved from the O2-O2 cloud algorithm (Fig. 9c) noticeably differ from that retrieved from the RRS cloud algorithm (Fig. 7c). According to Fig. 9c, lower altitude clouds (with OCP > 800 hPa) are observed more frequently over the ocean than over land. For high altitude clouds (OCP < 450 hPa) the situation is reverse: they observed more frequently over land than over the ocean. Both patterns in the vertical distribution of clouds are much less pronounced in the histograms of OCP retrieved from the RRS algorithm.”

Questions and textual comments

- Eq. 4: please say that I_g and I_c are at top-of-atmosphere

Done

- L. 67: is $A_c=0.8$ also assumed in this paper?

Yes. We added: “In this paper we also assume $R_c=0.8$ for the OMI cloud and NO2 algorithms”.

- L. 71: add here a reference to Stammes et al. (2008)

Thanks, done.

- L. 76: add here a reference to Sneep et al. (2008)

Done.

- L. 121: remove: its

Corrected.

- L. 141: does the RRS ECF hold for $R_c=0.8$?

Yes, see the comment to L. 67 above.

- L. 175: please make a separate equation of the in-text formula.

Done.

- L. 185: please clarify: do you use in the paper the climatological ratio $R_g(354)/R_g(470)$ or a ratio of unity?

We use the ratio of unity in the paper because (1) the climatological ratio $R_g(354)/R_g(470)$ can be close to unity for some types of land. An example of the spectral dependence of climatological LER is shown in Figure below. (2) we want to avoid possible uncertainties that could be potentially involved with the use of climatological spectral dependence of LER from existing data sets. The possible uncertainties are related to inconsistency of the spectral LERs from different data sets. For instance, according to the climatological data base of Kleipool et al. (2008), land is brighter in the UV than in the VIS for most areas (see Fig. 15 of Kleipool's paper), which contradicts the common understanding that the land is darker in the UV than in the VIS. We rewrote the text:

“In the paper we assume that the BRDF coefficients are spectrally independent to focus on the surface BRDF effects only. Using climatological data of Kleipool et al. (2008) we find that this assumption can be valid for some areas, e.g. the climatological ratio $R_g(354)/R_g(470)$ is close to unity (within $\pm 5\%$) over the eastern part of North America. However, this is not the case for arid and semi-arid areas. We plan to release our geometry-dependent LER product computed for wavelengths other than 470 nm using a spectral correction of the BRDF coefficients. This spectral correction will be based on the ratio $R_g(354)/R_g(470)$ derived from a critical analysis of different existing data sets of climatological satellite-derived LERs.”

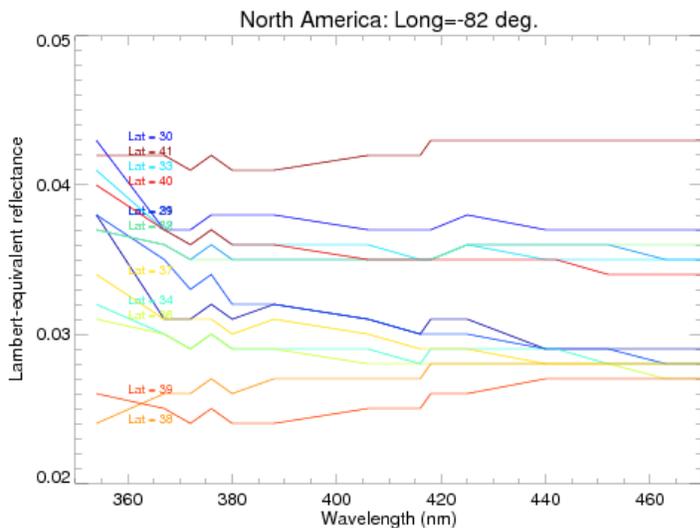


Figure. Spectral dependence of the climatological OMI-derived surface reflectivity over North America along the longitude of 82° for different latitudes (30° to 42° N).

- L. 208: please give a reference for MYD43GF.

*Typo, should be MCD43GF. We additionally provided a link to the product:
ftp://rsftp.eeos.umb.edu/data02/Gapfilled/.*

- L. 215: I_{TOA} : why is a new symbol introduced? Where the other radiance symbols not at top-of-atmosphere? How does it relate to I_m of Eq. 4?

We introduced a new symbol I_{TOA} for the computed TOA radiance to distinguish it from the measured TOA radiance I_m . To avoid a possible confusion, we replaced I_{TOA} with a new symbol I_{comp} .

Please do not introduce unnecessarily new quantities and symbols. Please also relate θ , ϕ , and θ_0 to the earlier introduced angles.

The angles θ and ϕ characterize the observational geometry at TOA; the angle θ_0 is the SZA. The earlier introduced angles in Eq. 1 and 2 are defined at the surface.

- L. 217 ff: the explanation of T is unclear. T is the total two-way transmission of the atmosphere.

The explanation of T is not simple (ours adopted from the original paper by Dave, 1978). T is not simply the total two-way transmission of the atmosphere because transmission is dimensionless while T has the dimension of radiance. We modified the definition of T to the following:

“ T is the total (direct + diffuse) solar irradiance reaching the surface converted to the Lambertian-reflected radiance by dividing by π and multiplied by the transmittance of reflected radiation between the surface and TOA in the direction of a satellite instrument.”

- L. 245: Land is mostly darker in the UV than in the VIS. So why not use the climatological OMI data base at 354 nm?

According to Fig. 15 of Kleipool et al. (2008), land is brighter in the UV than in Vis for grasses, broadleaf forests, and other types. See the answer to comment to L. 185.

- L. 265: please indicate the orbit and date.

Done.

- L. 300: is in Sect. 6 only the O2-O2 algorithm used and not the RRS algorithm because the latter has very little impact of BRDF?

The O2-O2 cloud product is used in Section 6 because the wavelengths which it uses (466 for ECF and 477 nm for OCP) are closer to the NO2 fitting window 405-465 nm specified in Section 2.3.2. , and therefore light at these wavelengths follows a more similar light path compared to those the RRS algorithm uses, in the UV.

- L. 301: why are the NO₂ profile shapes from June and not from November, for which month the satellite data were chosen?

We thank the reviewer for pointing out this inconsistency. We have redone the figure using the November profiles.

- L. 313: can you please explain how this formula is derived?

Eq. 8 was derived by differentiating Eq.7 assuming that AMF_g and fr are independent variables and both depend on $\Delta(R_g)$. We clarified this in the manuscript.

- L. 355: please mention here that the background aerosols are included in the climatological LER, but are missing in the BRDF, so that the ECF from the BRDF has a low bias.

We added the following:

“It should be noted that the background aerosols are included in the climatological LER; therefore, they are virtually accounted for in the ECF derived using the LER climatology. The geometry-dependent LER is calculated for aerosol-free conditions, thus the corresponding ECF should have a bias.”

- L. 366: the use > to use

Done.

- L. 385: missing: Chandrasekhar

Done.

Figures and captions:

Fig. 1: please use larger font for lat/lon (like in Fig. 2). What is the spatial resolution of these maps?

Done, font size was increased. The spatial resolution of the maps is equal to the original resolution of the MODIS-derived BRDF product, i.e. 30 arc sec or about 1 km. We added this information to the figure caption.

Fig. 2: please use a, b, c for the subplots. This also holds for the other figures with 3 subplots.

Done.

Fig. 4: which orbit and date? With which LER figure should this be compared? RRS-derived > RRS-retrieved

Orbit 12414 of 14 Nov 2006. Data in Fig. 4 correspond to LER shown in Fig. 3 (b). We added this to the caption. Corrected.

Fig. 5: which orbit and date?

Orbit 12414 of 14 Nov 2006, now listed in the caption.

Fig. 7: please write out the caption.

Done.

For Fig. 7 and Fig. 9 please consider inverting the axes, thus from 1000 to 0 hPa, because that looks more natural (low clouds at the origin of the plot).

Done.

Fig. 9: Please use better caption; the reference to the caption of Fig. 5 leads to another reference to another caption. What are the straight lines in the left plot?

Changed to

“(a) Scatter plot of O2-O2-retrieved OCPs computed with geometry-dependent LERs versus climatological LERs, the 1:1 line is in black; (b) similar for $ECF < 0.25$ with linear fits; (c) the mean ECF difference (diamonds) and standard deviation (error bars) as a function of ECF; (d) normalized histograms of OCP.”

Fig. 10: reflectivity > surface reflectivity

Done.

Fig. 11: which orbit and date?

Orbit 12414 of 14 Nov 2006, now listed in the caption.

Fig. 12: please number the subplots. Please add LER, OCP, fr to the legend of the lower 3 subplots.

Done.

Fig. 13: which date and orbit?

Orbit 12414 of 14 Nov 2006 for data over America and orbit 12391 of 13 Nov 2006 for data over China, now listed in the caption.