Review of paper:

Evaluation of aerosol optical depths and clear-sky radiative fluxes of the CERES Edition 4.1 SYN1deg data product *by D.Fillmore et al.*

Positives

- Overdue assessment of Match aerosol properties used in the CERES data product
- Comparisons between MATCH and MERRA
- Using AERONET and BSRN references
- Efforts to match scales and conditions in data-comparisons

Concerns

- focus on AOD (also modulated by prescribed water uptake), while rad.flux disagreements are also effected by aerosol absorption (varies regionally/seasonally) and aerosol size.
- focus only on shortwave radiative (clear-sky) closure, while the added use of the longwave radiative (clear-sky) closure would provide extra constraints.
- Limiting AERONET data analysis to AOD, while detailing and complementing data (AODf, AODc, AAOD and even water vapor) are available.
- Ignoring a focus on (wildfire and dust) seasons, where aerosol signals are stronger.

*The authors would like to thank this reviewer for the careful reading and keen interest in the work presented. Throughout the review interesting comments and valuable suggestions are given and many are acted upon. However, we would like to address some of these major concerns, which echo throughout the review, at this time. The paper has two primary foci. The first is to describe the MATCH chemical transport model and its interface with the radiative transfer calculation in the CERES SYN1deg product, and the second to validate the resultant global AODs used in the radiative transfer calculations available from the CERES SYN1deg data product. In summary of the paper's introduction, we state: "*In this paper, we evaluate aerosol optical depth used for irradiance computations in the CERES project and analyze how the error propagates to clear-sky surface irradiances." *And though the reviewer has many thought-provoking ideas for further analyses we cannot address many at this point as it would require a rewriting of significant portions of code and re-running or the operational process that produces the SYN1deg product. For example, the reviewer suggests several times the separation of our results into more detailed analyses of aerosol species/properties with respect to their effect on radiative transfer calculations. However, the MATCH model does not resolve the aerosol size. Therefore, assimilation of fine and coarse modes separately is not possible though we do attempt such a comparison using our dust AOD components. Results are shown in our response to minor comment 18 below and are shown to be inconclusive. (We have ordered the reviewer's* *comments and responses are in italics. Figure and line numbers in our response refer to the original paper's.)*

General comments:

A. The paper investigates the quality of the aerosol representations of the Match model in radiative transfer applications for the surface (and atmospheric) radiation flux product. Considering that the surface (and atmospheric) energy budget are important for surface processes (and atmospheric dynamics) this contributions is overdue. First AOD data are compared to MODIS noon-time (retrievals) and to Merra (assimilations), then spatially limited (sparse, land-based) comparisons to AERONET data are analyzed and finally the calculated clear-sky downward radiative fluxes are compared to (also) spatially limited BRSN data. Finally, also necessary corrections, not just limited to aerosol properties are discussion so that closure with the (stronger to observed tied) TOA fluxes are achieved.
There are apparent limitations, that cannot be changed, such as (1) the climatological emissions (without the ability to cover specific dust or wildfire events … other than general noon-time (total) AOD adjustments with MODIS retrieval data) and (2) assumed aerosol types (refractive indices, size, water uptake).
Many of the offered comparisons are interesting. For instance the separation between less cloudy and cloudy events, the relatively strong (stronger than in Merra) aerosol water uptake is revealed. Also, the separation of the analysis to the reference (AERONET, BSRN) into region for the focus on the representation biases of specific aerosol is commendable but in the end the final conclusions leave more questions than answers.
In order to get closure with TOA CERES clear-sky data, the full potential of aerosol properties is not investigated by rather changes to water vapor and solar surface albedo are 'invited'. This is disappointing from an aerosol property perspective (AERONET offers a split into fine and coarse mode AOD contributions, AAOD absorption data for high aerosol load cases on which I would focus first, and even water vapor column data, for LW closure) and from a radiative flux (closure) perspective (as SW data are also accompanied by LW data).
I know that the paper has already some volume but the last sentence of the conclusion is not satisfying at all.

Though the last several sentences in our conclusion may not be satisfying to the reviewer, they do state succinctly the current state of our ability to evaluate outputs from the MATCH model and impact on radiative transfer results found in the SYN1deg product. We use comparisons of clear sky shortwave irradiance calculations with observations as a tool to measure MATCH inputs, not as a study of radiative closure. Though obviously closely intertwined, a full discussion of radiative closure, or lack thereof, within the SYN1deg product, is beyond the scope of this paper. We address the use of fine and coarse mode observations from AERONET in our response to comment 19. from the reviewer.

B. On another note, I would also look to compare the (clear-sky) surface (and also TOA) radiation budgets of CERES (with the Match data) to those in Langley SRB product. Maybe in this context even aerosol optical and radiative (also component) properties of MACv2 (derived from optics) could be compared.

C. The MACv2 (1x1, mon) aerosol climatology is available via anonymous ftp … and even single scattering properties for your 31 (17 +14) band spectral resolution are available
ftp-projects.zmaw.de/aerocom/climatology/MACv2_2018 all
subdirectories are useful … but those 4 most useful for you
/documents - documentation in papers
/550nm – 550nm properties for the reference year
/spectral/ssp_31bands - your spectral resolution for the 2010 reference year
/spectral/ssp_31bands - aeback … are pre-sel aero components with assumed opt properties)
/spectral/ssp_31bands/by_years - your spectral res. for indiv.years (only anthro. AODf changes)

(for access: use filezilla [FIREFOX does not work anymore] or use lftp from a linux machine)

Release 3 of the Langley SRB product used a simpler aerosol scheme based on continental and marine aerosol types whose initial values were drawn from modal values from MATCH results. SRB Release 4 uses the MAC v1. However MACv1 provides climatological mean aerosol optical thickness. Hence it misses large events such as smoke and volcanic ash. We do not think that a comparisons of climatological means add any additional value to the manuscript as we already include significant comparisons to AERONET observations at higher temporal resolution.

Minor comments:

1. Line 33 "AOD are greater at all-sky conditions" not necessarily in modeling … "supported by AERONET" how? as AERONET only samples at cloud-free view.

Though AERONET inversions require their cloud masking algorithm to indicate 'clear', Figure 8b) of the manuscript shows AERONET observations taken under various cloud fractions as determined by upward looking surface shortwave radiometers via the Shortwave Flux Analysis (SWFA) algorithm (Long et al, 2006). The figure delineates a distinct difference in AOD observed when the SWFA indicates clear sky (SWFA=0.0) relative to when it does not. Likewise, our primary source of cloud fraction for this study is based on the percentage of clouds in a 1deg grid box in which an AERONET site is located. Figure 9 shows that as the satellite-based cloud fraction increases within a 1-degree grid box AERONET retrievals of AOD also increase. We elaborate on the relationship between AERONET observation, cloud fraction and water vapor in Section 3.

2. Line 35 Merra like Match are also using MODIS data … so we compare to model applications of satellite retrievals (which could be incorrect and biased) but not against the truth.

We produce a global product and so compare our results with those from MERRA to give a global picture. We state that MERRA assimilates MODIS AOD, as well as some AERONET and fire information, which implies the MERRA data is not entirely independent of our results. After MODIS assimilation MATCH remains slightly closer to MODIS AOD which we consider to be a good result. 'Truth', in so much as it can be defined, is reserved for comparison with AERONET which we discuss in detail and quantify in Tables 2 and 3 against both MATCH and MERRA results.

3. Line 46 Differences can be attributed not just to amount (AOD) but also to aerosol absorption and aerosol size (SSA). For larger differences in case of dust aerosol it would be also great to look for consistency with broadband longwave fluxes. (This however requires not only good data on dust size and dust IR absorption but also accurate data for water vapor profiles and dust altitude).

We note that a 20% decrease in column precipitable water commonly results in a decrease in downward longwave irradiance (DLF) at the surface of ~4%. On the other hand, keeping water vapor fixed and changing aerosol from 1 micron dust to water soluble sulfate aerosol reduces the DLF by ~0.8%. Given that we have found good agreement between the GEOS5.4.1 column precipitable water with micro-wave radiometer observations we decided to not extend the paper with analyses showing LW comparisons.

We understand that differences are attributable to more than just AOD, however the output we retained from MATCH and radiative transfer model runs did not include the combined aerosol properties. That is, the various constituents (and so their associated scattering/absorption properties) are weighted and averaged for each RTM run. We did not retain that information. This makes it almost impossible to 'unscramble the egg' of the aerosol properties that were used in the RTM calculations without modifying and re-running the production code which is not possible at this time.

4. Line 140 are the needed ancillary data (10m winds, climatology oxidants fields and emission inventories .. what databases?) for each specific year (since 2000) applied … or are these based only a general climatology?

In Line 114/115 we state that "MATCH is a transport model …driven by offline meteorological fields from …NCEP reanalysis." Table 1 (and it's description in lines 138-148) lists details of how each aerosol type is modeled and whether or not it is based on a climatology.

5. Line 149-158 the assumptions for the aerosol component optical properties are essential, thus at least component reff and RFimag at 550nm (and for dust components also the RFI at 10um) and resulting SSA values at 550nm for all components should be listed. I also assume a component external mixing … correct?

For the aerosol types used in the running of the Langley Fu & Liou radiative transfer model we have added a plot (now Fig 1) of SSA and g at 550 nm. Hygroscopic aerosols are shown as a function of relative humidity.

6. Line 183 By assuming that AOD differences drive the changes in aerosol mass, it is likely postulated that the model assumed mixtures and mass extinctions apply, which may not be the case especially if AOD changes are associated with a singular aerosol component. In that sense it would be better to assimilate at least fine-mode and coarse mode properties separately as their properties are quite different. Another limitation is that the fine and coarse mode assumption for absorption and size in MODIS retrievals likely differ from those assumed in the Match model, so that the AOD comparison are biased.

This is an interesting idea but outside the scope of this research. The MATCH model does not resolve the aerosol size. Therefore, assimilation of fine and coarse modes separately is not possible.

7. Line 197 it is interesting that Merra considers more input than just MODIS AOD … but I wonder in what way other day will and can override MODIS AOD data… thus I think the Merra data cannot really serve as reference. (In that context also the aerosol component treatment is likely different). Figure 2 line 205 the multi-annual differences between Merra and Match are large and even often with different signs in some regions (and more than 0.3 is very large!)

That MERRA assimilates more information than MODIS retrievals does not remove it as a source of comparison. In fact, it enhances the comparison by showing places/times (such as the recent spate of intense forest fires) where MATCH is dependent upon MODIS identifying the increase in AOD. It points to the need to update MATCH to be more responsive to high time resolution events and to better identify the source of such event. For example, though MATCH may assimilate the AOD from a smokey fire, after the AOD is viewed by MODIS and assimilated, it does not know the source of the aerosol and so misses the increase in black carbon from such an event.

8. Line 215 could not the daily MODIS data be subsampled for improved Match model comparisons (although MODIS may be still biased). Then it also would be interesting to

compare fine-mode AOD and coarse mode AOD. On the other hand more than 15 years of data twice a da(y) averaged (via monthly) into multi-annual global averages should provide sufficient statistics.

To return to the model inputs and sample MATCH values at MODIS observation times constitutes a significant effort that, while it might be interesting, does not change our results and will not add significant content to the paper.

9. Line 220 the number of MODIS AOD –compared to other AOD data- will dominate so differences in AOD input between Merra and Match should not matter that much

This is true and we've added to this sentence " when and where these events might occur."

10. Line 224 AOD are generally smaller over ocean than over land (expect for outflow regions) so that AOD differences should be smaller. Generally, oceanic assimilated oceanic AOD differences are smaller although Merra has significantly larger (MODIS-like) AOD over the southern oceans.

It does appear that the MERRA product is slightly higher than MODIS along the storm tracks in the southern ocean.

11. Line 225 the sharp land/sea contrast off northern Africa in differences (likely a model feature) are concerning, as well Merra's much lower values over SE and E Asia and Match's larger values over E Asia, E. Europe/N.Asia and over the Andes mountains stand out. I would investigate in what way a too strong absorbing aerosol type in the model would cause an AOD overestimate (e.g. in Match) or a too waekly absorbing aerosol type in the model would cause an AOD underestimate (e.g. in Merra) – assuming that the retrieval absorption assumption are correct. (It also would not hurt to compare SSA maps between Merra and Match to better understand the large AOD differences in the models in some regions).

The purpose of Figure 2) is to describe, succinctly, differences between the MODIS AOD, which is assimilated by both MATCH and MERRA, to the AOD's output by these models after the assimilation process. We discuss in detail the tendency of MATCH to overestimate AOD over land due to the dominance of the influence of aerosol climatology under cloudy sky conditions throughout the discussion portion of the paper. While it is interesting, for instance over the equatorial rain forests to find differences of opposite sign, we can only speculate on why this might be so for MERRA.

12. Line 233 the log/log plot choice hides the (MODIS high) bias at lower AOD values. Nonetheless the scatter (consider that these are assimilation) are considerable. Overall, the assimilated global annual AOD values are lower at 0.142 in Merra and 0.160 in Match. It is known that MODIS is biased high (mainly at lower AOD values) so the relatively large global

average in Match surprises. It would be nice to compare by AOD-bin and by region/seasons at least for ideas on how to find clues for better comparisons … so Figure 4 offers some insights but many regional differences are so large that they need some explanation.

Figure 3 is in essence, a scatter plot analog to Figure 2. It encompasses a large number of comparisons over a significant time span, 20 years. Hence the need for the log density plot. Figure 3 says that, compared with MODIS AOD, MERRA-2 AOD is lower by 0.032 and MATCH AOD is lower by 0.014. MODIS AOD is higher Scatter is large with RMS of each model approaching 75% of the mean MODIS value. The primary conclusion is that after assimilation of the MODIS data, the MATCH model remains closer to the mean MODIS values and the overall fit to the MODIS data is slightly better in MATCH where the linear slope is 0.66 for MATCH and 0.54 for MODIS.

(The difference between MERRA-2 and MATCH AOD shown in Figure 4 is probably caused by aerosol models (we need to ask Fillmore about his thoughts on the reason for the difference).)

13. Figure 4 Line 261 why just 1 month (jan 2020) and not 15+years? It is interesting that AOD increase from clear-sky to all-sky in Match apparently only happens pollution regions over E. Asia US and Europe, which begs the question if assumed ambient rel. humidity aerosol water uptake in Match at higher rel.hum is too strong (also clouds with 100% hum. only occupy specific layers). And with clouds in the neighborhood there is not only the issue with aerosol size swelling but also the issue with wet removal. Thus, global models are highly diverse if AOD under all-sky are actually larger or smaller with respect to the clear-sky value. The large difference over biomass regions suggest that aerosol (fine-mode) absorption is much stronger in Match. Thus I would compare fine-mode SSA and water uptake between both models.

We deal with only one month for this analysis as it is necessary to see the effect of clear sky on results. One cannot make a multiyear clear sky comparison. We attribute the increase in AOD from clear sky to all sky MATCH to the climatological aerosol used in the MATCH model. Clear sky results should generally correspond to time assimilated values matching more closely with the AOD from MODIS which should provide a more robust result.

We disagree with the reviewer's comment "The large difference over biomass regions suggest that aerosol (fine-mode) absorption is much stronger in Match". First, MATCH does not separate a fine mode from a coarse mode. Second, AOD is constrained by MODIS and Figure 4 shows AOD comparisons. SSA plays a minor role for the difference shown in Figure 4. Regarding MATCH having increased AOD over tropical forests relative to MERRA we state in the text that we suspect this is due to our lack of utilizing Quality Assurance values from the MODIS product. Whereas MERRA using the MODIS combined Deep Blue/Dark Target (where MODIS, when combining the two products, uses the QC parameters) MATCH assimilates both Deep Blue and Dark Target into its noon zonal band (as shown in Figure?) and we do not check the QC *parameters. We believe this allows for higher AOD's, possibly due to cloud masking errors in the individual products, that we are not filtering out, but are filtered out of MERRA. This will be corrected in Edition 5.*

14. Line 268 … and aerosol absorption (and dust size)

We do not do these other comparisons because of limitations described in the summary paragraph above.

15. Figure 5 line 291, Bejing is an urban difficult site with a lot of near surface pollution during winter. Both models suggest larger AOD with clouds, whereby the increase is much stronger in Match than Merra. Otherwise the AERONET values are larger, most likely due to nitrate aerosol, which is missing in Match and possibly also Merra.

We concur with the reviewer's comment.

16. Line 304 the cases with less than 1% (in 1deg regions) are probably too few for useful statistics. (I would split all cases in ca equal counts with more and less clouds). I am bit surprised than with the 1% threshold relative many cases are found … so do I misinterpret here? Also note that in the comparisons many AERONET sites are more local (urban) and not regionally representative.

In fact the reviewers comment is pertinent. If we restrict AERONET observations to when an approximately 111Km2 grid box is completely free of clouds (as determined by CERES satellite cloud analyses) the sample is quite small, particularly over cloudy regions like the Amazon and Congo. But, by increasing the filter to 1% the numbers increase significantly giving more robust samples.

AERONET sites were chosen based on regional location and length of record. We did not consider rural vs. urban in our decision to include a site.

17. Line 325 … would this make you want to reduce the water uptake in Match?

We do not know if the water uptake in MATCH is too large or simply MATCH produces too much aerosol. Our sense of the error as described in the discussion is that MATCH is too high compared with AERONET in summertime over Beijing.

18. Table 2 Line 341 I wonder about the many matches for Australia, the small AOD values over Brazil with the biomass burning, the relatively large AOD values over central Africa (although the sites are spread. and the small values for N.Africa associated with dust. I strongly recommend to use AERONET as reference not just for AOD, but also for the split in AODf and AODc and also for AAOD data (at larger AERONET AOD cases AOD550 > 0.25). Given the large differences between the models in some regions (in Fig 4) the bias differences among the models are relatively small … why?

We have at our disposal no simple method to separate out fine vs. coarse mode aerosols from the output retained. Though we note that the distinction between fine and coarse is somewhat arbitrary as it is based solely on the observed AERONET size distribution. Thus a fine aerosol might be 0.1um at one site and 1.0um at another. (Figure 9 below, taken from Dubovik et al. 2000.)

DUBOVIK ET AL.: ACCURACY OF RETRIEVED AEROSOL PROPERTIES

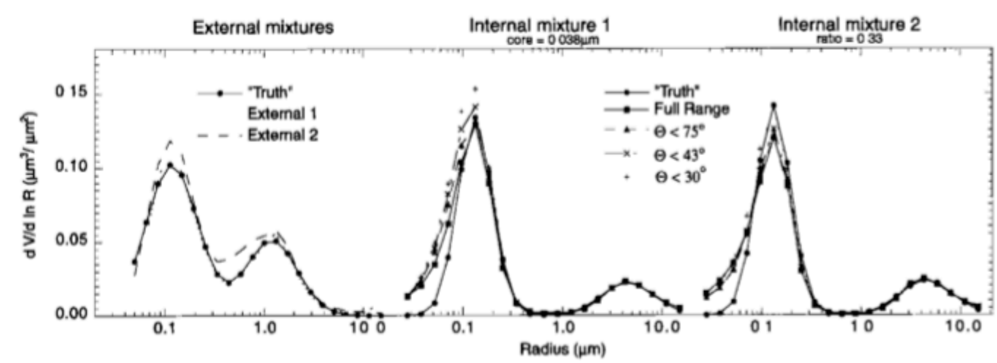
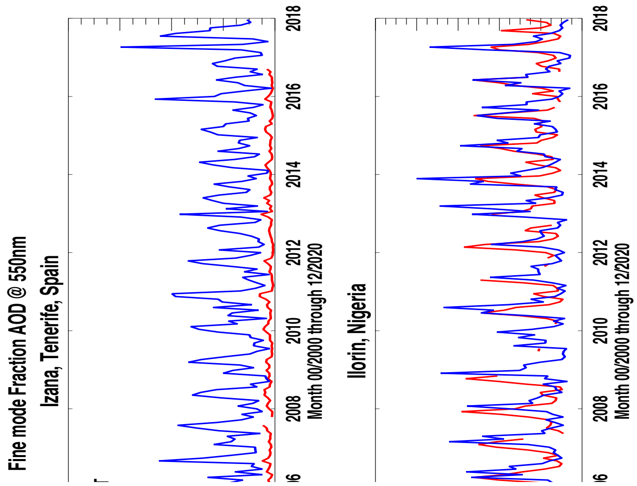
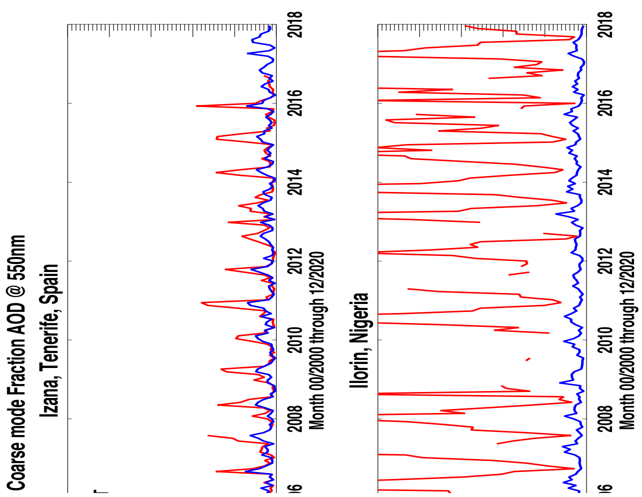


Figure 9. Volume size distributions of inhomogeneous aerosols (externally and internally mixed) retrieved using the model of scattering by homogeneous spheres.

None the less we did attempt such a comparison simply using large and small dust particles as defined by MATCH and plot them here against fine and coarse mode observations from AERONET at two sites likely to be affected by dust, Ilorin, Nigeria and Izana, Tenerife, shown below.



AERONET Fine mode fraction of AOD compared to MATCH average of dust particles < 1um. At Ilorin there is some correlation and similarity in magnitude, but not at Izana.



AERONET Coarse mode fraction of AOD compared to MATCH average of dust particles >1um. At Ilorin there is some correlation and large disparity in magnitude while Izana, there is a good correlation and similar values.

The point of these plots is that the correlation between the Fine and Coarse mode AERONET observations with, in this case dust aerosols from MATCH, is somewhat random. True fine and coarse modes would require a detailed extraction of all the aerosol profile data, after water uptake by soluble aerosols had been taken into consideration. These values are not retained and would require significant code changes and re-running of the product.

19. Line 440 Figure 10 (not 8

Thank you for catching that mistake, it has been corrected.

20. Line 469 also dust size is an issue (as larger dust for the same mid-vis AOD has lower SSA and also larger spectral near-IR AOD)

This is true and as MATCH does not resolve size per se it is an issue for the MATCH/Langley Fu & Liou aerosol scattering properties as well.

21. Line 511 I do not follow the argument of a likely lower dust AOD … as such a tendency seems to go the right direction … given the 0.07 bias in Table 2…??

We state in this paragraph that the in order to better match observed TOA reflected SW up, the EBAF-surface product adjusts the AOD upward, on average, globally, by ~0.02. Further we state this seems reasonable for mid-latitude and Asian regions based on our comparisons with AERONET. Lines 511 through 513 point out that this increase in AOD, however, is inconsistent with results shown in Table 2 for North Africa where we are already biased high relative to AERONET observations. We have changed the sentence to: "The positive bias found in the downward shortwave irradiance for the North Africa group (Fig 12c) is not consistent with the positive bias of aerosol optical depth shown in Table 2."

22. Line 560 I wonder about the surface albedo treatment (at 14% solar broadband values are mentioned and now a significant 3% increase was mentioned). I hope the Kato model uses the spectral dependency for local soil conditions from MODIS. I would tinker not just with AOD but also with size and absorption before starting to change the surface albedo.

The spectral albedo shape is derived from the MODIS surface albedo data product. However, we believe that the effect of surface albedo to downward shortwave irradiance under clear-sky conditions is small compared to the effect of AOD. The spectral shape of the albedo is not adjusted in the EBAF process, only the broadband albedo difference.

Computing surface irradiance are with spectral albedo. Irradiance adjustment in the EBAF process uses only a broadband albedo difference.

23. Line 571 … exactly … and NO it should be part of this study.

While we appreciate the desire to see more results, we will have to leave this to a future study where we anticipate the variables needed and output them as the model is run.