Response to the Anonymous Referee #2 comments for the manuscript "Retrieval of aerosol properties using relative radiance measurements from an all-sky camera" By Roberto Román et al. in AMTD

First, we are grateful for the effort of referee #2 and his/her review in detail. Reviewer comments are in black font (RC), and author comments (AC) in red font.

Author's answer to Anonymous Referee #2

General comment

RC: The manuscript covers aerosol retrievals using normalized radiances from an all-sky camera (simulated and measured) and the GRASP algorithm. The study has been very thoroughly performed and described, and presents interesting and relevant results regarding generalizing all-sky cameras (or normalized radiances) towards aerosol retrievals. The subjects also fits the scope of the journal and I recommend its publication, with some very minor comments.

Specific comments

RC: P4, L117. Is there a reference, where the hybrid geometry is described in more detail?
AC: Section 2.1.2 refers to the hybrid scan as first time. Here, the reference of Sinyuk et al. (2020) is included. Section 4 of Sinyuk et al. (2020) describes in detail the geometry of hybrid scan. It has been added in the new manuscript version:

"The chosen geometry to extract relative radiances is the AERONET hybrid geometry (see Section 4 of Sinyuk et al., 2020) –rejecting the angles over the banned areas–, since this geometry allows long scattering angles even for low SZA values and it presents a symmetry with respect to the Sun position which is useful for cloud-screening."

RC: P7, L192pp. I think the explanation of NSR sensitivity to AOD with dominance of aerosol scattering (Rayleigh vs. aerosol) is not very convincing (wouldn't this AOD sensitivity be the same in an atmosphere without Rayleigh?). Maybe it is because the normalization factor (sum over all radiances) increases with AOD and reduces the relative differences in NSR.
AC: The sensitivity of NSR to AOD has been studied for an atmosphere without Rayleigh in order to support our hypothesis. The same simulations shown in Figure 2 have been obtained with GRASP forward module but assuming no Rayleigh atmosphere. Figure R1 shows the obtained values for three aerosol types (Figure R2 shows all aerosol types). As result, we can observe that normalized radiances do not present a clear dependence on AOD load as it happens in the real atmosphere (Rayleigh + aerosol) at least for low aerosol loads (Figure 2 of the manuscript). In fact, all NSR values of Figure R1 are like the ones obtained in Figure 2 for high AOD loads (dominance of aerosol scattering). All

these results support our hypothesis about AOD sensitivity in the range between pure Rayleigh and pure aerosol.

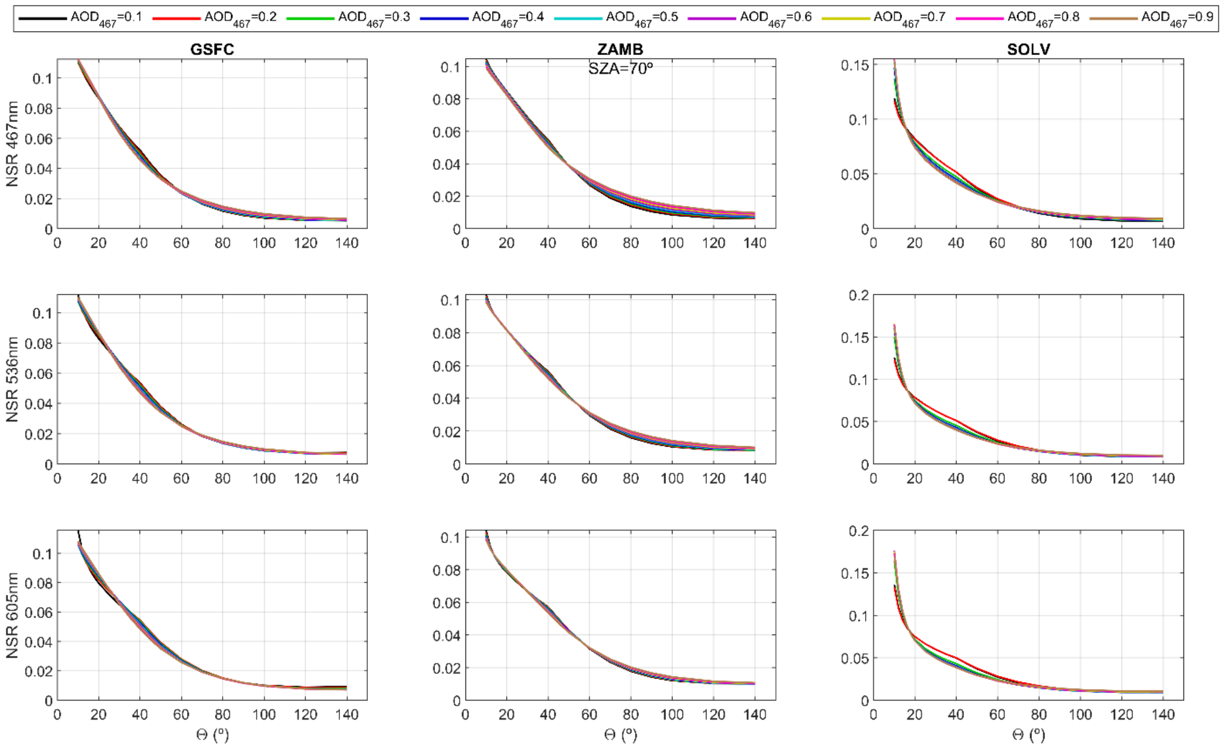

Figure R1: Normalized sky radiance (NSR) for solar zenith angle (SZA) of 70º at: 467 nm (top row), 536 nm (middle row) and 605 nm (bottom row), as a function of scattering angle (Θ) for different AOD (at 467 nm) values. Left, middle and right columns correspond to GSFC, ZAMB and SOLV aerosol models, respectively, under an atmosphere without Rayleigh scattering.

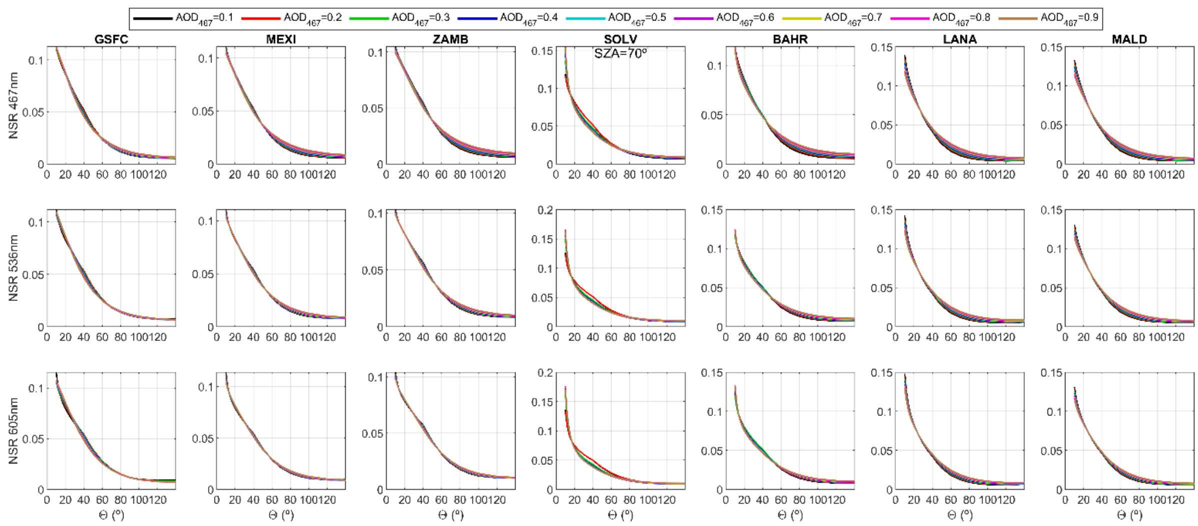

Figure R2: Normalized sky radiance (NSR) under a solar zenith angle (SZA) of 70º at 467 nm (top row), 536 nm (middle row) and 605 nm (bottom row) as a function of scattering angle (Θ) for different AOD (at 467 nm) values and for nine aerosol models under an atmosphere without Rayleigh scattering.

Regarding the normalization factor, it has been represented in Figure R3 for all the conditions used in the paper as a function of AOD. As can be observed, especially for SZA=70º, this normalization factor is not increasing always with AOD. Therefore, we have discarded the hypothesis suggested by the reviewer.

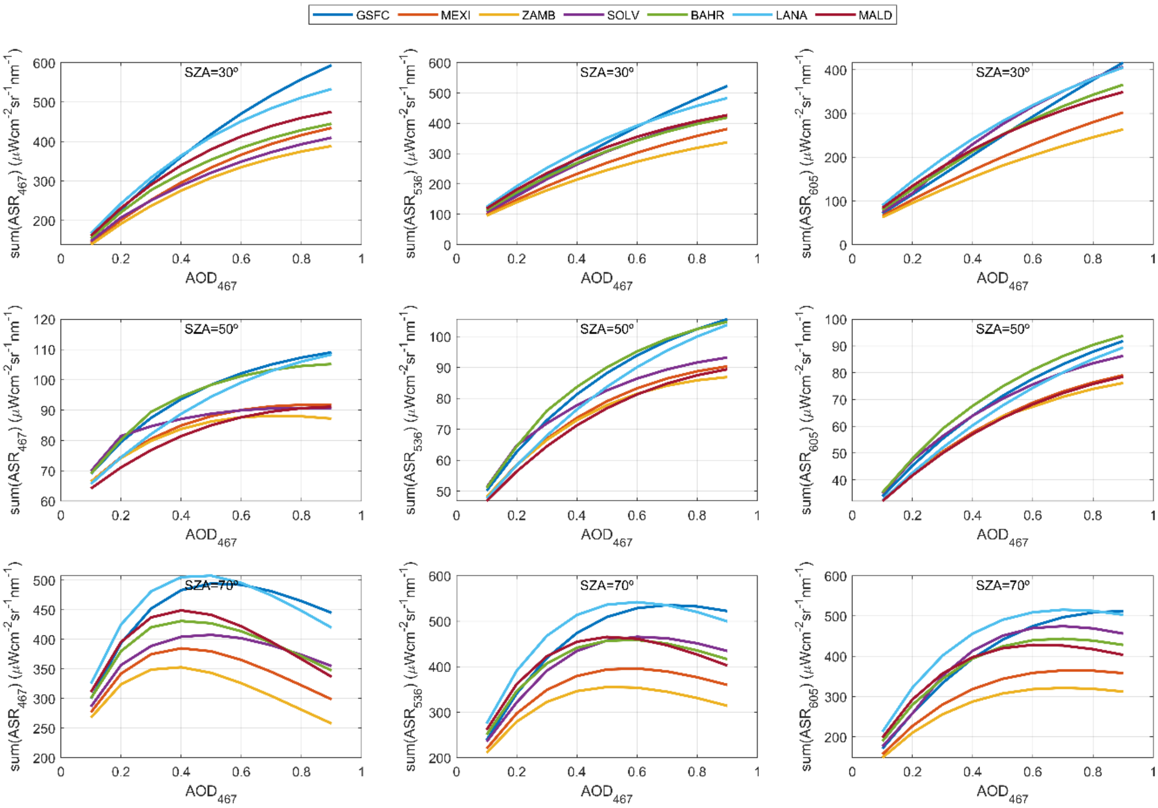

Figure R3: Normalization factor, sum of all sky radiances, to normalize sky radiances at 605, 536 and 467 nm, as a function of AOD (at 467 nm) values and for nine aerosol models under a solar zenith angle (SZA) of 30º, 50º and 70º.

Finally, to clarify these results, Figure R2 has been added as supplementary material (Figure A5) and the following text has been included:

"To confirm the proposed explanation, the same simulations as in Figure 2 (and Figure A1) have been calculated but considering an atmosphere without Rayleigh scattering in GRASP. These NSR simulations are shown in Figure A5 and point out that NSR does not significantly depend on AOD when Rayleigh scattering is negligible, even for low AOD values, showing always similar values than the ones observed in Figure 2 (and Figure A5) for high AOD values; this result supports our hypothesis. Finally, multiple scattering and surface albedo also affect NSR but their impact on NSR is small, at least for the analyzed aerosol loads"

RC: Fig 2. What is the reason for the "kinks" in the radiances at around 40° scattering angle? If I am not mistaken, these features do not appear in almucantar scans (radiance plotted against azimuth not scattering angle).
AC: Reviewer is right, this strange behaviour (kinks or smoothness break points) is not observed in a standard cloudless almucantar scan, either as function on scattering or

azimuth angle. However, we are dealing with hybrid scans. To have a better idea about how this scan works, we recommend observing Figure 1 of the present paper and Figure 12 of Sinyuk et al. (2020). When the SZA is above 75º, the hybrid scan starts pointing the sky angles from sun aureole and then it goes increasing the azimuth and zenith angle until the zenith is 75º (sun altitude below 15º). After reaching the elevation angle of 15º the scan further proceeds at a fixed zenith angle by varying the azimuth angle similarly to that of an almucantar scan except that the view angle is not equal to the SZA (Sinyuk et al., 2020). The observed kinks appear just in the change of scanning when the elevation of 15º is reached. This change produces the change in the variation of sky radiance with scattering angle. The view scattering angle when hybrid scan reaches elevation angle of 15º (where kinks should appear) depends on SZA (lower SZA, higher scattering angle); this can be observed in Figures A2 and A3.

RC: P9, L218. So the noise in the synthetic data is the same as stated on p5, L128? Also, what is distribution of the random noise? I would guess normal, but it should better be stated.
AC: Yes, the noise is the same as stated on L128, and the distribution is normal. We add in the new manuscript that the noise distribution is Gaussian:

"To obtain more realistic results, random noise (Gaussian distributed) has been added to each simulated sky radiance in accordance with the NSR uncertainty of the camera product (see Section 2.1.3)."

RC: P11, L258. It works surprisingly well for SZA=30°, considering AERONET limit of 50° (is that correct?) with almucantar measurements only. So the hybrid scan seems effective at small SZA.
Would this mean that really most of the information is in the small scatting angles, <100°?
AC: Yes, it works well for low SZA values, this is the advantage of hybrid scan compared to almucantar. Hybrid scan can reach higher scattering angles even for low SZA values. Almucantar scans cannot do that. Sinyuk et al. (2020) remarked that: *"for a hybrid scan made at 25º SZA the scattering angle range of measurements is 100º, which is the same scattering angle range that the almucantar scan is capable of at 50º SZA"*. The limit of 50º of AERONET is for almucantar scans, but AERONET is also using now hybrid scans, extending the quality assurance of the derived products until SZA values of 25º. It is explained by Sinyuk et al. (2020): "*hybrid SSA retrievals for dust aerosols exhibit smaller variability with solar zenith angles (SZAs) than those of almucantar, which allows extension of hybrid SSA retrievals to SZAs less than 50º to as small as 25º."*

Each scattering angle range provide different information. In the present work we observed how the low scattering angles contain valuable information about the coarse mode. The AERONET criteria consider that a SSA retrieval with assured quality must include at least scattering angles up to 100º.

RC: Fig. 5. I am wondering if the higher deviations of the retrievals towards higher AOD, could also be due to (or at least affected by) the lower number of successful retrievals, i.e. a statistical effect. Of course, the retrieval success decreases due to decreasing sensitivity to AOD.

AC: This is an interesting issue, however, the deviations on all AOD values also increase from AOD=0.1 to AOD=0.4, and in this range the number of successful retrievals does not show any significant variation. The main problem is not only the deviation, which could be higher for the low number of data, it is also the median values, which represents the accuracy, and they reach high absolute values for high AOD loads.
A similar analysis of Figure 5 has been done but not considering more than 200 successful retrievals. It is shown in Figure R4. In this case we can observe how the deviation is similar for low AOD values even with less successful retrievals. It indicates that the results could be significant even when the number of successful retrievals available is low for high AOD values.

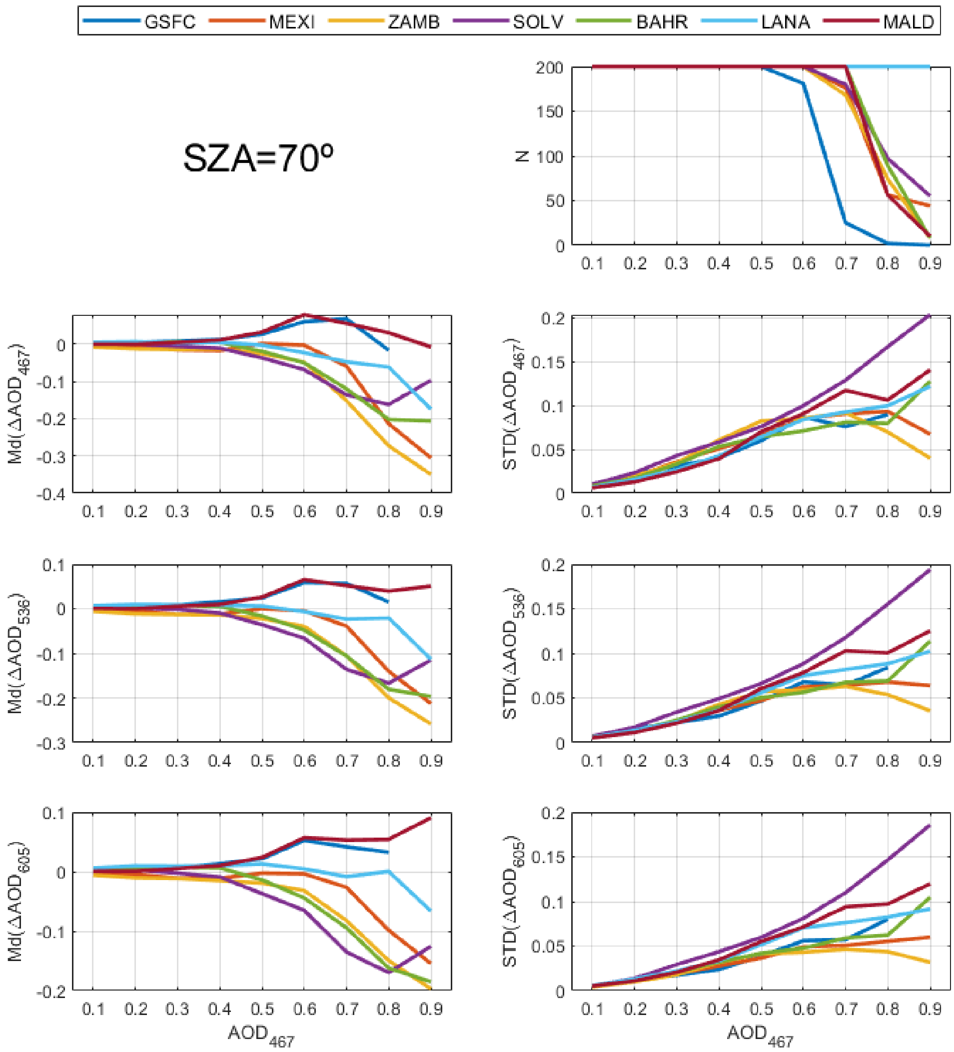

Figure R4: Median (Md) and standard deviation (STD) of the Δ differences between the available retrieved aerosol properties with noise perturbed radiances, and the original (reference) properties. The amount of available retrievals (N) is also shown. Only the retrievals with solar zenith angle (SZA) equal to 70º are used. The aerosol properties provided are: aerosol optical depth (AOD) at 467 nm (AOD_{467}), 536 nm (AOD_{536}) and 605 nm (AOD_{605}). The Md and STD are represented as a function of (AOD_{467}) for different aerosol types. A maximum of 200 successful retrievals have been used.

RC: Since the STD is really interesting in relation with the Md (e.g. is ΔAOD=0 within the errorbar also for high AOD?), I believe it would be a good alternative to combine right and left columns of the plots and plot STD as error bars (or uncertainty bands) for Md. Maybe with a second uncertainty of the mean MD/sqrt(N), N successful retrievals. This will be too much for all scenarios in one plot, so this would need a different grid of plots. Might be worth a try.

AC: We agree with the reviewer, and we would like to plot standard deviation as an errorbar. However, if this is done, only one type of aerosol could be represented in each panel, because part of the data and the error bars would overlap each other, making graphs very confusing. Putting only one aerosol type on each panel, then we would have to make many more graphs (3.5 times more). This makes the panels much smaller, and also does not allow us an easy comparison of the results between aerosol types. An example has been represented in Figure R5, with the standard deviation represented as a shadow. In this case we also have no space to represent the number of data. All these issues have made us decide to keep the Figure 5 and 7 as they were in the previous version.

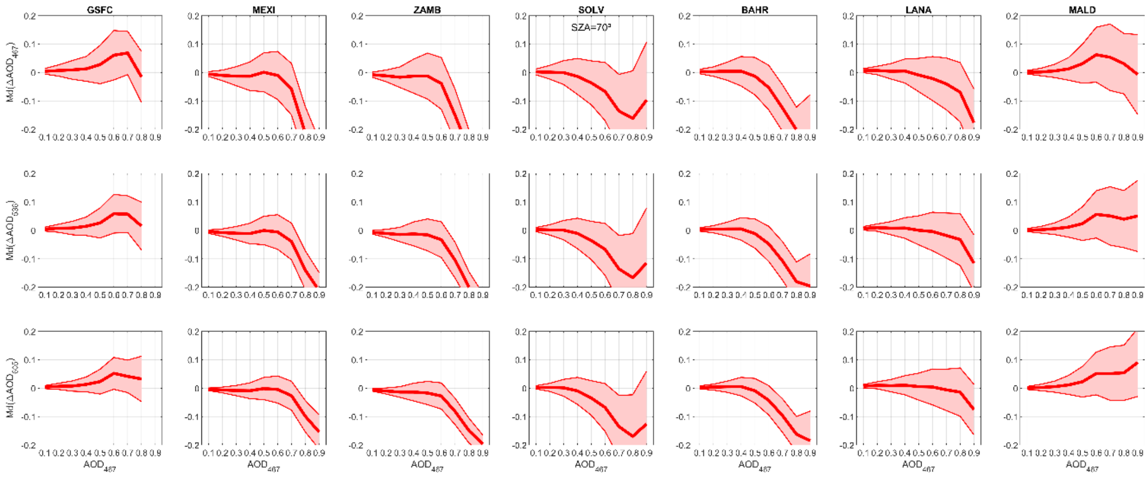

Figure R5: Median (Md) of the Δ differences between available retrieved aerosol properties with noise perturbed radiances, and the original (reference) properties as a function of (AOD_{467}). Only the retrievals with solar zenith angle (SZA) equal to 70° are used. The aerosol properties provided are: aerosol optical depth (AOD) at 467 nm (AOD_{467}), 536 nm (AOD_{536}) and 605 nm (AOD_{605}). ±standard deviation is added as a shadowband.

RC: Fig. 6 As a general question: If red is the median of noise retrievals, I would expect red and blue line to be very similar (as the retrieval input, the median of noised radiances should be the radiance without noise). This is almost always true except for the coarse mode of MALD. Any idea why?

AC: It is true that the mean of all NSR measurements calculated with noise should be equal to the NSR without noise. However, it cannot be extrapolated to the retrieved properties. The relationship between changes on NSR measurements and changes on aerosol properties is not linear, since the inversion process is more complex. Hence, in the case of MALD the differences between retrieved with and without noise can be related to the lack of information about coarse mode in the used NSR measurements (scattering angles above or equal 10º); in the case of MALD it is compensating a lower σC value with a higher VCC. In Figure A21 of the older version, the same size distributions are shown but retrieved with lower scattering angles (more coarse mode information), and the mentioned differences between retrieved with and without noise disappear. In addition, in the Figure A20 of the older version, the differences on the coarse mode of the size distributions between retrievals with and without noise are also significant in other aerosol models like LANA or SOLV.

RC: Fig.7. Again, as for Fig.5, I think it would better if Md and STD are plotted together.
AC: We have the same problem than in Fig. 5 (discussed above) and, hence, we have decided not to modify this figure.

RC: Fig. A33. There is actually quite little one can read from this plot of the complete time series. On this time scale, it would be easier to visualize aggregate values, e.g. monthly means.
AC: The main objective of this image is to give a broad vision of the amount of data that has been obtained with GRASP-CAM and to observe how they correlate with AERONET values during the more than two years. The monthly mean (and their standard deviation) values of AOD from GRASP-CAM and AERONET are shown in Figure R6, where we can observe how both data series correlate in time. However, our paper is focused on the performance of the instantaneous AOD obtained by GRASP-CAM, and hence, we think it is more in agreement with the figure of the previous version than with Figure R6.

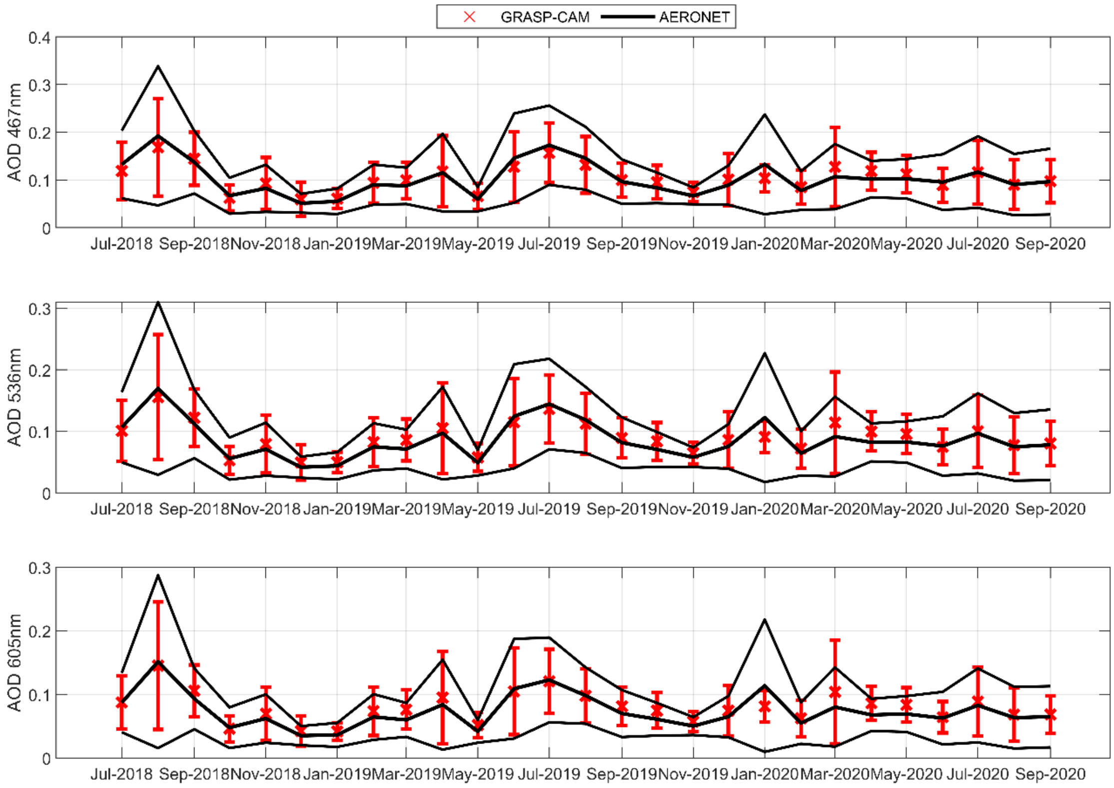

Figure R6: Monthly means (±standard deviation) of aerosol optical depth (AOD) at 467 nm (upper panel), 536 nm (middle panel) and 605 nm (bottom panel) retrieved by GRASP under single-pixel approach (GRASP-CAM) and by AERONET at Valladolid from July 2018 to September 2020. AERONET data have been interpolated to the all-sky camera wavelengths.

RC: Finally, the manuscript can in general be improved with respect to English grammar / language. For example, missing articles: P1, L1. the GRASP code. P1,L8. As a result.
AC: We have tried to improve English in the last version of the manuscript, including both reviewer suggestions about missing articles.