Response to Referee 2

We would like to thank the referee for her/his helpful comments and remarks. We expect that the revised version will address all comments.

Motivated by the referee's comment number 7, in this revised version we have revisited our post-processing algorithm of the MISR level 2 data. We no longer assume that the extinction efficiency is independent from the size of the aerosol and instead we compute the extinction efficiencies using the refractive index reported in the MISR products using a well-established Mie code. This improves the quality of the fine mode AOD derived from the MISR observations, but it decreases the fine mode AOD by approximately 15 %. The total AOD remains unchanged. We have recomputed the MISR analysis with this new dataset and we have included these new estimates in the revised version of the manuscript. The results for the MISR analysis only change marginally and the conclusions of the study remain the same.

We reproduce comments from the referee in "script" font followed by our answer. A document listing the revisions to the manuscript is also provided.

`The manuscript presents estimates of dust emission from Northern Africa and Arabian Peninsula for the year 2006. Aerosol optical depth (AOD) retrievals from five different satellite instruments are individually assimilated into a global model that includes a simplified aerosol model. The individual assimilation allows to evaluate the spread of the estimated dust emission due to the different AOD datasets. These are very interesting and new results in the study, which should be published. Besides providing new estimates for dust emission from Northern Africa and the Arabian Peninsula, which are based on the assimilation, these results demonstrate that using only selected AOD retrievals for estimating dust emission or model evaluation will likely lead to an underestimation of the uncertainty in the results.`

`The structure of the manuscript needs improvement in some parts. The authors should also carefully revise with respect to the English language, especially the phrasing of some sentences.`

We have done our best to revise the English language of the manuscript. We have also implemented all language corrections requested by Referee 1.

`Following points should particularly be taken into consideration before publication. Quotes from the manuscript are in italic:`

1. **Abstract, lines 11–12:** "*We also show how the assimilation of a variety of AOD products can help to identify systematic errors in models*".

`It is not clear to me how the manuscript has shown such a thing as a guideline that can be generalized to other models. The authors make some short general statements in the conclusions of the manuscript about possible biases in the specific model that was applied by them, but that is not sufficient for such a general statement in the abstract.`

`I recommend to remove the last sentence in the abstract.`

`Alternatively, the authors could add a more systematic discussion of how the assimilation of the AOD retrievals can help identify model biases in general. This would further improve the paper.`

We agree with the referee that this statement is not enough substantiated so we have removed this sentence from the abstract. We have however left the corresponding discussion in the main text.

2. **Page 2, lines 1–7**

The relevant scientific references should be added to each of the points about the importance of dust aerosols.

We have added more references.

3. **Page 2, line 27 to page 3, line 3**

The scientific references for each of the listed instruments should be added.

We have added the scientific references for the AOD products listed in the paragraph (when available).

4. **Page 4, lines 27–28:** "*...the use of efficient algorithms to ensure semi-positiveness of some matrices involved in the inversion ...*"

For the purpose of reproducibility, it should be specified what algorithms were used in the current study to ensure this, instead of making a general statement only.

We have modified the paragraph and have included the appropriate reference. The new paragraph reads:

"We have improved the data assimilation system presented in EBCH16 in order to deal with the longer control vector. To this effect we have carefully recoded some matrix multiplication and inversion routines, paying special attention to the computational memory management and minimizing numerical errors as much as possible. We have also applied the algorithm of Qi and Sun (2006) to ensure the semi-positiveness of some of the matrices involved in the inversion."

5. **Page 5, lines 11–12:** *Using this coefficient we derive the 550-nm AOD from these retrievals, for total and fine mode over ocean and fine mode over land.*

Even though it may appear trivial to the experts, the formula for deriving the 550-nm AOD should be presented here.

We have added the formula:

"...over ocean and fine mode over land. That is, we interpolate the AOD using the following relation:

$$\tau_{550} = \tau_{865}\left(\frac{550}{865}\right)^{-\alpha} \tag{1}$$

where τ_{550} is the AOD at 550 nm, τ_{865} the AOD at 865 nm and α is the Ångström coefficient between 670 and 865 nm."

6. **Page 5, lines 28–29:** "*(i) we calculated the contribution of each aerosol model to the total AOD, using the reported fitting parameters and considering the 8 basic aerosol models of MISR algorithm;*"

This statement is not clear. Were only eight basic aerosol models out of the 74 aerosol mixture models considered and their contributions calculated? In any case, the sentence should be rephrased to clarify what was done.

Each of the 74 aerosol models is a mixture (or weighted sum) of 3 basic aerosol models. The list of mixture and basic aerosol models can be found in Kahn and Gaitley (2015). To clarify this point, we have rephrased the sentence and added this information in the previous sentence:

"... radiances for each observed pixel, and the quality of the fit is estimated using a chi-square criteria (Kahn et al., 2005). Each aerosol mixture model is composed by the weighted sum of (at most) three *basic* aerosol models. The optical properties, the two parameters of the log-normal size distribution and the relative contributions of each basic aerosol model to the mixture aerosol models are reported in the Level 2 of the MISR products along with the fitting parameters computed in the AOD retrieval. With this information and with the reported Level 2 AOD, we have calculated an estimate of the MISR 555 nm AOD with the same diameter cut-off than the SPLA model, i.e., for fine (less than 1 µm of diameter), coarse (between 1 and 6 µm of diameter) and super-coarse (larger than 6 µm of diameter) aerosols. Briefly, the post-processing of the MISR AOD consists of the following steps: (i) we calculated the contribution of each basic aerosol model to the total AOD for each observed pixel; (ii) assuming that both, the reported refractive index for each model is independent of the size distribution, and the aerosol particles are spherical; we estimated the contribution of each bin (as the SPLA definitions) to the total AOD. In this work we only used the recomputed fine mode and total 555 nm MISR AOD."

7. **Page 5, lines 31–33:** "*In practice, our approximation of the AOD reprojected on the three modes of the SPLA model is accurate with a relative error of (maximum) 5% of the total AOD for the 5% less accurate recomputed retrievals*"

How was this relative error estimate derived? The information about the methodology how this relative error was obtained should be added to the manuscript.

We thank the referee for this question. We have taken the opportunity to recompute the MISR AOD with a better reprojection method, and we have updated the manuscript accordingly.

The updated method computes the optical properties of the aerosol populations using a Mie code, and we think that this is a better option than the one used in the previous version of the manuscript. To assert the accuracy of the reprojection method, the only possible reference dataset is the reported MISR small, medium and large AODs. These AODs are only published in their Level 3 product, while the reprojection process has to occur at the Level 2 stage.

In contrast to the total AOD, we did not find any documentation for the computation of the Level 3 of these AODs (by bin of size) in the MISR product. Thus, we assume that MISR computes the Level 3 small, medium and large AOD in the same way as the total AOD, that is, with the *mean* estimator of the Level 2 products.

Even if we cannot directly evaluate our reprojected AOD, a table is available ("Mixture Fractional Spectral Optical Depth Per Classification" from the Level 2 products) which relates each mixture model with their contribution (in AOD) to the estimate of small, medium and large AODs. These parameters are written in terms of relative contributions to the total AOD, that is, for each mixture model, the sum of the 3 parameters is unity. We have compared this table with an equivalent table computed through our Mie code. We have found that the differences in the values of these tables are small (less than 0.0035 in the table). These comparison indicates that is it possible to recompute the Level 2 AODs with an acceptable accuracy.

As we cannot completely simulate the MISR Level 3 product (because of the lack of documentation explained above), we do not expect that our approximation exactly matches with the reported Level 3 AODs. In fact, the RMSE between the AODs (for all of them, small, medium and large AODs) is close to 0.02, and the bias is not significant. The total AOD is not affected by this error.

In consequence, we have removed the sentence from the manuscript, as it refers to the accuracy in the recomputation of the total AOD in the Level 2 products from the previous version of the manuscript.

8. **Page 7, lines 3–4:** *"The standard deviation of the observational errors have to be prescribed to the data assimilation system."*

This sounds more like an introductory statement to the discussed aspect and seems to be out of place in the structure here. It rather should be moved to the beginning of the paragraph.

The referee is correct and we have added this information at the beginning of the section.

9. **Page 8, lines 17–18:** *"..., so we decided not to inflate the covariance matrices."*

This has already been stated at the beginning of the paragraph. The repetition here is redundant, and it can be removed from the text.

We have followed the referee's recommendation.

10. **Page 8, lines 18–19:** *"Additionally, a common configuration for all the inversions is fairer to draw consistent conclusions across the five observational datasets."*

This statement is a little bit difficult to understand. What does "fair" mean in this context here? Are the conclusions the ones that are consistent? Or does choosing a common configuration ensure a consistent approach for all the inversions to draw conclusions across the five observational datasets?

We agree with the referee's comment. We have clarified this point in the modified manuscript:

"Additionally, a common configuration for all the inversions ensures a consistent methodological approach to compare the five data assimilation experiments."

11. **Page 9, lines 3–14**

This whole part is an introduction in the five satellite instruments that have been used for the assimilation. This part is presented after details of the treatment of the data from the instruments have already been discussed. It should be moved to the beginning of the section on the observations, before the details are discussed.

We have moved this part to the beginning of the section.

12. **Section "3. Results", Figures 1 and 2**

Figures 1 and 2 present very interesting information about the differences between the AOD retrievals from the various satellites. One part of this information are the differences between the retrievals with respect to the relative fraction of the AOD that is coming from the fine mode relative to the total. However, this is difficult to evaluate from Figure 1 or 2, especially due to the different scales that are used for the fine mode AOD and the total AOD. I suggest to add a figure that displays the geographical distribution of the relative fractions of the fine mode AOD compared to the total AOD for the instruments for which it is available.

We have followed the referee's recommendation and we have added a third column in Figures 1 and 2. We are aware that the different color scales make the comparison harder, but we have included a note in the caption of the figure, indicating that the color scale of the fine AOD is exactly half of that of the total AOD, making an easier comparison. The caption now reads :

"Averages for the year 2006 of the satellite-derived AOD products used in this study. The AOD products are all regridded to a regular latitude-longitude grid of 0.5° resolution for MISR and SEVIRI and 1° for

MODIS and PARASOL. The total AOD is shown in the left column, the fine mode AOD (when available) in the middle column, and the ratio between the average fine mode AOD and the average total AOD is shown in the right column. Please note the 2:1 ratio of the color scales between the left (total AOD) and middle (fine model AOD) columns and the (somewhat) different wavelengths of the reported AODs."

13. **Subsection "3.4 Mineral dust flux"**

One result that is puzzling to me is the decrease in the mineral dust flux simulated with the model after assimilation, in the case of almost all satellite products (except for PARASOL), even though the prior AOD in the model is on average lower than the AOD from the observations. This appears to be counter-intuitive. If the model AOD increased after assimilation of the observations I would expect that this increase comes with a higher dust load and higher dust emission.

How do the authors explain this? This should be discussed in the manuscript.

The referee is right and this behaviour of the analysis seems indeed counter-intuitive. We have to clarify why, on average, the analysis AOD is lower than the prior AOD (Figure 4 and more quantitatively in Table A1), which is consistent with the decrease of the dust emissions after the assimilation. Even though the observational AOD is larger than the prior, the data assimilation system attempts to decrease preferentially the extremes of the departure distribution. This decrease of the departures is more effective on the left side of the histograms. The preferential decrease for the extremes of the distribution is due to the formulation of the cost function, where the distance to be minimized is related to the square of the departures and thus this is the preferred behaviour.

Additionally, the construction of the control vector does not allow creating emissions if the dust production module does not produce them in the prior. We have done a qualitative comparison between the assimilated, prior and analysis AOD at the daily resolution. This comparison suggests that the larger prior departures of AOD, that is, when the observations are larger than the prior AOD, are mostly due to the dust produced in individual dust events which are not simulated by the prior. With the current configuration of the data assimilation system, these departures cannot be decreased in the analysis. In summary, the system "easily" decreases the largest model overestimations of AOD, but it has a hard job to increase the largest model underestimations of AOD. This is also reflected in the decrease in the mean simulated AOD and the increase in the bias (in comparison with AERONET AOD).

We have included in Fig. 1 of this document, a frequency plot for one of the experiments, which illustrates the decrease of the left tail of the departure distribution. It is possible to observe, by comparing the first and second columns, that the large departures in the upper-left region of the Obs. vs Prior (that is, large prior and small observational AOD) panels are decreased in the Obs. vs Analysis panels, while the large departures in the lower-right region (small prior and large observational AOD) are not decreased.

The manuscript has been changed accordingly. We have included the following paragraph in Section 3.2:

"A common feature is observed in all the analyses of Fig. 3, which is the preferential decrease of the left tail of the departure distributions after the assimilation. In other words, the data assimilation system is more efficient (in terms of minimizing the cost function) in decreasing larger values of model AOD than in increasing small values of model AOD. The reason for this preference is linked to the constraints imposed by the dust production model and also to the definition of the control vector. The dust production module emits dust only if some conditions are met, for example, only when there is no vegetation, the wind speed is above a threshold value (depending on the soil texture), etc. These conditions are parameterised in the model, so they depend on the model performance, but it is important to note that these conditions are based on the physical mechanisms of the natural emissions of dust. The control vector is, in practice, a multiplicative factor for the aerosol emissions. If the dust production model has no positive emission flux, the analysis cannot increase these emissions. On the contrary, if the dust emission flux is too large, the analysis can decrease the emissions. In consequence, we think that the preferential decrease of the left tail of the departure distributions is due to deficiencies of the prior in simulating some dust emissions events."

We have included the following comment at the end of Section 3.2:

"... We would like to stress that, even though the mode of the departures is closer to zero in the analyses, the average of the departures is not necessarily closer to zero. For MODIS/Aqua, MODIS/Terra and MISR, the average of the departures for the *all* curve of Fig. 3 is larger in the analyses than in the prior. This means that for these experiments (as the average of the prior departures is positive), the average AOD in the analyses is smaller than the prior AOD. This is exemplified in the comparison with AERONET, in the Appendix A, and will be related with the overall decrease of analysed emissions in Sect. 3.4."

And the following comment in Section 3.4:

"...for the super-coarse dust emission panel. The decrease of emissions of the analyses with respect to the prior is consistent with the results discussed in Sect. 3.2, where the average AOD is smaller in the analysis than in the prior, for the simulated AOD coincident with the assimilated observations for the MODIS and MISR experiments."

Language and typos:

1. **Page 4, line 26:** Replace "*The later is mainly...*" with "The latter is mainly ...".

We have replaced this paragraph with the following (already written in comment number 4):

"We have improved the data assimilation system presented in EBCH16 in order to deal with the larger control vector. To this effect we have carefully recoded some matrix multiplication and inversion routines, paying special attention to the computational memory management and minimizing numerical errors as much as possible. We have also applied the algorithm of Qi and Sun (2006) to ensure the semi-positiveness of some of the matrices involved in the inversion."

2. **Page 5, line 30:** Replace "*independent from*" with "independent of".

Done.

3. **Page 6, line 32:** Replace "*... difference with EBCH16 ...*" with "... difference to EBCH16 ...".

Done.

4. **Page 6, line 33:** Replace "*... the standard deviation of the observational errors were set to ...*" with "... the standard deviation of the observational errors was set to ..."

Done.

5. **Page 9, line 21:** Replace "*for year 2006*" with "for the year 2006".

Done.

6. **Page 9, lines 21–22:** *"Several characteristics can be identified in these yearly averages of AOD and they will impact the assimilation analysis."*

I propose a rephrasing of the statement as follows: "Several characteristics that will impact the assimilation analysis can be identified in the yearly averages of the AOD."

We thank the referee for the suggestion. The sentence has been modified accordingly.

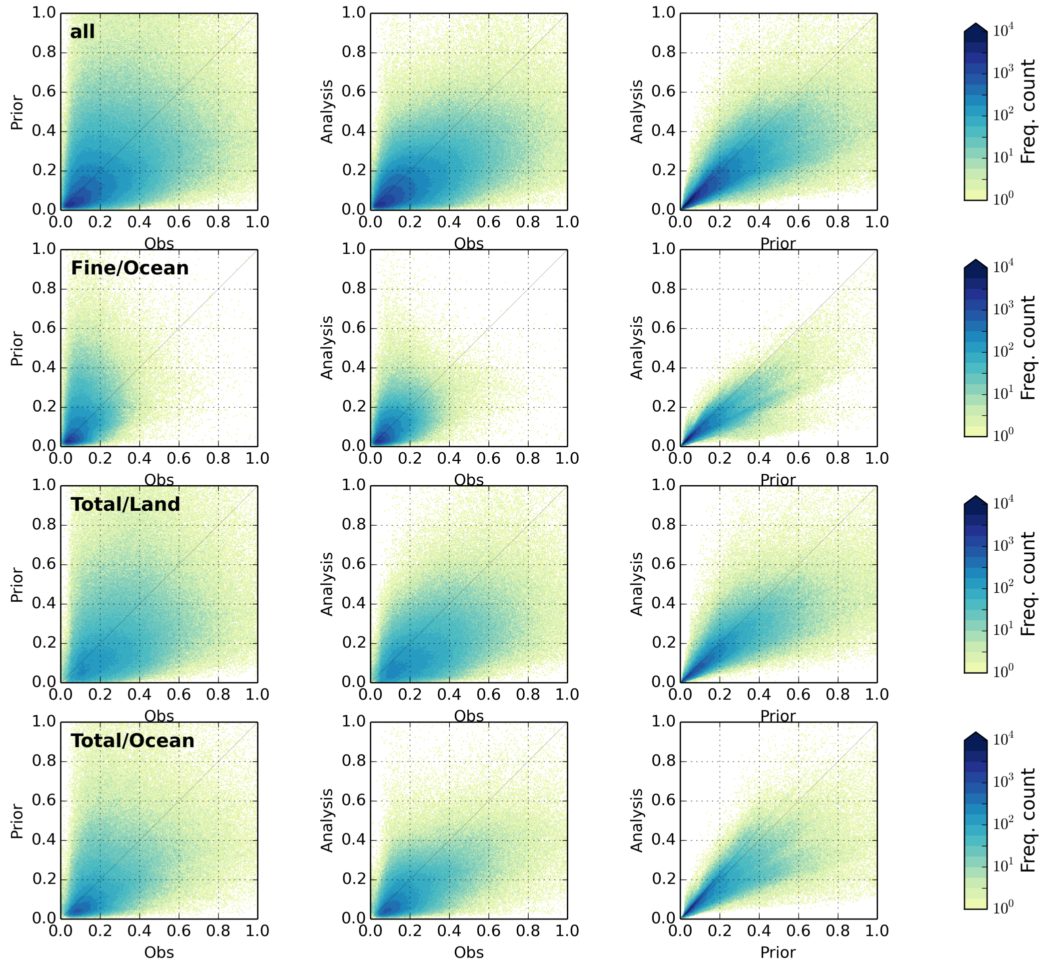

Figure 1: Frequency plots comparing the Prior, Analysis and Observational AODs for the MODIS/Aqua experiment. The two-dimensional histograms are made of 200 bins, so the color scale indicates the quantity of matchups between the variables in a range of ΔAOD = 0.005. Please note the logarithmic color scale.

References

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Kahn, R. A., Gaitley, B. J., Martonchik, J. V., Diner, D. J., Crean, K. A., and Holben, B. (2005). Multiangle Imaging Spectroradiometer (MISR) global aerosol optical depth validation based on 2 years of coincident Aerosol Robotic Network (AERONET) observations. *Journal of Geophysical Research: Atmospheres*, 110(D10). D10S04.

Qi, H. and Sun, D. (2006). A quadratically convergent newton method for computing the nearest correlation matrix. *SIAM Journal on Matrix Analysis and Applications*, 28(2):360–385.