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Retrieving UV-VIS Spectral Single-scattering Albedo of Absorbing Aerosols above Clouds from Synergy of ORACLES Airborne and A-train Sensors

Jethva et al.

Review round # 2

Response to the Anonymous Referee # 1

We thank and appreciate the anonymous reviewer for taking the time to review our revised manuscript and offering constructive and valuable comments and suggestions.

The following are the one-to-one responses to a couple of comments made by referee # 1.

Referee comment **RC in RED**
Author's response **AR in BLACK**

RC: In Figure 9, when comparing 9a and 9b using different aerosol models, why does the total number of collocated data points change? It seems Figure 9b missed the data at Sep. 12, and it would affect the statistics. Is there any criteria used to keep the quality or reliability of the retrieval? An apple-to-apple comparison is required to give valid conclusions.

AR: The total number of collocated data points changed from N=23 (Figure 9 a) to N=20 (Figure 9 b) due to the change of the aerosol model, in which the latter aerosol model could not retrieve SSA at 388 nm due to an out-of-bound issue. The revised aerosol model with the relative spectral dependence between the two near-UV wavelengths could not resolve the observations within the aerosol-cloud look-up table. No criteria adopted in retrieving the data shown in Figure 9, where retrieved values for all AODs and CODs are included.

To make both datasets/plots equivalent in terms of the number of matchups, we have excluded the three additional collocated data points from Figure 9 (a) and included a revised figure (along with statistics) in the manuscript as well as shown in this report.

RC: The additional Tables 3-6 provided important and helpful information, but they look cumbersome and I suggest the authors to make them more concise.

AR: We have considered the referee's suggestion and combined Tables 3 and 4, and Tables 5 and 6, showing the error matrix of the retrieved SSA at 388 nm (OMI) and 470 nm (MODIS) in the same table. The revised format looks modular and facilitates a direct comparison of errors at 388 nm and 470 nm to various sources of uncertainties in the algorithmic input parameters.

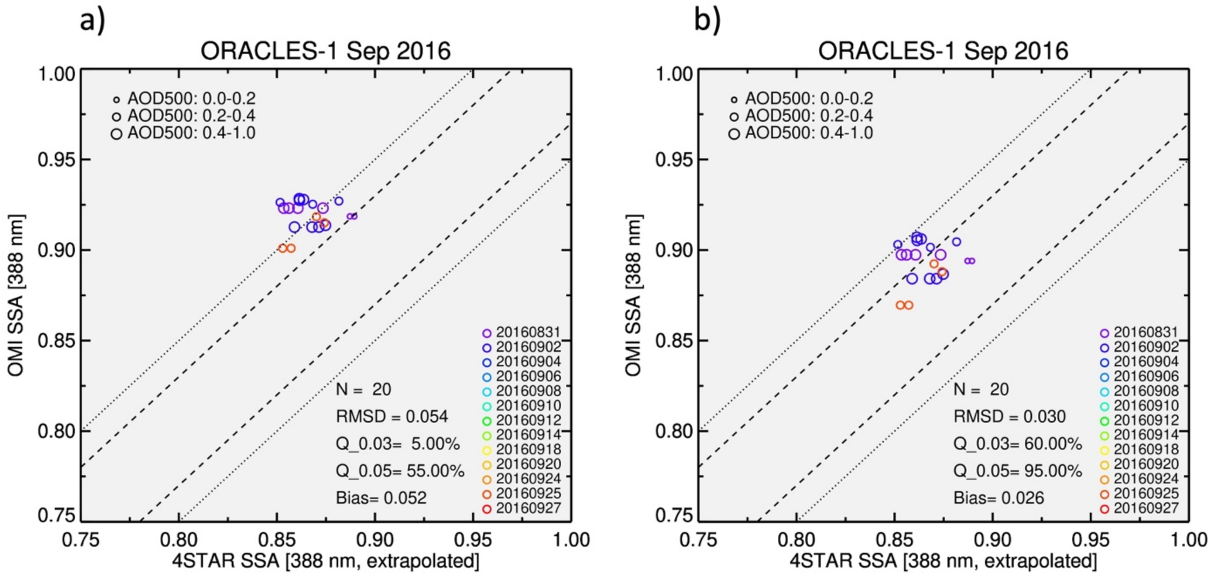

Figure 9. Comparison of spatiotemporally collocated above-cloud aerosol SSA retrieved from OMI (388 nm) against those derived from 4STAR sunphotometer sky scan observations for the ORACLES-1 September 2016 campaign. The OMI SSA retrievals using the original aerosol model (a, left) with 20% relative spectral dependence in the imaginary part of the refractive index (AAE ~2.45-2.60) and modified aerosol model (b, right) with 10% spectral dependence in the imaginary index (AAE ~1.72-1.87) are evaluated against those of 4STAR inversions. The Q_0.03 and Q_0.05 are the % matchups falling within the relative difference of ±0.03 and ±0.05, respectively. The OMI-4STAR matchups are color-coded according to the date of observations shown in legends. The sizing of the circles corresponds to the magnitude of coincident AOD (500 nm). The statistical measures of the comparison are printed in the lower left of each plot.

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Response to the Anonymous Referee # 2

Referee comment **RC in RED**
Author's response **AR in BLACK**

RC: The major changes requested in the first review are clearly not accepted by the authors. The response extensively explains why the original criticism should be ignored, instead of changing the manuscript. Of course, the authors know their work best and this may be the best way forward. However, the new manuscript contains new material that requires a careful consideration. It would not make sense to do this review again, knowing that it will not be accepted by the authors. Therefore, I suggest to look for new reviewers.

AC: The referee's comments on the response and revised manuscript look unreasonable. We have put our sincere efforts to address and include each of referee's comments and suggestions in the revision. The major change introduced in the revised manuscript after the first round of review was the change in the cloud model effective radius, which was adequately justified and described in the response as well as in the manuscript.

In the following response, we further clarify each of the comments and concerns raised by the referee and its consideration in revising our manuscript.

1) RC: "Second, the manuscript lacks a comparison with existing work. Section 6 is interesting, if it would be compared to what we already know. … The main conclusion of the section is this, which should be put in perspective: … "These results are significant and further signify the importance of aerosol absorption above clouds in the UV to VIS-NIR spectral region in at least two ways. First, aerosol absorption above clouds, if not accounted for in the remote sensing inversion, can potentially introduce a negative bias in the retrieved cloud optical depth retrieval, whose magnitude depends on the strength of aerosol 560 absorption (AAOD) and cloud brightness (COD) underneath the aerosol layer. " It would be nice to see how significant actually the results are, by comparing it with the expectations and results from earlier studies."

I suggest that you include some more discussion in the paper, either in a separate discussion section or by adding a paragraph to the conclusion section. Relating your work to previous findings and giving an outlook on additional work needed in the future would certainly improve your paper (see also the next two comments).

AC: We understand that the reviewer's comments are associated with section 6 describing the cloud optical depth (COD) retrievals. Let us emphasize here that our paper focuses on demonstrating the new retrieval technique to retrieve spectral aerosol SSA from space when combined with the independent direct measurements of aerosol loading above clouds. Of course, the aerosol-corrected CODs are also co-retrieved in this method. The purpose of adding a section on COD results was two-fold:

1) to show the impact of aerosol absorption effects on COD retrievals, which, if ignored, can introduce a significant bias in the cloud retrievals, as shown by other researchers in previous studies, and

2) to further parameterize the bias in COD values as a function of aerosol absorption effects on CODs. The latter results have shown us that given the same magnitudes of aerosol absorption above clouds, the magnitudes of bias in CODs depend on the true value of COD underneath the aerosol layer.

These results have important implications not just in cloud remote sensing but also in correctly estimating the aerosol radiative effects over clouds. Both these research topics are currently out of the scope of the present analysis, but they should be further investigated in depth in future studies.

2) RC: "Also, the sensitivity section is interesting and the amount of work is appreciated, it provides the necessary feel of the accuracy of the proposed method, and AMT is the right place for this kind of information. However, the provided tables of increased or decreased numbers of quantities are tediously repeated from the table into the text, and not compared to anything. It would quite interesting to have a few sensitivity studies from the RTM be compared to the retrievals. Then we could actually see if what is expected is also being found from the satellite measurements when aerosol properties are properly and sufficiently constrained from the aircraft campaigns, or that still more information is needed."

Here, it would probably be helpful to add some explanation at the beginning of Sec. 7 to motivate your approach. Even without performing additional sensitivity studies, some further discussion might be helpful (see my suggestion above).

AC: The sensitivity analysis entirely based on RTM simulations is a standard approach for quantifying the theoretical uncertainties in satellite-based inversions. On the other hand, quantifying the actual uncertainties involved in various assumptions made in the algorithm is a daunting task since the information on the true state of aerosol and cloud parameters is often unavailable. Therefore, we adopted another approach in which the RTM simulations, or aerosol-cloud look-up tables in the present context, were first carried out by considering uncertainties in different algorithmic assumptions individually. In the next step, the revised aerosol-cloud look-up tables were used in the inversion algorithm and applied to the actual airborne-satellite measurements. The resultant changes in the retrievals were then interpreted as the expected uncertainties in the retrieved spectral above-cloud aerosol SSA caused by realistic uncertainty in each algorithmic assumption separately. The suggested approach integrates different sets of RTM simulations and actual observations to derive realistic estimates of the errors in the derived aerosol SSA retrievals.

We have added the above description at the beginning of Section 7 in the revised paper.

Regarding the comment about "not compared to anything", we assume that the comment is related to the uncertainty estimates reported in the paper. Since the proposed retrievals of aerosol SSA above the clouds and associated uncertainty estimates are first-of-its-kind information from the satellite measurements, there aren't well established equivalent datasets available to facilitate a direct comparison. However, we already have made a reasonable effort to compare our satellite-based above-cloud aerosol SSA retrievals with the *in situ* measurements, airborne 4STAR sunphotometer-based SSA inversions made during the ORACLES campaign, as well as ground-based AERONET SSA datasets (Figures 8, 9, and 10). Overall, we find the satellite-based retrievals of SSA are found to compare well with these independent sets of measurements on an average sense, albeit all these SSA datasets do show some variability, which can be partly attributed to the inherent uncertainties involved in different techniques of measurements and inversion procedures.

3) RC: “Last, the manuscript lacks a proper motivation of the proposed synergy method. Obviously, the ORACLES data can only be used to test a proper constraint of the aerosol during the flights. CALIOP is mentioned as a replacement of the ACAOD measurements, noticing that (l776.) "CALOP [sic], OMI, and MODIS sensors fly in formation and make measurements within a few minutes of time difference.", in the present tense. The Calipso mission has ended and OMI is hardly producing useful measurements any more. Is the purpose to derive a SSA-over-cloud climatology from the past 10-15 years? Or can this also be applied to existing and future missions?

We have adequately responded to the referee’s comment during the first round of review. The response is added below for the reference.

AR: We believe the motivation for developing the proposed synergy method is adequately discussed in the Introduction section. The above-cloud AOD retrieved from the passive sensors (such as OMI & MODIS) using multispectral algorithms is sensitive to the choice of aerosol model, as shown in our previous publications as well as by others (e.g., Meyer et al., 2015). Of various assumptions made in the model, the single-scattering albedo, followed by the spectral dependence of absorption (or AAE), is known to be the largest source of uncertainty in the retrieved ACAOD. These uncertainties, if not addressed, can proportionately result in errors in above-cloud aerosol radiative effects. Radiative transfer simulations show that the top-of-atmosphere measurements are sensitive to columnar ACAOD, SSA, and COD. Therefore, constraining the ACAOD in the algorithm allows two-parameter retrievals of SSA and COD. To test our hypothesis and the proposed algorithm, we used direct airborne measurements of ACAOD collected during the ORACLES campaign synergized with the OMI and MODIS observations over the Southeastern Atlantic Ocean.

A successful application of the synergy algorithm to the ORACLES and OMI-MODIS observations opens a new opportunity to extend the algorithm to CALIOP-OMI-MODIS synergy. Yes, we acknowledge that the CALIPSO mission has ended, and its light was turned off sometime this summer. OMI on Aura is also heading towards the end of its life. So, the intended application of the proposed algorithm is to produce the past record of SSA above clouds from the coincident and overlapped period, i.e., 2006-2020.

RC: Or can this also be applied to existing and future missions?
AR: The proposed algorithm relies on accurate measurements of ACAOD for the retrieval of above-cloud aerosol SSA. The ACAOD algorithms applied to the existing passive sensors, such as OMI, MODIS, and POLDER, are dependent on the optical-microphysical models of aerosols. These retrievals carry errors due to the uncertainties in the assumed aerosol model. We’re unaware of any existing satellite sensor that provides direct measurements of AOD above the cloud. Regarding the future missions, an HSLR-2 like active lidar sensor onboard satellite mission would provide the desired direct measurements of ACAOD for the proposed SSA retrievals.

We direct the reviewer and the Editor to refer to the restructured sections 8.1 and 8.2 in the revised paper that discusses the potential application of the proposed synergy to the existing long-term A-train satellite record (CALIOP, OMI, and MODIS), and future satellite missions, such as NASA’s AOS and ESA’s EarthCare.

RC: I feel there is an increased interest in aerosol-cloud-radiation interaction and upcoming mission focus exactly on this topic, like 3MI/Sentinel-5 and EarthCare. The results presented here would be interesting for those missions as well and deserve a discussion, especially in a section named FUTURE IMPLICATIONS.

You have provided a detailed response to this comment, but you have not clearly indicated what has changed in the manuscript as a result. Obviously, you have added some text, but the structure with the new subsection 8.1 at the end of the paper is a bit strange, and the discussion is not complete (given your response). Again, improving the text in terms of discussion, conclusions and outlook might help to round off the paper.

AC: Considering the referee's comments during the first round of review, we have already added a discussion on the implications of the present synergy algorithm and resultant above-cloud aerosol absorption retrievals on the existing and future missions in sections 8.1 and 8.2, respectively. ESA's 3MI/Sentinel-5 sensor mentioned by the referee is an imager and would not provide direct measurements of AOD, like that from space-based HSRL lidar and/or airborne sunphotometer/lidar, which is required as an input to the present synergy algorithm. Therefore, we didn't include it in the discussion on future implications.

However, we have already added a brief discussion on ESA's upcoming EarthCare mission (https://earth.esa.int/eogateway/missions/earthcare#) and NASA's futuristic AOS mission (https://aos.gsfc.nasa.gov/mission.htm) potentially relevant to the present work. Of course, future suborbital airborne campaigns with targeted measurements of aerosols and clouds in the same atmospheric column, such as demonstrated with ORACLES airborne data in the present work, would provide additional opportunities to test and apply the synergistic approach for characterizing the aerosol absorption in the cloudy atmosphere.

In the revision, we've further restructured the final section 8 as follows.

8 Final Remarks

8.1 Application of the Proposed Synergy Method to Existing Long-term A-train Record

8.2 Future Implications