Response to reviewers

“Spatial distribution of dust’s optical properties over the Sahara and Asia inferred from Moderate Resolution Imaging Spectroradiometer”

We would like to thank the Anonymous Referee#1 for the recommendations for publication and constructive comments. According to the comments, we modified the manuscript and we believe that the revised paper is improved. Our point-by-point responses and actions for the comments are listed as below. The comments from reviewers are *emphasized*, and our responses and actions are shown in blue. Modified part in the revised manuscript is shown in red. English correction by several native speakers is shown in green**.** The original sentences removed in the revised manuscript are shown as orange.

This paper uses satellite observations in the visible wavelength to infer optical properties of the aerosol. The estimate is based on the spatial variability of the measurement and its linear relationship with the same in clear conditions. The retrieved optical parameters are compared to surface remote sensing measurements, and the spatial distributions are interpreted. There are several very good points in this paper. It is the first time, to the reviewer knowledge, that the method originally proposed by Y Kaufman has been used on such a large scale. The authors must be praised for putting so much effort in the data analysis. The paper is also rather complete as it includes the practical implementation of the method, the data processing and analysis, the validation of the results, and an interpretation of the spatial and temporal distributions of the products. The paper does offer original data and products which could be of interest for the community. On the other hand, the paper also shows several weak points that prevent its publication in the present state.

(1) First of all, the wording is poor which makes the reading difficult. I strongly suggest an extensive re-writing of the paper. As two of the authors are native English speakers, this sounds like an acceptable request (?).

Thank you very much for your comment. The manuscript is revised by native English speaker once again.

(2) The method description is very unclear (see detailed comments). It never states what are the assumptions, and I had to read the paper several time to finally understand what is done for the data analysis. For instance, it is never stated explicitly that the method assumes that the aerosol optical properties (optical depth, single scattering albedo) are constant at the 1x1_ scale.

We really appreciate your effort to read our paper several times and make valuable comments. In the revised manuscript, the basic assumptions are clearly stated according to your comments. As for the aerosol optical properties at 1 x 1 scale, please see our reply to "Detailed comments" 3) and 13) below.

(3) The data interpretation is unconvincing. The authors find a strong correlation the single scattering albedo and both the surface reflectance and the optical depth. They choose for an interpretation which is a physical link and do not even mention a possible spurious correlation which appears more probable to this reviewer. Overall, I think this paper should be published after significant revision to (i) make it clearer and (ii) be more prudent in the data interpretation.

We add discussions on the possible correlation as the reviewer #1 pointed out to the revised manuscript. We also give additional explanation on our interpretation and assumptions of our method in the revised manuscript.

<u>Detailed comments</u>

1) *Abstract could be more quantitative, providing values of the retrieved single scattering albedo, and accuracy of the retrieval P31108_L14: "are suitably minor". This statement does not agree with the paper results that show rather weak correlations and significant difference with the ground truth.*

The term "uncertainty" used here means the uncertainty in our estimation as discussed in Section 3.1. We modified the manuscript as follows.

[P31108_L13]
We estimate the uncertainties in ω_0 over the Sahara (Asia) to be approximately 0.020 and 0.010 (0.023 and 0.017) for bands 9 and 1, respectively, while the uncertainty in τ_a is

approximately 0.235 and 0.228 (0.464 and 0.370) for bands 9 and 1, respectively. On the other hand, the 5-95% range of the spatial distribution of ω_0 over the Sahara (Asia) is about 0.90-0.94 and 0.96-0.99 (0.87-0.94 and 0.89-0.97) for bands 9 and 1, respectively, and that of τ_a over the Sahara (Asia) is about 0.8-1.4 and 0.8-1.7 (0.7-2.0 and 0.7-1.9) for bands 9 and 1, respectively. Therefore, the uncertainties are suitably minor compared to the spatial distribution.

As for the difference between the model estimation and ground truth, we modified the manuscript as described in the response **13), 15), 19), 21)** below.

2) P31108_L18: "w0 is determined mainly by [: : :] and/or the optical depth of airborne dust in Sahara". This is certainly and impossible statement. W0 is a microphysical properties of the aerosol whereas the optical depth is a property of the layer.

Thank you very much for your comment. We removed this sentence in the revised manuscript.

[P31108_L17] Abstract, removed
Therefore, ω_0 is determined mainly by the mineral composition of surface dust and/or the optical depth of airborne dust in the Sahara.

3) P31113_L7-12: Sentence to be re-written Section 2.1. Method description. It should be made clear that the big assumption of the method is that the aerosol optical properties do not change at the 1x1 resolution. In addition, there are regions that are very homogeneous spatially. For these regions, the proposed method cannot work or may provide very unreliable results. One expects the aerosol signal to be much more homogeneous than the surface structure. Is that always the case?

Thank you very much for your comments. First, we do not assume that "the aerosol optical properties do not change at the 1x1 resolution" in our method. The basic concept is to investigate the average of optical properties within 1degree x 1degree grid as well as its uncertainty. The uncertainty is caused by some reasons (e.g., the spatial heterogeneity in 1deg x 1deg grid), which is investigated in Section 3.2. We give an explanation in Section 2.1 as follows.

[P31113_L20] Section 2.1

The estimated τ_a and ω_0 can be considered as the average of 1 degree x 1 degree grid. We also evaluate the uncertainties of our estimation in Section 3.2.

As for the homogeneity of the surface structure, it was not written in the original manuscript but we did not include the grids that are very homogeneous spatially in our analysis. These are shown as white in Fig. 7. We give an explanation of the criteria for selecting grids that are not used for the analysis as follows.

[P31116_L13] Section 2.4

From the scatter plot of the $\rho^t_{clear} - \Delta\rho^t$ diagram, we derive the critical surface reflectance (ρ_c^t) and slope (α). In this method, it is important to have spread in ρ^t_{clear} for reliable estimations of ρ_c^t and α. Therefore, we do not include the grids whose surface reflectance should be homogeneous and thus the spread in ρ_{clear}^t is very small. For this purpose, we divide ρ_{clear}^t into bins with 0.05 widths, and select grids whose data spans for more than 5 bins (the number of data at each bin is more than 7). Then, both ρ_c^t and α are estimated only when they are statistically significant in the least-squares method.

As for the aerosol signal, we performed a test of statistical significance (conventional F test) as described in Section 2.4. By this procedure, we rejected the case where the spread in scatter plot is too large and thus ρ_c^t (x-intercept) and α (slope) are not properly estimated. The spread in scatter plot is mainly caused by the spatial heterogeneity in 1deg x 1deg grid. The spread in scatter plot causes uncertainties in the estimation of ρ_c^t and α, which brings uncertainties in the estimation of aerosol optical properties (τ_a and ω_0) as shown in (b) and (c) in Table 2 and Table 3. In the revised manuscript, therefore, we emphasized that a test of statistical significance is performed.

[P31116_L14] Section 2.4

Then, both ρ_c^t and α are estimated only when they are statistically significant in the least-squares method.

In addition, we also describe the uncertainties caused by the special heterogeneity in 1deg x 1deg in the revised manuscript.

[P31116_L21] Section 2.4

By the statistical test, we can reject the case where the spread in scatter plot is too large and thus ρ_c^t (x-intercept) and α (slope) are not properly estimated. Even though the regression line is deemed statistically significant, the spread in scatter plot causes uncertainties in the estimation of ρ_c^t and α, which brings uncertainties in the estimation of aerosol optical properties (τ_a and ω_0). Uncertainties in τ_a and ω_0 are evaluated in Section 3.2 (Table 2 and Table 3).

We also found a small mistake in our calculation of Table 2 and 3 (b), but the new results are not so much different from the original.

4) P31114_L22: I am surprised that the authors use a non spherical aerosol model together with the microphysical parameters from an AERONET inversion that assumes a spherical aerosol model. I see a strong inconsistency that may have a significant impact on the aerosol phase function.

The AERONET data used in our analysis assumes a non-spherical (spheroids) aerosol model. In the revised manuscript, we add an explanation of the aerosol model in AERONET data and a reference as follows.

[P31114_L25] Section 2.3

Non-spherical aerosol is assumed in the inversion of the AERONET data (Dubovik et al., 2006).

5) P31116_L1. The method assumes that the observation is "clear" when the OMI index is less than 2, and aerosol-loaded when it is larger than 3. How have these thresholds been chosen and to what optical depth do they correspond ?

In our method, the difference in aerosol optical depth between "hazy" and "clear" conditions should be large enough. In addition, the number of data points should be large enough. That is the reason why we chose these thresholds. We modified the revised manuscript as follows.

[P31116_L9] Section 2.4

We chose the threshold value as 3 because it is the value that we can get enough difference in ρ^t and ρ^t_{clear}, as well as enough number of data points for the analysis.

We also describe the relationship between AI and aerosol optical depth as follows.

[P31116_L9] Section 2.4

We evaluate the average of AERONET data, and find that the aerosol index 2 and 3 corresponds to the aerosol optical depth 0.39 and 0.57 at 0.440μm, respectively.

6) P31116_L11. Even if the view zenith angle is the same, the sun angle is likely different so that the observation geometry varies

Thank you for your comment. We modified the sentence in the revised manuscript. We also add this effect of solar zenith angle as an error source in the uncertainty analysis in Section 3.1. We found that our main results are not different from the original because the uncertainties from this effect are small compared to those of other error sources.

[P31116_L11] Section 2.4

For the calculation of $\Delta\rho^t = \rho^t - \rho^t_{clear}$, we use a ρ^t_{clear} value with sensor zenith angle identical to that of the ρ^t during hazy conditions.

[P31120_L9] Section 3.1.1

(6) difference in solar zenith angle between clear-sky and hazy conditions; and (7) satellite calibration errors.

* According to this modification, the numbers of error sources from (7) to (11) are modified as well.

[P31121_L9] Section 3.1.1

With respect to the category (6), the standard deviation of the differences in solar zenith angle between cleary-sky and hazy conditions in our analysis is 2.3 degree. The uncertainty in ω_0 and τ_a due to the difference in solar zenith angle of 2.3 degree is shown in (d) of Table 2 and 3.

* According to this modification, the alphabet in Table 2 and 3 from (d) to (l) are modified as well.

7) P31116_L15. It is absolutely not clear what means "statistically significant" here. Does it mean that the sign of the retrieved slope is known, or that the slope is known within x % accuracy, or what ???. Equation (2) does not help. It is said that SE is the square sum of errors but what are the errors ?
P31116_L21. "We assume the level of significance of rejection to be 5%". I guess this is not an assumption but rather a criteria for rejection. So the data point is rejected when F is lower than 0.05, or lower than 0.95 ??? Please explain.

Thank you very much for your clarification. We make a brief explanation on "statistical significance" to the revised manuscript as follows.

[P31116_L15] Section 2.4

Results are deemed as statistically significant when the test of null hypothesis (population regression coefficient $\alpha = 0$) is rejected with a level of significance of 0.05. The test of null hypothesis $\alpha = 0$ is performed under the assumption that the statistic F described below follows an F-distribution with (1, n-k-2) degrees of freedom:

We also give explanation on the meaning of the statistical test as follows.

[P31116_L21] Section 2.4
By this statistical test, we can reject the case where the spread in scatter plot is too large and thus ρ_c^t (x-intercept) and α (slope) are not properly estimated.

8) *P31117_L14. Section 2.5 I fully disagree with this section. The equations are valid only in the case of small optical thicknesses _0.2 and smaller. The authors use cases with large optical depths, often larger than 2. For such cases, the equations are not valid. They do not bring anything to the paper and I therefore suggest to remove section 2.5 entirely.*

Thank you very much for your comment. As you pointed out, Eq. (4) of the original manuscript is the formulation under the assumption of small optical thickness. However, Eq. (10) and (11) of the original manuscript can be derived without using Eq. (4), and thus the equations are valid for the optical depth larger than 0.2. We removed Eq. (4)

and its explanation of the original manuscript, and modified Eq. (7), (8), and (11) in the original manuscript (corresponding to the Eq. (6), (7), and (10) in the revised manuscript).

[P31117_L26] Section 2.5, Removed

If the solar zenith (θ_0) and viewing angles (θ) are small enough (Chandrasekhar,1960):

$$\rho_0^t = \pi \sec\theta_0 \sec\theta \omega_0 \frac{p}{4\pi}\tau \quad (4)$$

where p is the scattering phase function, normalised such that its integral over all angles equals 4π. τ is the total optical depth of the gaseous and aerosol scattering.

[P31118-P31119] Section 2.5

By substituting Eqs. (4)-(5) to Eq. (3):

$$\rho^t = \rho_0^t + \frac{\rho_g}{(1-s\rho_g)} \exp\{\{-\tau_a[1-\omega_0(1-\beta^a)] - \tau_m/2\}\{\sec\theta_0 + \sec\theta\}\} \quad (6)$$

The TOA reflectance during clear conditions can be formulated in the same manner:

$$\rho_{clear}^t = \rho_{0\_clear}^t + \frac{\rho_g}{(1-s\rho_g)} \exp\{\{-\tau_{a\_clear}[1-\omega_0(1-\beta^a)] - \tau_m/2\}\{\sec\theta_0 + \sec\theta\}\} \quad (7)$$

where τ_{clear} and τ_{a_clear} are the total and aerosol optical depths during clear conditions, respectively, and $\rho_{0\_clear}^t$ is same as ρ_0^t but during clear conditions. The relationship between $\Delta\rho^t$ and ρ^t_{clear} is then calculated using Eqs. (6) and (7):

$$\Delta\rho^t = \rho^t - \rho_{clear}^t = \alpha\rho_{clear}^t + \beta \quad (8)$$

α and β in Eq. (9) are calculated as follows:

$$\alpha = \exp\left[-(\sec\theta_0 + \sec\theta)\left(\tau_a - \tau_{a\_clear}\right)\left[1-\omega_0\left(1-\beta^a\right)\right]\right] - 1 \quad (9)$$

$$\beta = \rho_0^t - \left\{-\exp\left\{-(\sec\theta_0 + \sec\theta)\left(\tau_a - \tau_{a\_clear}\right)\left[1-\omega_0\left(1-\beta^a\right)\right]\right\}\right\}\rho_{0\_clear}^t \quad (10)$$

* According to this modification, the numbers of equations are changed in the revised manuscript.

We also confirmed that the equations are valid for the optical thickness 0.2 and larger. The figure below shows that the relationship between τ_a and $|\alpha|$ calculated by the radiation transfer simulations described in Section 2.3 (red), and by the approximated equations (10) described in Section 2.4 in the original manuscript (black). This figure demonstrates that equations are valid to some extent.

The main message of Section 2.5 in the original manuscript is to derive the physical relationship between τ_a and $|\alpha|$ by approximated equations. The derivation has not been demonstrated in the previous studies, so we do not believe that "they do not bring anything to the paper". On the other hand, it is true that the derivation of the relationship is not related to the main point of the manuscript. Therefore, we moved Section 2.4 in the original manuscript to the Appendix.

[P31113_ L17] Section 2.1

In Appendix, the relationship between the slope of $\rho^t_{clear} - \Delta\rho^t$ diagram (α) and τ_a as well is derived by approximated equations.

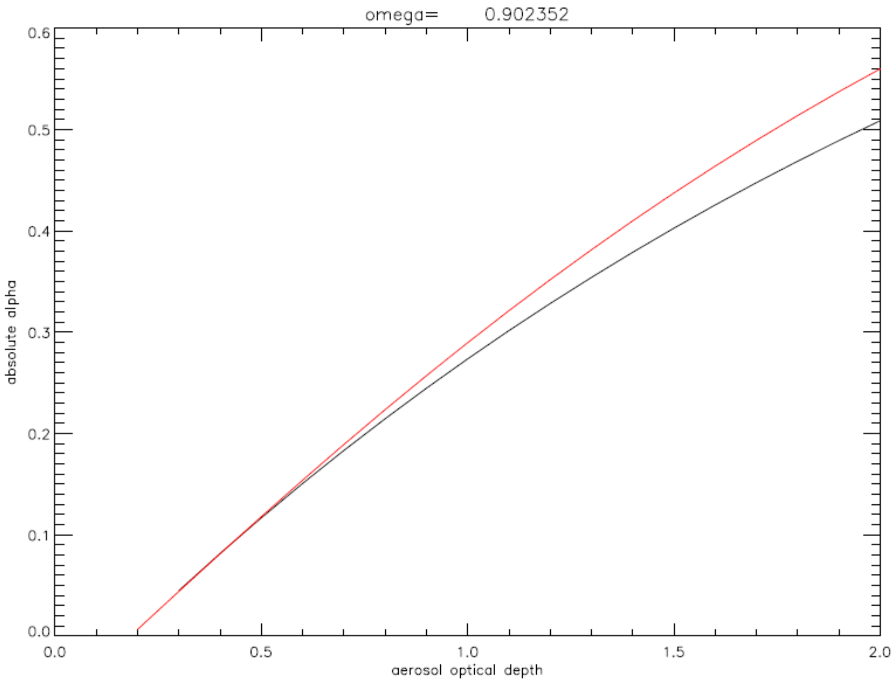


Figure. The relationship between τ_a (aerosol optical depth, abscissa) and $|\alpha|$ (absolute alpha, ordinate) calculated by the radiation transfer simulations described in Section 2.3 (red), and by the approximated equations described in Section 2.4 in the original manuscript (black)

9) *P31121_L5: "These variations correspond to the spread of the scatter plot: : :". This is an assumption. There may be other causes for the scatter, including measurement noise, undetected clouds, or directional effects.*

Thank you very much. Among the above causes, the "directional effects" is quantified as category "(5) spatial variations in the geometry in 1 degree x 1 degree grid points". It is explicitly described in the revised manuscript. The other causes are also described in the revised manuscript.

[P31121_L3] Section 3.1.1

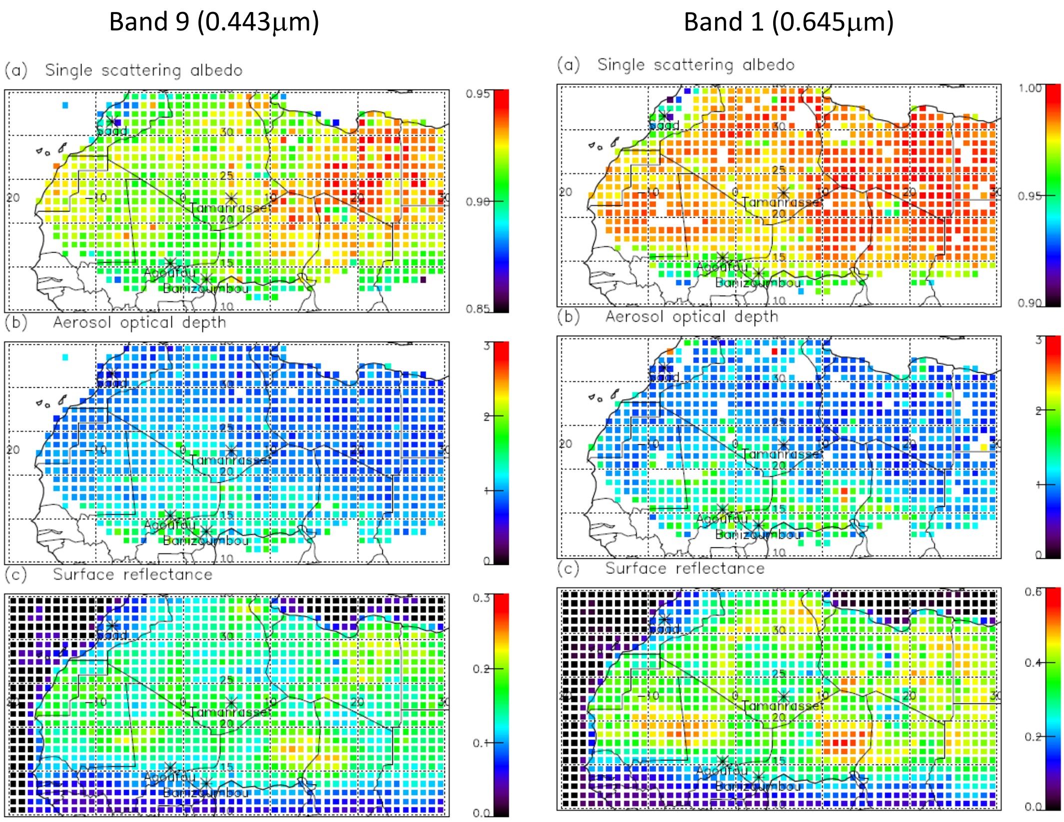
Uncertainties in aerosol optical characteristics and geometry, represented by categories (3)-(5), are caused by their spatial variations in 1degree x 1degree grid. . These variations are represented by the spread of the scatter plot in the $\rho^t_{clear} - \Delta\rho^t$ diagram. The spread of the scatter plot in the $\rho^t_{clear} - \Delta\rho^t$ diagram is also caused by the measurement noise and undetected clouds, and thus categories (3)-(5) includes these effects. The uncertainties in ω_0 and τ_a are caused because they are estimated from the slope (α) and x-intercept (ρ_c^t) in the scatter plot by the least-squares method, as shown in Fig. 2. The errors from α and ρ_c^t caused by the least-squares method are shown in (b) and (c) of Table 2 and 3, respectively.

10) *P31122_L13: You show temporal composite but do not explain how these have been achieved. Is it a simple average of aod and w0, or a weighted average (I would do an average of w0 weighted by the aod if I were you, as the uncertainty is probably smaller for large aod)*

We showed a simple average of ω_0 and τ_a in the original manuscript. We agree with your opinion, and we took the temporal average of ω_0 and τ_a weighted by the total uncertainty at each grid in the revised manuscript. The new figures are shown below, and the difference from the original figure is small.

[P31125_L18] Section 3.3

We take the temporal average of ω_0 and τ_a weighted by the total uncertainty at each grid.



Revise Fig.8 (Original Fig.7)

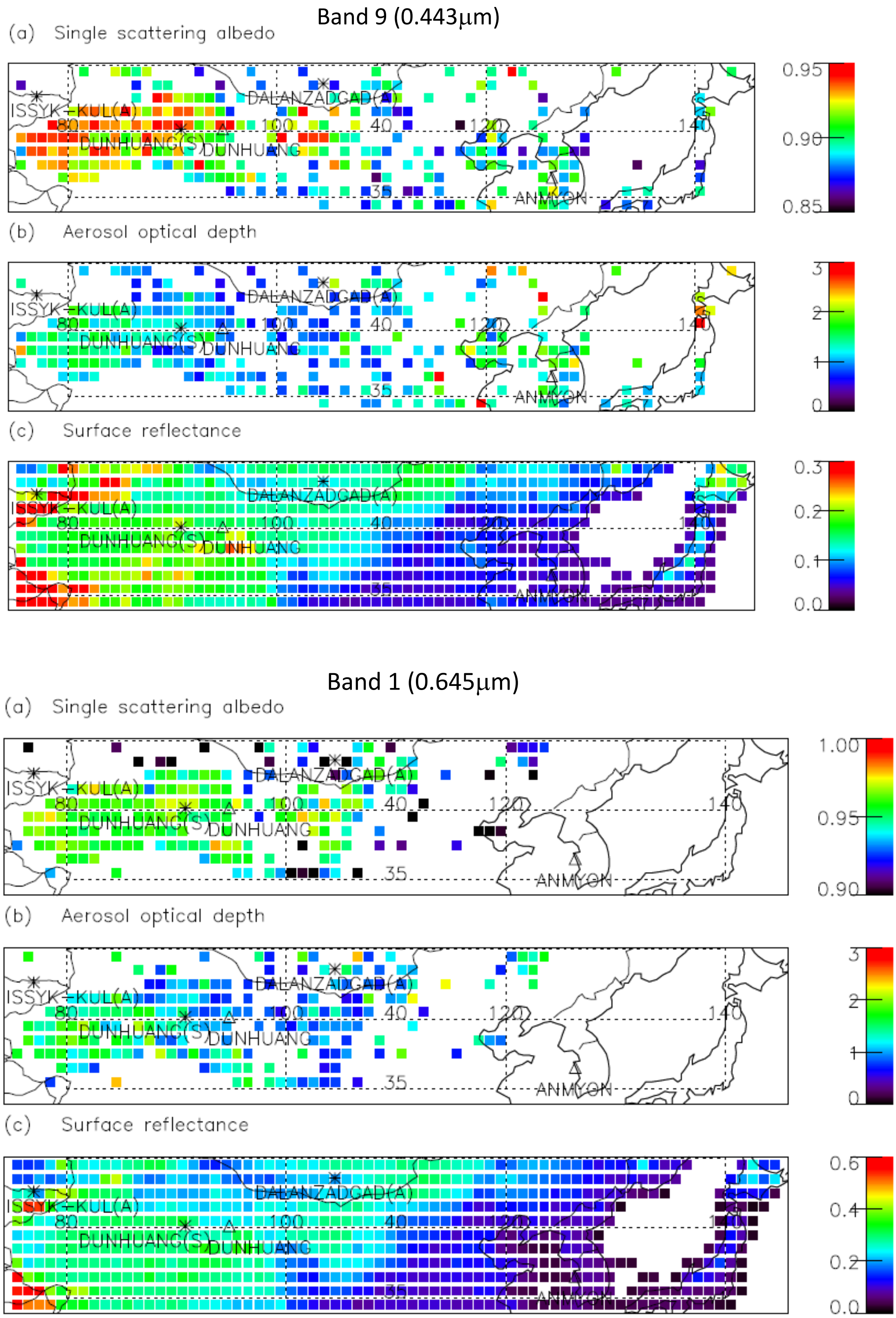


Fig.9 in the revised manuscript (Fig.8 in the original manuscript)

11) *P31122_L17: Not clear why the uncertainty in the aerosol optical properties are larger in the southern region. In this region, there is a seasonal cycle of the surface reflectance. This may be a factor.*

We confirmed that the standard deviation of surface reflectance was not especially large in the southern region during May to August. We did not consider the spatial variation of standard deviation of surface reflectance in our analysis (Fig. 4), because the spatial variation was not so large. The total uncertainty of τ_a is large over the southern region probably because the estimated value of τ_a is large.

[P31122_L17] Section 3.1.2

The total uncertainty of τ_a becomes large over the southern region, which contains AERONET sites. In this region the uncertainties in the categories (3)-(5) are large, probably because the estimated value of τ_a is large.

12) *P31122_L21: "the total uncertainties are concluded to be suitably minor". One can only say that I requirements have been defined and uncertainties quantified, and the latter be smaller than the former. Please be quantitative to claim such statement.*

In the revised manuscript, we add a quantitative discussion as follows.

[P31122_L19] Section3.1.2

As shown in Table 2 (m) and Table 3 (m), the total uncertainty in ω_0 over the Sahara (Asia) is 0.020 and 0.010 (0.023 and 0.017) for bands 9 and 1, respectively, and that in τ_a is 0.235 and 0.228 (0.464 and 0.370) for bands 9 and 1, respectively. On the other hand, the 5-95% range of the spatial distribution of ω_0 over the Sahara (Asia) investigated in Section 3.3 is about 0.90-0.94 and 0.96-0.99 (0.87-0.94 and 0.89-0.97) for bands 9 and 1, respectively, and that of τ_a over the Sahara (Asia) is about 0.8-1.4 and 0.8-1.7 (0.7-2.0 and 0.7-1.9) for bands 9 and 1, respectively. Therefore, total uncertainties shown in Table 2 and 3 are suitably minor compared to the spatial distribution over Sahara and Asia.

13) *P31123_L8: “: : :most likely because the former is in the form of point observation, while the: : :” The method developed in this paper relies on the hypothesis that aerosol optical properties are constant over 1x1. It is bizarre to claim spatial heterogeneity as the reason for poor agreement with validation data.*

Thank you very much for your comment. As we describe in our response to 3), we do not rely on the hypothesis that aerosol optical properties are constant over 1deg x 1deg. The basic concept is to investigate the average of optical properties within 1deg x 1deg grid as well as its uncertainty (spread). The uncertainty is partially caused by the spatial heterogeneity in 1deg x 1deg grid. Therefore, the vertical axis in Fig. 5 (MODIS) is the average of SSA and AOD in 1deg x 1deg grid, while the horizontal axis (AERONET) is the value obtained by point observation. This basic concept is described in the revised manuscript.

[P31113_L20] Section 2.1

The estimated τ_a and ω_0 can be considered as the average of 1 degree x 1 degree grid. We also evaluate the uncertainties of our estimation in Section 3.2.

[P31116_L13] Section 2.4

From the scatter plot of the ρ^t_{clear} $-\Delta\rho^t$ diagram, we derive the critical surface reflectance ($\rho_c{}^t$) and slope (α). In this method, it is important to have spread in ρ^t_{clear} for reliable estimations of $\rho_c{}^t$ and α. Therefore, we do not include the grids whose surface reflectance should be homogeneous and thus the spread in $\rho_{clear}{}^t$ is very small. For this purpose, we divide $\rho_{clear}{}^t$ into bins with 0.05 widths, and select grids whose data spans for more than 5 bins (the number of data at each bin is more than 7). Then, both $\rho_c{}^t$ and α are estimated only when they are statistically significant in the least-squares method.

[P31116_L21] Section 2.4

By the statistical test, we can reject the case where the spread in scatter plot is too large and thus $\rho_c{}^t$ (x-intercept) and α (slope) are not properly estimated. Even though the regression line is deemed statistically significant, the spread in scatter plot causes uncertainties in the estimation of $\rho_c{}^t$ and α, which brings uncertainties in the estimation of aerosol optical properties (τ_a and ω_0). Uncertainties in τ_a and ω_0 are evaluated in Section 3.2 (Table 2 and Table 3).

14) *P31123_L21: ": : :is more consistent". Than what ? How does one knows that?*

In the revised manuscript, we add regression lines without considering measurement error (lines that are not weighted by measurement error) to the scatter plot of Fig. 5. Then we modified the manuscript as follows.

[P31123_L21] Section 3.2.1

The regression line that considers measurement error of τ_a (red line in Fig. 5) is more consistent with the AERONET observations than the line that does not consider measurement error (blue line).

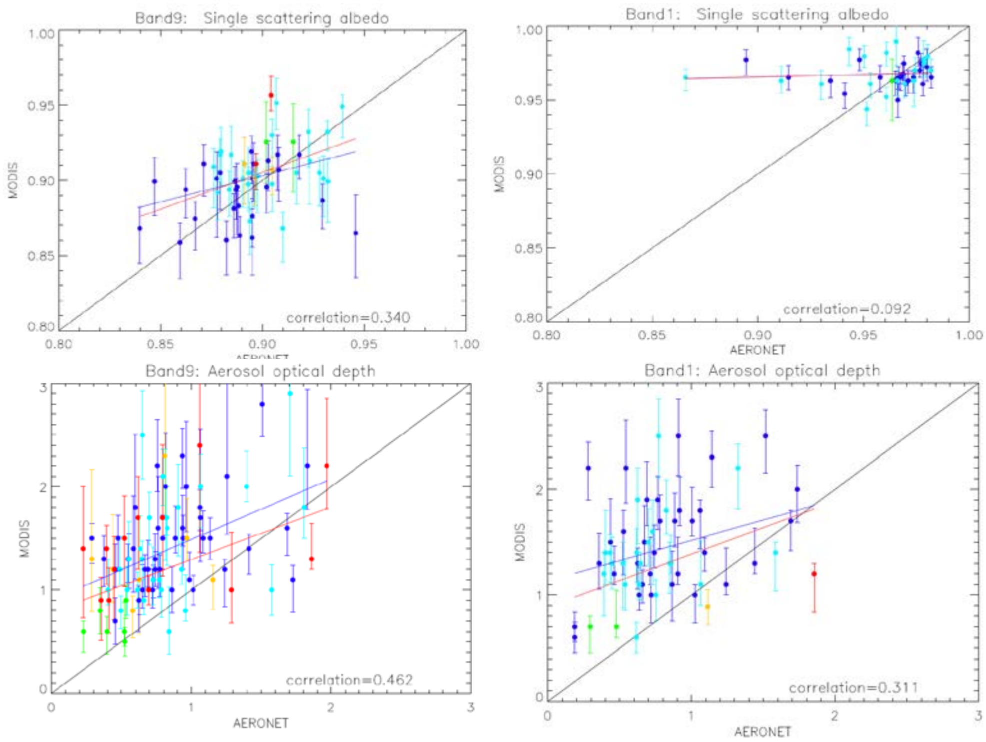


Figure 5. Comparison of the single scattering albedo (ω_0) and optical depth (τ_a) values we estimated from the MODIS satellite data and model simulations with the AERONET ground observational data. The error bars are the total uncertainty described in Section 3.1. We sample the results of grid boxes that include the AERONET sites Agoufou (blue), Banizoumbou (light blue), Saada (green), Tamanrasset_INM (orange), and Tamanrasset_TMP (red). The lines indicate the regression by considering the error bars as the "measurement error" (red) and not considering the measurement error (blue), the details of which are described in the main text.

15) *P31123_L23-27: I fully disagree with this statement. A tendency to reject small aod may result in a high bias on temporal averages, but your validation is made on individual retrievals. Then, even if your method selects only high aod cases, it has no reason to result in a high bias in the validation procedure.*

As discussed in the manuscript, AODs estimated from MODIS have large spread as shown in Fig. 5. Some AODs of MODIS are larger than those of AERONET, and others of MODIS are smaller than those of AERONET. In our method, AOD is estimated from the slope of the scatter plot ("α" as shown in Fig. 2), and small AODs tend to be rejected by the statistical test (the null hypothesis of $\alpha = 0$) because small α is indistinguishable from zero. Therefore, AODs of MODIS which is smaller than those of AERONET tend to be rejected more often (compared to AODs of MODIS which is larger than those of AERONET). On the other hand, we do not reject the smaller τ_a from AERONET measurements.

In the revised manuscript, we add the below description.

[P31123_L26] Section 3.2.1
As shown in Fig. 5, the τ_a estimated from MODIS have large spread. In general, the data with small slopes α (and small τ_a) tend to be rejected by the statistical test in our method using the null hypothesis of $\alpha=0$, because very small α is not distinguishable from zero. τ_a of MODIS which is smaller than those of AERONET tend to be rejected more often compared to τ_a of MODIS which is larger than those of AERONET. On the other hand, AERONET data with small τ_a are not rejected in Fig. 5.

16) *P31125_L14. Section 3.3 This concerns the interpretation of the spatial structure of the results. The validation has shown that there is a rather wide spread between the retrievals and the ground truth. Besides, there are few validation sites. Then, if the method shows a bias that depends on the ground reflectance, it may not be seen by the validation procedure and generate spurious structures.*

Thank you very much for your comment. As for the difference between the retrievals and the ground truth, we discussed in our response to your "Detailed comments" 13). We give more discussion at Section 3.3 in the revised manuscript.

[P31127_Last] Section 3.3

It should be noted that we cannot validate the spatial distribution of aerosol optical properties and the relationship between ω_0, τ_a, and the surface reflectance because the number of ground observations is limited (only four AERONET sites).

[P31127_Last] Section 3.3

If we can increase the number of observation sites, it helps us to validate the spatial distribution and the relationship between the aerosol optical properties.

As for the "bias that depends on the ground reflectance", we do not believe that our method has such kind of structural bias. Since our method do not explicitly use the surface reflectance (we use the TOA reflectance), the possible bias that the reviewer #1 pointed out should be related to the TOA radiance. Possible sources of bias related to the radiance are as follows.

1. Difference of extrapolation distance

If the surface reflectance is small, ρ^t_{clear} tends to be smalls and the extrapolation distance from ρ^t_{clear} to $\rho_c{}^t$ (x-interception in Fig. 2) tends to be large. Therefore, the spread in scatter plot cause the larger uncertainties in ω_0 if the surface reflectance is small. This uncertainty is already considered by the category (b) in Section 3.1.1.

2. Error in the sensor calibration

It is well known that the Aqua/MODIS satellite is well calibrated and radiance calibration error is less than 5%. This is considered by the category (6) in Section 3.1.1.

3. Nonlinearity of scatter plot in Fig. 2.

The critical reflectance, $\rho_c{}^t$ are estimated as the x-intercept of Fig. 2 by extrapolating the scatter plot. As shown in Fig. 1, the ρ^t_{clear} and $\Delta\rho^t$ diagram has small non-linearity, which causes errors in estimation especially when ρ^t_{clear} is small (the radiance is small). In our method, we consider the nonlinearity of the diagram by creating the different LUTs depending on the four different ρ^t_{clear}. This is described in Section 2.4 as follows.

[P31117_L4] Section 2.4

When the surface reflectance is low enough and there are no data with $\Delta\rho^t$=0 (and thus $\rho_c{}^t$), the regression line of the scatter plot is extrapolated to find $\rho_c{}^t$ where $\Delta\rho^t$=0. As shown in Fig. 1, the relationship between $\rho^t{}_{clear}$ and $\Delta\rho^t$ is almost linear, but includes non-linear components. Therefore, we create four different LUTs for the four different $\rho^t{}_{clear}$.

In the revised manuscript, we summarize the above points and describe that our method may not have structural biases that depends on the ground reflectance.

[P 31126_ L22] Section 3.3

One may wonder that the correlation between ω_0 and the surface reflectance in Fig. 9 is caused by errors inherent to this method. Possible sources of errors that related to the surface reflectance are i) the spread in the scatter plot demonstrated in Fig. 2, ii) the errors in the radiance calibration, and iii) the nonlinearity of scatter plot in Fig. 2. The error source of i) is investigated by the categories (3)-(5), and that of ii) is investigated by the category (6) as described in Section 3.1. The error source of iii) is treated by creating the four different LUTs for the four different surface reflectances as described in Section 2.4. Therefore, the correlation between ω_0 and the surface reflectance in Fig. 9 may not be spurious structural bias.

17) *P31126_L11. "because the spread in Asia is larger". Are you saying that the correlation is lower because the non-correlation is larger ?*

Thank you very much. We remove this sentence in the revised manuscript.

P31126_L11: The below sentence is now removed.
This result is partly because the spread in Asia is larger than that in the Sahara.

18) *P31126_L15-19: These lines discuss previous estimates of the single scattering albedo. This is also done in the introduction, and the two are not fully consistant. Please harmonize (or rather remove one of the two instances)*

Thank you very much for your suggestion. We modified the manuscript as follows.

[P31126_L15-19] Section 3.3

As shown in Introduction, the observed ω_0 over Sahara were slightly higher than that of Asia in the previous studies. These results are consistent with our results shown in Fig. 9, in which the average of ω_0 over the Sahara is higher than that over Asia.

In the revised manuscript, we add the below sentence to the introduction.

[P31110_L12] Section 1

Huang et al., (2009) reported ω_0 of 0.89 at 0.67μm by Cloud and the Earth's Energy Budget Scanner measurement.

19) *P31127_L3-9: The author hypothesize that there is a true relationship between the optical depth and the single scattering albedo. I feel that a bias in the method is much more likely. The authors have the possibility to check their hypothesis against sunphotometer products. Do they find any w0-AOD in the Aeronet data ? If so, this is a most interesting result. If not, the authors should conclude that their method generates such spurious correlation.*

Thank you very much for your good comment. As we discussed in the response to your comments #16), we cannot validate the spatial distribution of aerosol optical properties and the relationship between the ω_0 and τ_a because the number of validation sites is limited. Therefore, we investigated the relationship between ω_0 and τ_a based on the daily data. The figures below show the scatter plot of ω_0 and τ_a using the daily data where both AERONET and MODIS1 x 1 degree data are available. Note that the dots in Fig. 9 in the original manuscript are the temporal average during 2003-2012 of the 1 x 1 degree grid. As shown in the below figures, the correlations between ω_0 and τ_a are not significant with a level of significance of 0.05, except AERONET 0.675 μm Agoufou site. The below results are discussed in the manuscript.

[P31127_L9] Section 3.3

It should be noted that we cannot validate the spatial distribution of aerosol optical properties and the relationship between ω_0, τ_a, and the surface reflectance because the number of ground observations is limited (only four AERONET sites). In order to investigate the relationship more carefully, we take the correlation between ω_0 and τ_a

using the daily 1 x 1 degree MODIS data and the AERONET data. The correlations between ω_0 and τ_a are not significant except AERONET Agoufou at 0.675 μm (not shown). Data is only available for the two sites (Agoufou and Banizoumbou of AERONET site) because the matched-up data between MODIS and AERONET are very limited, and thus we cannot find the significant difference between the satellite retrievals and the ground observation at this stage.

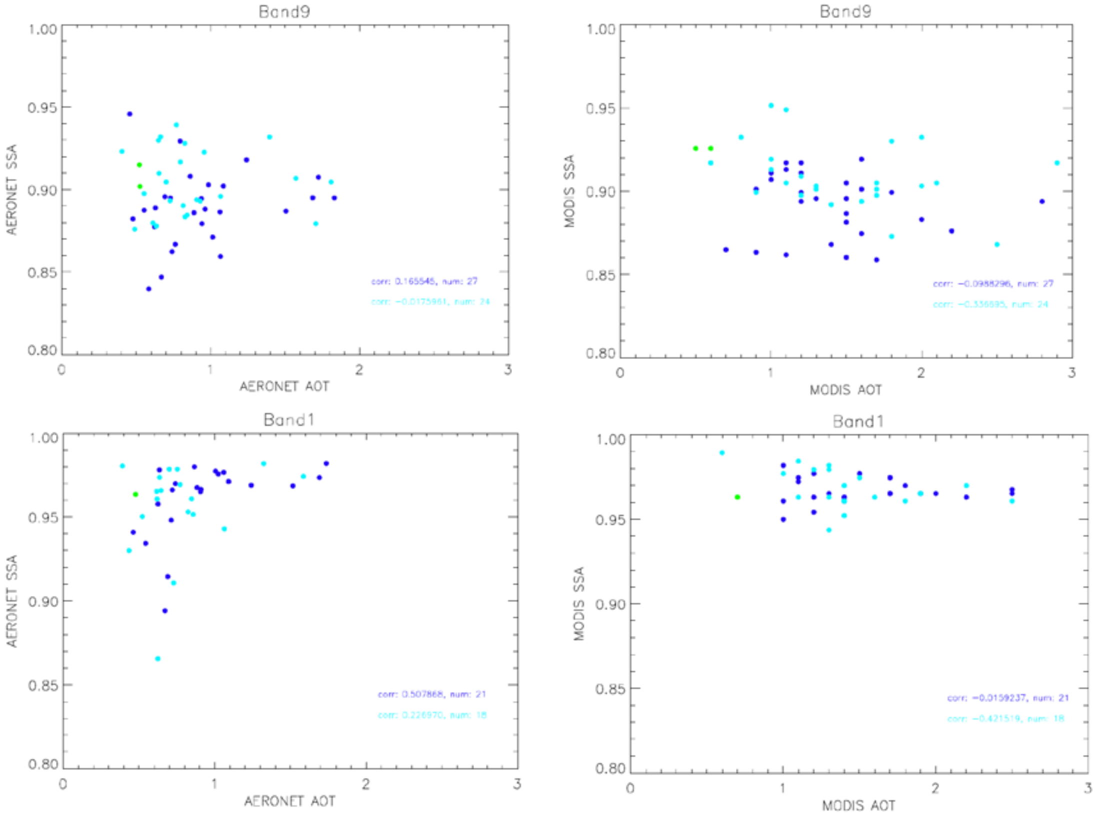


Figure. The scatter plot and the correlation between the ω_0 and τ_a for AERONET (left) and MODIS (right) The color is same as Fig.5 of original manuscript.

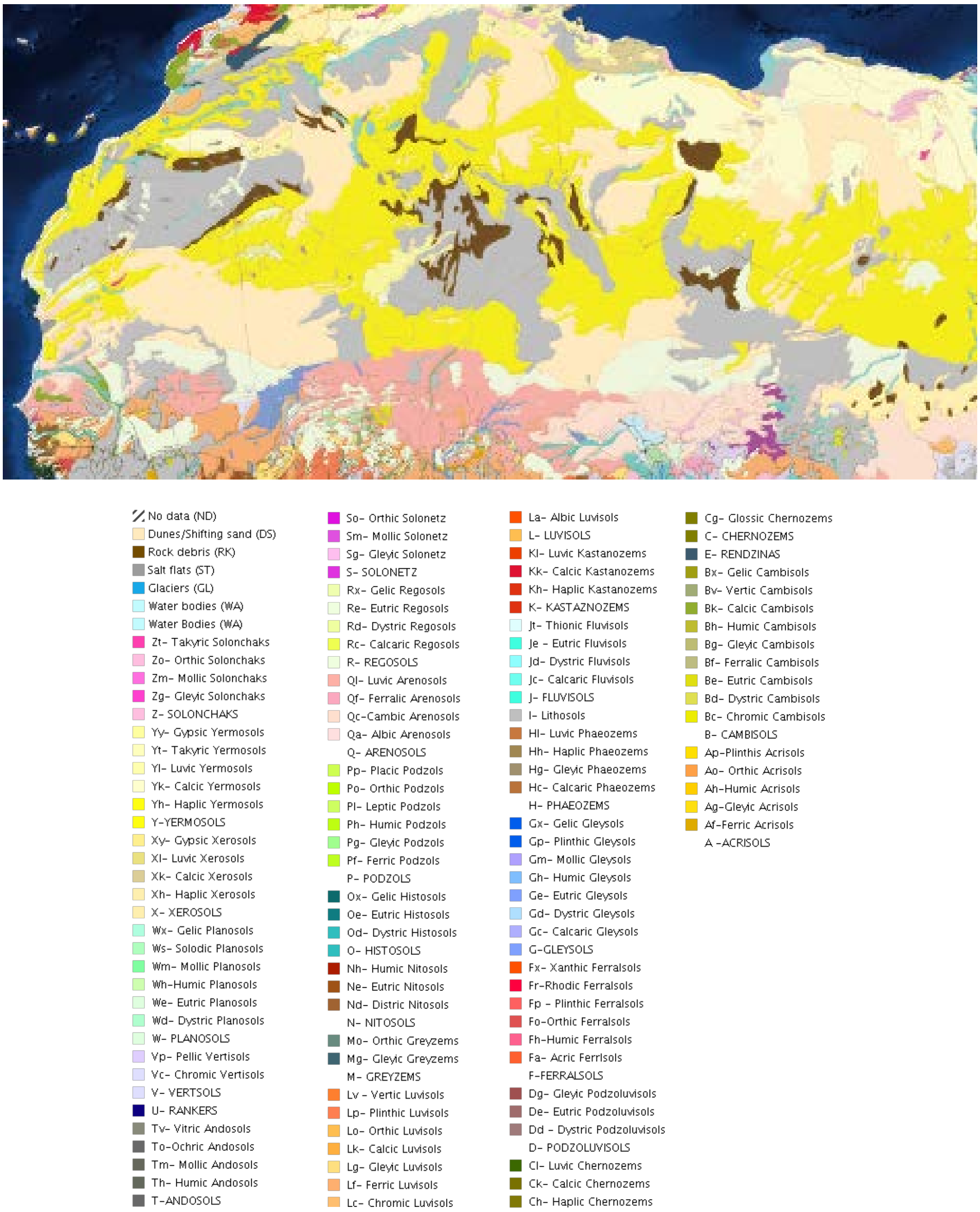
20) *P31127_L10: Section 3.4 In this section, the author discuss the spatial distribution of the dust optical properties. In particular, they interpret the correlation between the surface reflectance and the dust absorption. They fail to mention that many regions are NOT dust sources, and that the dust may be transported over considerable distances. One should therefore be much more careful than they are in the result interpretation*

Thank you very much for your comment. We include discussions about the regions that are not dust sources. We also comment that dust may be transported over considerable distances in the revised manuscript. We show the soil map of FAO/Unesco (Food and Agriculture Organization, 1991) bellow, although it is not shown in the revised manuscript.

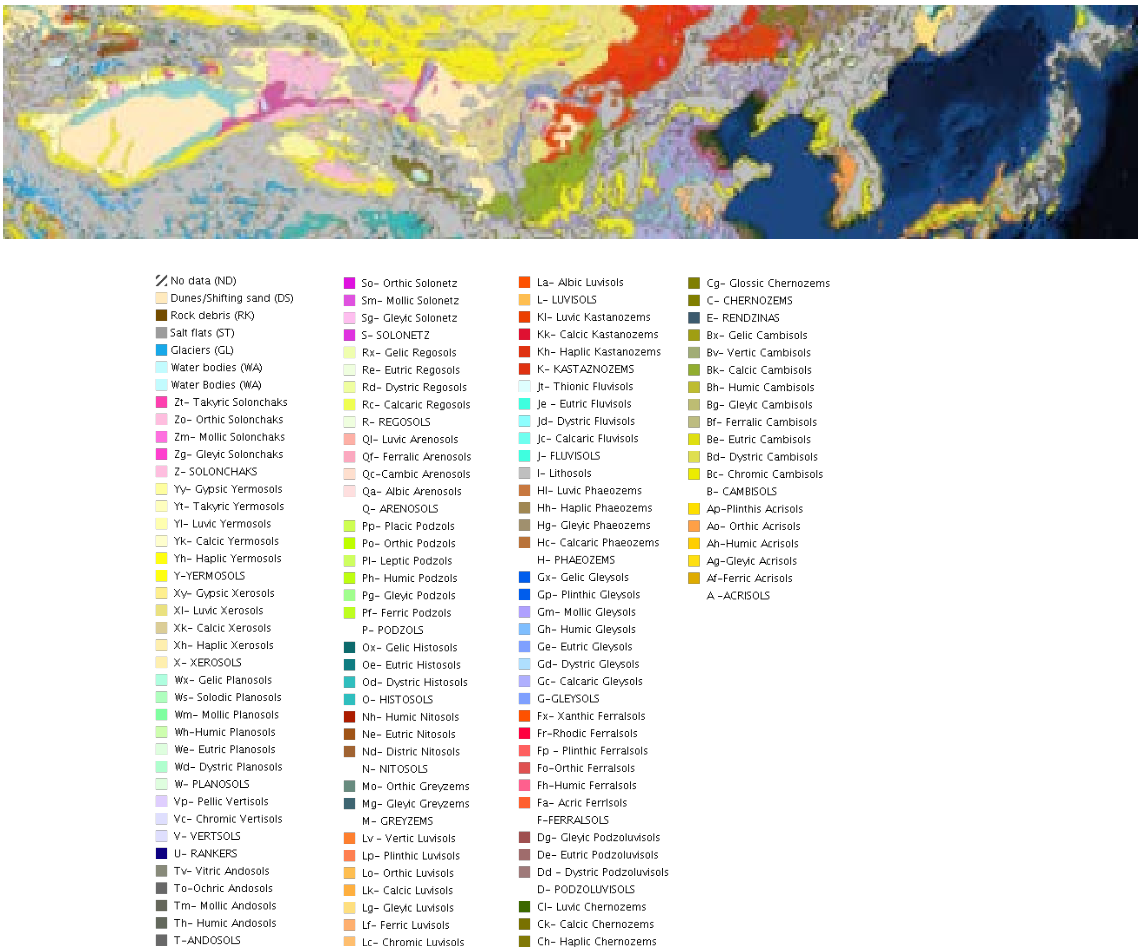
[P31126_ L26] Section 3.3

We should note that there are regions that are not the dust sources. In addition, dust can be transported over the considerable distance. The areas shown in Figures 7 and 8 contain the vegetation and bedrock area, which cannot be considered as the dust source regions. In these areas, ω_0 we estimated may not be related to the dust on the surface. In order to identify regions which can be the dust source regions, we compared spatial distribution of the surface reflectance with the soil map of FAO/Unesco (FAO, 1991). The soils properties in Sahara and Asia regions mainly consist of dunes/shifting sand, Yemosols, rock devris, Lithosols, Regosols, Arenosols, Kastanozem, and Cambisols (not shown). Among these categories, the regions with dunes/shifting sand and Yemosols can be considered as the dust source regions (FAO, 1991). When we compare the soil maps with the spatial distribution of the surface reflectance (Figures 7 and 8), the regions with these categories (dunes/shifting sand and Yemosols) tend to have high surface reflectance especially at band1.

On the other hand, the regions with rock devris and Lithosols tend to have the low surface reflectance less than about 0.12 (band9) and 0.25 (band1). For these regions, we cannot discuss about the relationship between the surface mineral composition and ω_0, because the atmospheric aerosol should not be related to the surface reflectance.



Soil maps of FAO/Unesco in Sahara.



Soil maps of FAO/Unesco in Asia.

21) *P31129_L17 Summary: In the summary, there are several strong statements that are presented in the paper as possible hypothesis. The validation procedure shows a large bias on the AOD, and a significant spread on w0 so that, in the reviewer opinion, the spatial distribution should be interpreted with more caution.*

Thank you very much for your comment. As you pointed out, some sentences in "Summary" are modified as follows.

[P3113-_L21-27] Section 5

The good correlation between ω_0 and the surface reflectance and between ω_0 and τ_a in the Sahara suggests that the temporal average of ω_0 is largely affected the underlying mineral composition and the optical depth of the airborne dust, although there should be many complicated factors to determine the individual ω_0.

We removed this sentence in the original manuscript.

[P31131_L14～L17] Section 5, removed

The spatial distributions of dust in the Sahara may contain information on the dynamic behaviour of dust aerosols, and the relationships between ω_0 and the surface reflectance and between ω_0 and τ_a could be especially useful for the validation of dust transport processes in numerical models.