Response to comment of Anonymous Referee #2 on "Restoring the top-of-atmosphere reflectance during solar eclipses: a proof of concept with the UV Absorbing Aerosol Index measured by TROPOMI" by Victor Trees et al.

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We thank the reviewer for his/her careful reading and for the comments and suggestions, which have improved the manuscript. Below, we give in *black italic* the reviewer's comment, in black our response, and in red the changed text in the manuscript.

The paper describes a method to correct TROPOMI/S5P observations during solar eclipses. The shadow of the moon reduces the incident irradiance. In the derivation of reflectances from this observations the irradiance of non-eclipse conditions is used, therefore these reflectances are wrong and retrieval algorithms using these reflectances yield wrong results. Therefore observations during eclipses are currently not used for further analysis. The observations can be corrected quite easily by using the reduced incident irradiance to derive the reflectance. Consistently with other studies, it is shown that in order to compute the reduced irradiance it is important to take into account the solar limb darkening. The authors derived such a correction method and apply it to the derivation of the aerosol absorption index. Using the corrected reflectances they obtain reasonable results also during the eclipse which are consisted with observations derived in non-eclipse conditions. Satellite based aerosol and trace gas measurements my reveal interesting effects of the solar eclipse on the composition of the atmosphere, however this is not investigated in the study. The paper is generally well written in good English and the number of figures is appropriate. I recommend publication in ACP after some revisions as suggested in my comments below.

General comments:

- *In the paper the method to correct observations during solar eclipses is described. It is mentioned in the introduction that corrected observations can be used to study effects of the solar eclipse on atmospheric composition. I suggest to include such a study, this would increase the scientific relevance of the paper significantly.*

  We agree with the reviewer that the application of the reflectance correction to trace gas products is of scientific relevance. The goal (and title) of this paper, however, is to show that the TOA reflectance during solar eclipses can be restored, which is proven with the application to the AAI product. Applying the correction to a trace gas product is another application of the method presented in this paper, and is therefore beyond the scope of this paper.

The AAI was the most straightforward product for such a proof of concept, because the AAI depends on the absolute reflectances at only the two wavelengths 340 and 380 nm. The retrieval of a trace gas product such as the NO2 column is based on the differential features on a fitted polynomial through the UV-VIS reflectance spectrum. We note that the accuracy of such an eclipse corrected retrieval may depend on the accuracy and wavelength resolution of the solar limb darkening measurements. Also, high wavelength resolution solar spectrum features that are not captured by the solar limb darkening measurements have to be taken into account in the retrieval. We leave this challenge for a future study, but added the following sentence to the Discussion:

l.462: "However, high wavelength resolution solar spectrum features that are not captured by the solar limb darkening measurements may have to be taken into account in the retrieval."

– *Motivate, why it is interesting to study solar eclipses and their effects on atmospheric composition. In the abstract it is written that it is "may be of particular interest", this sounds as if the authors do not know themselves whether it is really interesting ...*

Using the restored measurements during solar eclipses, our conceptual understanding of the atmospheric response (e.g. solar eclipse induced absorbing aerosol changes or atmospheric chemistry changes) can be enhanced. In this paper, we did not find an indication of absorbing aerosol changes in the Moon shadow (e.g. that are spatially correlated with the recent eclipse ground track). Restored measurements of a trace gas product can be used to potentially detect such eclipse induced trace gas changes and possibly to verify irradiation responses in atmospheric chemistry models.

We changed the sentence in the third paragraph of the Introduction:

l.42: "Studying the speed and significance of this atmospheric response could contribute to the understanding of the sensitivity of planetary atmospheres to (variations in) their irradiation." -> "Measurements of the speed and significance of this atmospheric response could contribute to the understanding of the sensitivity of planetary atmospheres to (variations in) their solar or stellar illumination and could possibly be used to verify atmospheric chemistry models."

We changed this sentence in the Abstract:

l.6: "... may be of particular interest to users studying solar eclipses and their effect on the Earth's atmosphere." -> "... is of particular interest to users studying the atmospheric response to solar eclipses."

We added this sentence to the Abstract:

l.15: "No indication of local absorbing aerosol changes caused by the eclipses was found."

We added this sentence to the Conclusion:

l.489: "In this paper, we did not find an indication of absorbing aerosol changes in the Moon shadow (e.g. which are spatially correlated with the recent eclipse ground track)."

– *How important is this correction method? How frequently are the observations disturbed by solar eclipses?*

Every year, there are about 2 to 3 solar eclipses (with a yearly average of 2.4 solar eclipses)[1]. Since the start of the nominal operational mode of TROPOMI in May 2018, 7 solar eclipses occurred, 6 of which have been measured by TROPOMI. In the paper, in the second paragraph of the Introduction, we mention that, sometimes, such eclipse anomalies propagate into anomalies in temporal average maps without raising an eclipse flag, potentially resulting in false conclusions about the mean aerosol effect in that time period. An example of a *monthly average* AAI map of the GOME-2 satellite instrument that is distorted by a solar eclipse can be found on https://d1qb6yzwaaq4he.cloudfront.net/airpollution/absaai/GOME2B/monthly/images/2019/GOME-2B_AAI_map_201912.png. The formulae in the Appendix of this paper can also be used to only compute an eclipse flag. Indeed, an eclipse flag computation is not new and the eclipse anomalies could be omitted by raising an eclipse flag and discarding the data, however, the advantage of a correction is that data is not lost and can potentially be used to study solar eclipses from space. In addition, the successful correction shows that the physics of the shadow is understood.

We have added the following sentence to the second paragraph of the Introduction:

l.28: "Since the start of the nominal operational mode of the TROPOMI spectrometer instrument on board the S5P satellite in May 2018, 7 solar eclipses occurred, 6 of which have been measured by TROPOMI."

We have changed the last sentence in the second paragraph of the Introduction:

l.37: "Sometimes, such eclipse anomalies propagate into anomalies in temporal average maps without raising an eclipse flag, potentially resulting in false conclusions about the mean aerosol effect in that time period." -> "TROPOMI data contains an eclipse flag indicating the eclipse occurrence at a ground pixel. For satellite instruments that do not contain an eclipse flag, such as the GOME-2 instrument, these eclipse anomalies propagate into anomalies in temporal average maps, potentially resulting in false conclusions about the mean aerosol effect in that time period."

Also, we have added the following footnote to the second paragraph of the Introduction:

l.37: An example of a *monthly average* AAI map of the GOME-2 satellite instrument that is distorted by a solar eclipse can be found on https://d1qb6yzwaaq4he.cloudfront.net/airpollution/absaai/GOME2B/monthly/images/2019/GOME-2B_AAI_map_201912.png, visited on 22 February 2021.

Specific comments:

- *l.1 "Solar eclipses reduce the measured top-of-atmosphere (TOA) reflectances as derived by Earth observation satellites, because the solar irradiance that is used to compute these reflectances is commonly measured before the start of the eclipse." -> This sentence in the beginning is a little confusing, rephrase? First mention that solar irradiance is reduced in moon shadow. Then mention, that normalized quantity "reflectance" should not be affected when reduced irradiance is used for normalization and write that this is not yet done in the operational processing of the data ...*

We thank the reviewer for this suggestion. We changed the sentences, l.1:

[1] See https://eclipse.gsfc.nasa.gov/SEpubs/5MCSE.html, visited on 26 March 2021.

"Solar eclipses reduce the measured top-of-atmosphere (TOA) reflectances as derived by Earth observation satellites, because the solar irradiance that is used to compute these reflectances is commonly measured before the start of the eclipse. Consequently, air quality products that are derived from these spectra, ..." ->

"During a solar eclipse the solar irradiance reaching the top-of-atmosphere (TOA) is reduced in the Moon shadow. The solar irradiance is commonly measured by Earth observation satellites before the start of the eclipse and not corrected for this reduction, which results in a decrease of the computed TOA reflectances. Consequently, air quality products that are derived from TOA reflectance spectra, ..."

– *l.12 "in a maximum Moon shadow signature in the AAI of 6.7 points increase" -> what is a "point"?*

The AAI is a dimensionless quantity. We often use often 'points' as a 'placeholder unit' for the AAI because it helps in the communication, similar as 'percent points'.

– *l.206: "We provide the recipe for the computation of X ... "-> Have you compared your derivation to that presented in Ockenfuss et al. 2020?*

The definition of X in this paper is equivalent to the one used in the paper of Ockenfuß et al. (2020). Ockenfuß et al. (2020) retrieved emphemeris data for the Sun and the Moon from a JPL database (Giorgini et al., 1996), in order to compute X. We use the Besselian elements precomputed for each eclipse by NASA in order to compute X based on the work of Meeus (1989), Seidelmann (1992) and Espenak and Meeus (2006), as explained in the paper. We did not compare our computation of X to the one of Ockenfuß et al. (2020), because that would be a comparison of the astrodynamical calculations of Meeus (1989), Seidelmann (1992) and Espenak and Meeus (2006) to the calculations of Giorgini et al. (1996). We verified the ground track of $X = 0$ to the benchmark results published by NASA, as mentioned in the last two sentences of Section 2.

– *l.293: "The maximum underestimation of f_o at 380 nm, when using Γ = 1, was 0.06 at 6.04°N latitude and 107.19°E longitude." -> What is the maximum underestimation when limb darkening is taken into account ...*

The underestimation is with respect to the computed f_o at 380 nm taking into account solar limb darkening. To clarify this, we changed the sentence:

l.287: "The maximum underestimation of f_o at 380 nm, when using Γ = 1, was 0.06 at 6.04°N latitude and 107.19°E longitude." -> "The maximum underestimation of f_o at 380 nm when using Γ = 1, with respect to f_o at 380 nm when solar limb darkening is taken into account, was 0.06 at 6.04°N latitude and 107.19°E longitude."

– *l.318: "The negative mean AAI are partly caused by the scattering of cloud droplets, but also due to a radiometric calibration offset and degradation in the TROPOMI irradiance data ..." -> Please explain: 1. Why is AAI negative for cloud scattering, 2. Why is there a radiometric calibration offset, 3. Why is there a degradation in the TROPOMI irradiance data.*

1. The negative AAI due to cloud droplets (scattering aerosols) is explained in Section 3.3 of de Graaf et al. (2005): scattering aerosols generally increase the reflectance measured at 380 nm, resulting in a relative high computed scene albedo A_s (Eq. 17 of our paper). Therefore, the spectrally flat surface contribution in the DAK model is relatively high, resulting in a relatively flat UV model spectrum ($R_{340}^{\mathrm{model}}/R_{380}^{\mathrm{model}} \approx 1$). This model spectrum may even be more flat than the measured spectrum, which particularly happens in scenes with intermediate effective cloud fractions (i.e. intermediate geometrical cloud fractions or thin clouds, see Penning de Vries et al. (2009)). Hence, $R_{340}^{\mathrm{meas}}/R_{380}^{\mathrm{meas}} < R_{340}^{\mathrm{model}}/R_{380}^{\mathrm{model}}$ results in a negative AAI (Eq. 17 of our paper). Because the focus of this paper is on the solar eclipse signature, we refer the reader in the first paragraph of Section 3.1.3 to the above mentioned articles for the explanation of the sensitivity of the AAI to scattering by cloud droplets.

2. and 3. During in-flight commissioning some inconsistencies in the on-ground calibration results were found, which concern mainly the absolute irradiance radiometric calibration. In addition, the TROPOMI instrument properties change over time, such as the diffuser degradation or the gain drift of the CCD detector output nodes. More details about the offset and degradation, and the corrections that are applied for the planned version 2 of the L1b processor, can be found in Ludewig et al. (2020).

We have added the reference to Ludewig et al. (2020) to line 328:

l.328: Ludewig et al., (2020)

– *Fig.16: I have a general question about the interpretation AAI. It seems that in the figure most higher values of AAI are not due to aerosols but due to clouds and sunglint? Also values seem to be higher towards the edges of the orbit, are these AAI values correct? Can you indicate an area in the figure which clearly shows an increased AAI due to the presence of aerosol?*

Figure 16 does not contain regions where absorbing aerosols can clearly be identified. Indeed, the most significant AAI features in Fig. 16 are due to the sunglint and clouds (see Kooreman et al., 2020, for the effect of the glint and large-scale clouds on the AAI). An example of an AAI map in which absorbing aerosols are detectable is shown in Figure 1, which we discuss in the Introduction. We have added the following sentence:

l.336: "We note that no significant absorbing aerosol events can be identified in Figure 16."

The AAI indeed slightly increases toward the eastern edges of the orbit swaths at some latitudes. Here, the viewing zenith angles are relatively large. The AAI is based on a comparison of the measured UV reflectances to the UV reflectances modeled by the radiative transfer model DAK, the latter ones being an approximation of reality. de Graaf et al. (2005) showed that the AAI and its accuracy depend on the zenith angles when an absorbing aerosol layer is present (see their Figure 1). An additional possible reason for the AAI increases at some parts of the edges may be the presence of clouds. Although clouds generally decrease or neutralize the AAI (see previous comment), Kooreman et al. (2020) show that anisotropic scattering of light by clouds may increase the AAI at large viewing zenith angles and at the viewing zenith angle where the cloud bow occurs. These effects, however, also depend on the solar zenith angle and relative azimuth angle of light scattered by the cloud droplets. We refer to Kooreman et al. (2020) for more details.

– *l.385: "at 36°-42°N latitude and 78°-86°E longitude" -> could you mark this region in Fig.20?*

  We have marked the region in Fig. 20 and in Fig. 21 of the paper as shown in Figures 1 and 2 of this document, respectively.

– *l.440: "Hence, the solar irradiance correction of this paper could be used to potentially prove that the yellow and orange colors in satellite images are indeed caused by solar limb darkening." -> Can you try this and include a corrected image? This should not be much work?*

  It would be interesting to prove that the yellow and orange colors in VIIRS and/or MODIS true color satellite images are caused by solar limb darkening (TROPOMI does not measure at the green wavelengths and therefore has no true color product). This activity, however, is another application of the eclipse corrected reflectances and therefore beyond the scope of this paper. Indeed, in principle, such an application could be straightforward, but would require a proper implementation and discussion of the reflectance correction in the true color algorithms of VIIRS and/or MODIS, having their own post-proccesing steps that should carefully be considered (for example, the true color images found on https://worldview.earthdata.nasa.gov are actually corrected for Rayleigh scattering). In order for the paper not to loose focus, we leave this application for a future study.

Technical corrections:

– *l.17: "can be used to detect real AAI rising phenomena ... " -> "can be used to detect real AAI rising phenomena during a solar eclipse ... "*

  We have changed the text as suggested. l.17: "... can be used to detect real AAI rising phenomena ..." -> "... can be used to detect real AAI rising phenomena during a solar eclipse ..."

– *l.90: "and on phi-phi0" -> mention that if 3D effects matter the absolute azimuth angles need to be taken into account*

  Indeed, in case of azimuthally asymmetric reflecting objects such as 3D cloud structures, the reflectance depends on the absolute azimuth angles. We generalized the sentence such that it applies to all types of reflectors. l.92: "... and on $\varphi_0 - \varphi$ which is the viewing azimuth angle relative to the solar azimuth angle." -> ...", on the viewing azimuth angle φ and on the solar azimuth angle φ_0."

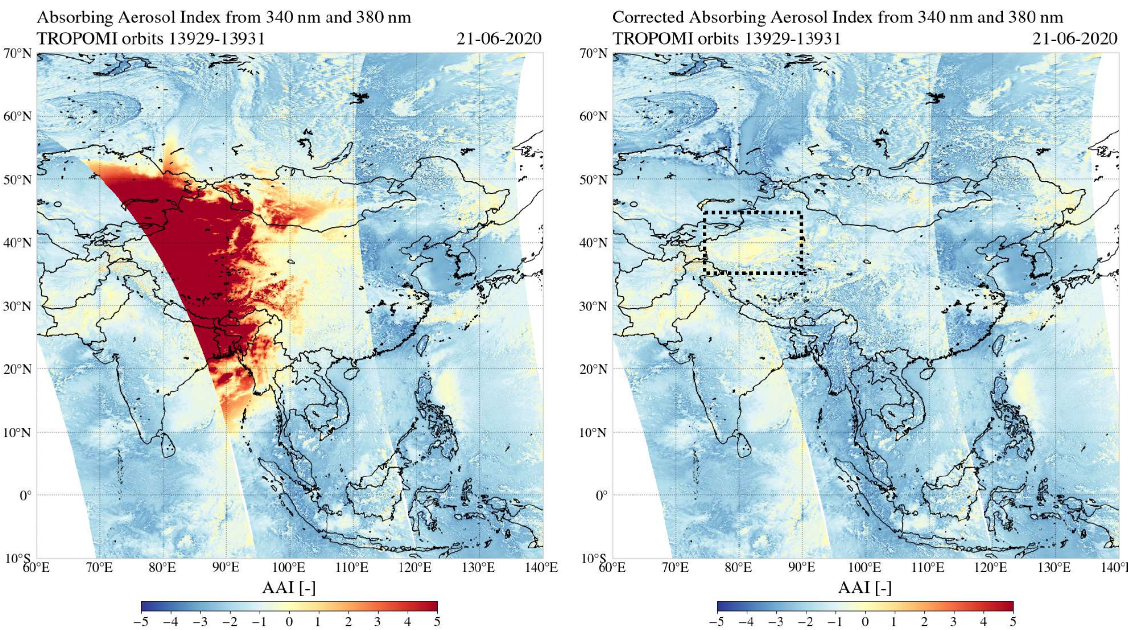

Figure 1. The Absorbing Aerosol Index from the 340/380 nm wavelength pair by TROPOMI on 21 June 2020 over Asia in orbits 13929-13931, uncorrected (left) and after the solar irradiance correction (right). In the corrected image, the Taklamakan desert is located in the rectangular dotted box.

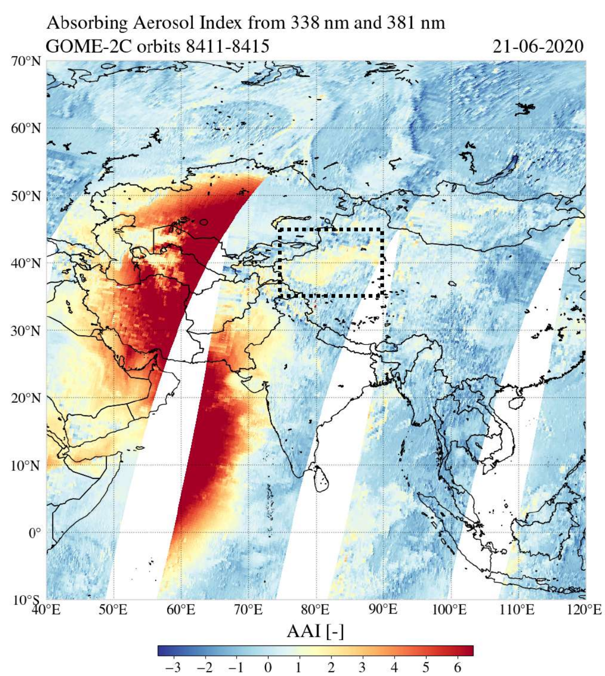

Figure 2. The Absorbing Aerosol Index from the 338/381 nm wavelength pair by GOME-2C on 21 June 2020 over Asia in orbits 8411-8415. The Taklamakan desert is located in the rectangular dotted box.

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