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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 âĂć Instrument uncertainty included in the estimate âĂć Regional bias correction of satellite data by AERONET âĂć Uncertainty in bias correction propagated through

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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 (2σ) 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 (blue italics) listed below.

Kind regards, David Ridley

Comments from Natalie Mahowald

This is a potentially really important paper, with a sound methodology, for the most part. The issues come with the error analysis, which appears to substantially underestimate the errors. The paper also fails to provide context with previous studies. If these issues are fixed, the paper is likely to be extremely influential.

Thank you. We hope that the additions we have made in response to your comments

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and those of the referees have improved the paper significantly.

The main errors associated with knowing the dust aod come from: 1. errors with the retrieval algorithm, 2) spatial and temporal hetereogeneity in dust distribution, 3) spatial and temporal variability in dust composition and/or shape, 4) errors in detecting dust versus other aerosols or clouds. The authors seem to deal fairly well with the 4th of these, but seem to underestimate the errors in the other three. Please discuss the issues with the retrievals and all the problems with the retrieval algorithms. Are the algorithms making the same assumptions about dust properties? That would then add another error, which will be difficult to assess by just comparing different datasets. For example, if they assume all dust is one optical property, or spherical, or at particular altitudes, etc. Please describe these sources of errors.

We agree that the uncertainty has been underestimated. We now incorporate the retrieval uncertainty in the first stage of the bootstrapping process. When bootstrapping to create a seasonal mean AOD with standard deviation, we include the instrument uncertainty on the daily AOD, and combine the errors for each day used in the seasonal mean AOD. This does not alter the mean, but increases the standard deviation of the AOD at a specific location. However, we find that the final global dust AOD uncertainty increases by $<5\%$ because the uncertainty is dwarfed by other factors, primarily the uncertainty on the new regional AERONET bias correction and the uncertainty on the satellite seasonal AOD derived from bootstrapping (Table 2). We recognize that region-specific retrieval biases may exist and will be unaccounted for. This is now acknowledged in Section 4.4, a new section for unaccounted uncertainties.

The retrieval algorithm assumptions will affect how well spatial and temporal hetereogeneity in the dust distribution, composition and shape are accounted for. We now discuss the retrievals in more detail in Sections 2.1 and 2.2 for MODIS and MISR to show differences in assumptions:

“The MODIS retrieval algorithm uses a look-up table of surface reflectance for a set of simulated aerosol properties to determine the AOD that best represents the observed reflectance. For the Deep Blue retrieval, the most relevant to this study over dust-influenced regions, the assumed optical properties of the dust aerosol have a single-scattering albedo (SSA) between 0.87 and 1.0 for the look-up tables at 412 nm and 490 nm and a refractive index of 1.55 – 0.0i (at 670 nm). The Mie calculation uses an effective phase function, derived from comparison of the Sea-Viewing Wide Field-of-View Sensor (SeaWIFS) instrument retrievals with AERONET, over the ocean to account for non-sphericity. Different locations and loading conditions trigger changes in the wavelengths used in the retrieval, more information can be found in Hsu et al. (2004, 2013)”

“The MISR retrieval algorithm uses simulated TOA radiances using properties for eight particle types to determine the AOD. The optical properties of the two aerosol particle types corresponding to dust are calculated using the discrete dipole approximation and the T-matrix technique to account for particle non-sphericity (Kalashnikova et al., 2005; Martonchik et al., 2009).”

The broad bias correction of satellite-retrieved AOD to AERONET may account for some of the biases in the retrieval, although this correction is very uncertain and we are neglecting that the AERONET retrieval is not perfect. We now account for the large uncertainty in the AERONET bias correction, propagating that through to the global dust AOD estimate.

In the comparison of the MODIS, MISR and aeronet, what is the rms error? This error represents a combination of the spatial and temporal variability as well as errors in the retrieval algorithms, and needs to propagate into the error in your final estimate. As it stands, only the mean bias propagates into your error estimate, which will underestimate your errors. If I look at Moon et al., 2015, the error bar on individual retrievals in

MISR are at least 30%: how can you claim smaller error than that in your results? You seem to be assuming that these errors will average out, but this seems unlikely and this assumption would have to be justified.

We wouldn't necessarily expect the retrieval uncertainty to be similar to the 30% of Moon et al. as we are averaging over longer timescales and larger regions so should be able to beat down the uncertainty. However, as before there may be unaccounted biases. As mentioned above, we have revised the bias correction of the satellite data to be regional, rather than global and have added the histograms with statistics of the AERONET-satellite retrieval comparisons in the supplementary materials (Figures S1-S3). We now 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. This propagates the uncertainty in the bias correction through the analysis and now accounts for half of the uncertainty in the global dust AOD (Table 2).

You include a comparison of AOD across all sites in the world, with all types of aerosols. How does this comparison over just dusty regions compare? Is it better or worse, please explain.

Our regional comparison of satellite and AERONET AOD should address this concern. We have included histograms of the daily AOD comparisons within each region in Figure S1 – S3.

Dust is not homogeneous in chemical composition, size and thus optical properties, but the retrieval algorithms assume that they are. You should explicitly discuss this point, and you could bound the error from mineralogy using Scanza et al., 2015, which suggest for the CAM5, the impact of spatially varying optical properties depending on mineralogy is 0.002 out of 0.033 aerosol optical depth or about a 6% error (1 sigma). Then it would seem you would need to add all these errors to the total estimated error, without letting them cancel each other, and then it seems likely that you will get a reasonable value.

Thank you. We now include reference to Scanza et al. and discuss the added uncertainties from mineralogy and morphology (among other factors) in Section 4.4. However, it is not clear if the difference in global dust AOD when including mineralogy in CAM-5 (a decrease from 0.033 to 0.031) from Scanza et al. (2015) would bias our observational estimate higher or lower. Combining this error with our current estimate yields only a small increase; therefore, we simply highlight this uncertainty in the extra Section 4.4, added to discuss the uncertainties and biases that may not be captured by this work.

The last comment is to consider how this estimate differs from previous model/data comparisons (e.g. Cakmur et al., 2007; Albani et al., 2014 or Balkanski et al. 2007). There are two main differences. Here the primary spatial and temporal variability relationships come from the satellite remote sensing data vs. model results in those papers. And secondly, because the first two papers include comparisons to concentration and deposition data. To understand how important the second is, please provide a comparison of your 'constrained' AOD-implied concentration and deposition to available datasets. This can be done very simply, but just using, for example, the GEOSCHEM dust AOD to deposition to surface concentration relationships, and your inferred AOD at that grid box. That will allow you to do a very simple comparison and show that indeed, your approach is (probably) fairly consistent with the other datasets. It probably won't be completely consistent, since none of the models seem to be able to match the AOD, concentration and deposition data the same time. This information could be added to the supplemental material and referenced briefly in the text.

Thank you for this suggestion. We have produced an estimate of the dust deposition following the method you suggest above and have included comparison with deposition network data in Figures S10 and S11. We note that the result is strongly dependent upon the model used (GEOS-Chem). Also, we are producing regional dust AOD estimates that are not conducive to comparison with clustered deposition measurements. Indeed, the correlation is only slightly better than for the GEOS-Chem model, and not significantly so – in part owing to the reliance on the model AOD distribution and the model relationship between dust AOD and dust deposition. For this reason, it is not easy to compare with previous model studies. We have made sure to reference this work so that the reader can dig deeper into the underlying assumptions in the models and how they affect the model representation of concentration and deposition as well as the AOD.

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