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# *Interactive comment on* "An observationally-constrained estimate of global dust aerosol optical depth" *by* David A. Ridley et al.

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Response to Reviewers

We would like to thank all reviewers for their helpful comments and criticism on this work. We believe we have addressed the comments and made changes to the methodology and manuscript where possible. We now include supplementary figures and several of the figures in the manuscript have been updated.

Key changes include:

âĂć Analysis and statistics generated for log(AOD) rather than AOD



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âĂć Instrument uncertainty included in the estimate

âĂć Regional bias correction of satellite data by AERONET

âĂć Uncertainty in bias correction propagated through analysis

âĂć Marine Aerosol Network (MAN) data included

âĂć Supplementary figures of AERONET and satellite AOD histograms

âĂć Comparison of model AOD with daily AOD from MAN

âĂć Supplementary comparison with deposition flux

The key changes are that the global dust AOD is decreased from 0.033 to 0.030 and the uncertainty increased from 0.006 to 0.011 ($2\sigma$) as a result of considering instrument uncertainty and the uncertainty on the updated AERONET bias correction of the satellite retrievals. The observational estimate is hence closer to the AEROCOM model estimate. We believe that this better corrects for regional biases in the satellite retrievals while representing the inherent uncertainty in using limited in-situ measurements to apply correction factors over large regions. The regional estimates of seasonal dust AOD from the different satellite instruments are generally in closer agreement. The observational estimate is also brought closer to the MERRAero dust AOD; the previous discrepancy was of some concern because MERRAero assimilates MODIS AOD and may be expected to represent the dust AOD better than models without assimilation. The agreement between model and observational estimate improves over the mid-Atlantic, reducing (but not eliminating) the potential for systematically high dust removal in the models. While many of the quoted numbers change as a result of our reanalysis, all other conclusions remain essentially the same.

Please find the reviewer-specific comments and responses listed below.

Kind regards, David Ridley

Comments from Paul Ginoux

This is a very nice work, which will provide a better constrained mean dust load and optical depth. Still, I wonder about some biases related to satellite data in general, and MODIS Deep Blue in particular. The authors note a lack of bias in MODIS AOD based on the scatter plot of daily values at AERONET sites. However, these sites are characterize by different aerosol environments and surface albedo. Uncertainties related to satellite retrieved AOD between sites will be different. In Figure 3 of Ginoux et al. (Rev. Geophys., 2012), you will notice very different biases between regions. For example Australia is biased high, while Africa is slightly biased low. Although this study was done with Collection 5.1, similar results are obtained with Collection 6, but with much more reduced bias in Australia. My point is that there is very little information we can extract from your Figure 2. A better approach would be to also plot seasonal variation at dusty sites (e.g. Tamanrasset, Birdsville, Solar Village. Dunhuang, etc.).

Thank you for your comments on this work. The simplistic bias correction method that we applied is certainly a source of uncertainty. In response to the review comments we have revised the methodology to apply bias corrections that are specific to each region. We have revised the bias correction of the satellite data to be regional, rather than global and to incorporate Marine Aerosol Network (MAN) daily AOD in relevant regions. We assess an uncertainty to the bias correction by calculating the standard deviation in bias corrections for each year with sufficient (>100) coincident satellite and AERONET retrievals. There are still significant uncertainties resulting in this methodology as the AERONET sites will not represent the entire region, but we believe this goes some way to addressing your concerns and improving the correction applied to each region.

(We did also attempt a bias correction that used the lag-correlation of the AOD from GEOS-Chem to propagate the bias correction to regions surrounding the AERONET site. However, this did not take into account the surface reflectance influence on satellite retrieval bias (which would not share the same lag-correlation). We did not believe there was enough justification for using this approach without also accounting for the





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influence of surface reflectance, which was out of the scope of this project).

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I am also concerned about your method of temporal average of observations. If you consider only days with retrievals you will have a high bias, as you discard all days with dust being washout and rainout (low dust). This will be also true for AERONET data. But, it is uncelar which method you are using.

Apologies that this was unclear in the paper. We did indeed look at this impact. Firstly, we sample the models to the satellite retrievals and compare the resulting dust AOD with and without sampling. Globally, sampling increased the modeled dust AOD by <1% for MODIS Aqua and Terra and 1-2% when sampling to MISR. Even on a regional basis the sampling bias is less than a few percent. This is obviously only sampling the 'model world' so may not represent reality. If we use the MERRA reanalysis meteorological fields to compare the model dust AOD with and without cloudy regions (masking columns containing grid boxes with >50% cloud cover) we still don't see a large impact (2%), other than in the Gulf Of Guinea where cloud cover is persistent. Intuitively, we would expect there to be a bias between in-cloud and clear-sky dust but this suggests it is more balanced than expected over the timescales considered, probably through many compensating factors.

We have added the following to highlight this potential bias and the work we did to test the effect by masking the model with satellite data and with MERRA cloud cover (pg11):

"We calculate the modeled global dust AOD with and without masking to match the MODIS and MISR sampling, testing whether sampling affects the derived global dust AOD. We find negligible (<1%) changes in the modelled global dust AOD when sampling to the MODIS instruments and an increase of 1 - 2% when sampling to MISR. Therefore, we determine that sampling frequency is sufficient to represent the AOD in the regions considered. Furthermore, because the masking effectively removes cloudy regions, the very small change in the modelled global dust AOD indicates that there is no obvious bias in the global dust AOD when including regions within cloudy air masses, relative to clear-sky only. We also calculated GEOS-Chem global dust AOD after masking columns that have >50% cloud cover in any grid box, based on MERRA reanalysis. This causes the global dust AOD to increase by 2%, relative to when no masking is used, indicating that the difference between clear-sky and all-sky dust AOD is small. However, we acknowledge that poor representation of clouds in the reanalysis meteorology or potential satellite misclassification of heavy dust loading as cloud (Darmenov and Sokolik, 2009) could lead to a stronger perceived relationship between dust loading in cloudy and clear sky conditions."

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None of the models simulate dust from agricultural regions or with dynamic vegetation. Their contribution is highly uncertain but may affect your results regionally.

This is certainly true. It will not be an issue inside the regions considered (as we do not use model dust AOD here) but it may contribute to errors in model dust in other regions that will affect the global scaling. We have added the following caveat to highlight this uncertainty:

"Finally, dust emissions schemes currently used in the models are unlikely to reproduce emissions where vegetation cover is variable and will not represent dust from agricultural regions (Ginoux et al., 2012). Therefore, it is expected that the tuned emissions in models will overestimate emissions from large, permanent dust sources to compensate and partially explain the bias towards African emissions."

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Finally, you are most likely using MODIS quality flag 3 (QA=3) aerosol products, as advised by Sayer et al. (2013). However, it is not a good choice over dust sources as clearly shown in Figure 1 of Baddock et al. (Geophys. res. Lett., 2015). This choice of







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QA=3 may induce a low bias, if you use all days rather than just days with QA=3. On the other hand, if you divide the sum of all valid AOD by the number of days with QA=3, you will again create a high bias. In fact, it may be very high in some areas. Take a look at the factor 10 difference of frequencies between QA=1 and QA=3 in Figure 1 of Baddock et al. (2015). Hopefully this will help improve your results. Paul Ginoux.

Yes, the Baddock et al. work is very interesting. I spoke with Rob Levy about this, but unfortunately isolating QA=1 is not possible with the Level-3 product; that provides Quality-Assurance weighted AOD (giving a weighting of 1.0 to QA=1, 2.0 to QA=2 and 3.0 to QA=3 data) and standard AOD using no weighting but excluding QA=0 data. The merged ocean-DarkTarget-DeepBlue Level-3 product that we use has QA=3 data over land and QA=1-3 data over ocean. However, we have included reference to the Baddock et al. paper to highlight this possibility and to make sure people using Level-2 data in future studies consider the findings of that work. Thank you.

Addition in the MODIS description:

“The merged Level-3 product uses QA=3 data over land and QA=1-3 data over ocean, where higher quality data is given commensurate weighting. Baddock et al. (2016) show that correlation between the frequency of high AOD and dust source location is actually improved when using only QA=1 data. For data to be considered QA>1 the standard deviation in AOD between 1km retrievals must remain below a threshold of 0.18. Therefore, some legitimate dust-influenced retrievals over source may be discarded when using the Level-3 merged product. However, this is a trade off in terms of improving the quality of the retrieval away from source regions.”

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