

ANSWERS TO THE REVIEWERS:

“Comparison of aerosol optical depth from satellite (MODIS), Sun photometer and pyrhelimeter ground-based measurements in Cuba” by

Juan Carlos Antuña-Marrero et al.

Anonymous Referee #1

Antuña-Marrero et al. have compared aerosol optical depth (AOD) retrievals from the spaceborne MODIS instruments to ground-based observations done in Cuba. The ground-based observations include sun photometer (AERONET) and pyrhelimeter measurements from several sites. The authors conclude that both MODIS instruments produce AOD data with corresponding accuracy, the Dark target retrievals are in better agreement with the ground-based observations than the Deep blue retrievals, and the pyrhelimeter measurements could be used to construct reliable time-series of broad-band AOD at sites which do not have sunphotometer measurements.

The manuscript has the potential to be an interesting paper but it requires some work.

- First of all, the manuscript is hard to follow due to complicated sentences and other language issues. The English language has to be improved throughout the manuscript to make it easier to understand.

Answer: The manuscript has been revised by a Professional Translator of English maternal language. We understand the difficulties because the analysis includes different comparisons with two criteria, with two algorithms and two sensors. All this does not facilitate the comprehension of such different number of situations.

- Secondly, I do not see the value of doing the comparison between the MODIS and AERONET observations using single observations. Single observation pairs may not represent the same air mass thus, they might have different values for the right reasons. In addition, the uncertainty/noise in single observations is larger than in spatially or temporally averaged values. As the comparisons using single observations and the so-called “daily means” produced comparable statistics I do not see any reason to use single observations in the analysis. Therefore, I suggest that the authors leave out the discussion/results regarding single observations.

Answer: Precisely, the purpose of the comparison in this case is to test if single observations could be used for the determination of the aerosols climatology over land in Cuba because of the mixing of water and land areas in our area of study. A new version of Figure 1 has been included to highlight the reasons for using L2 MODIS data instead of L3. The sentence “The grid cell of 1° in latitude and longitude shown in red in figure 1 is an example of the limitations of the MODIS L3 products to represent land areas in the case of Cuba.” has been included on the 1st paragraph of the Section “2.4 Coincidence criteria for MODIS and Sun photometer measurements”

A priori we cannot ensure that both criteria give similar results, we must test this in our area, taking into account the different number of data and the characteristics of the land/water surface. After that, obviously we analyzed only the results of one criterion. We think that this position is correct. Furthermore in the case of solar direct radiation, only single data are available.

We also rewrote part of this paragraph and unified the description of both criteria in section 2.4

Otherwise, we cannot understand why single observation may not represent the same air mass and median values do. Single observation or median values during a time overpass are currently used by the satellite community to do this type of studies. Despite the variability of aerosols, the time between the pairs of observations of MODIS and sunphotometer is generally smaller than the time of air mass changes. Bear in mind that these measurements are of columnar type, and the AOD parameter represents the total load content of particles including whole atmospheric column and they are not influenced by winds in the sense of particle concentration at surface.

- Thirdly, not all the methods are described accurately enough. For example, the calculation of broadband AOD (BAOD) or monthly averages are not described at all.

Answer: The section 2.3 was implemented in order to describe in detail the main retrieval equation and the parameterized variables. In addition, the main assumptions are described. Anyway, the reader is referred for further details to the original paper for where all the assumptions are described in detail.

The monthly average was described by the new sentence: “based on the mean of each month for every year of the measured period”.

- Fourthly, the manuscript lacks discussion on the results. What do the results mean and how do

they compare with are studies done in this region?

Answer: We think that we analyze and discuss the results of the comparison between sun-photometer and MODIS with an extend number of statistics and the linear correlation methodology in an extensive and correct way. We have experience in this type of studies/analysis as can be seen by other published works for aerosol studies (Bennouna et al., 2011; 2013) or by other atmospheric components as water vapor (Vaquero-Martinez et al., 2017, <http://dx.doi.org/10.1016/j.jag.2017.07.008>; Vaquero-Martinez et al., 2018; <http://dx.doi.org/10.1016/j.rse.2017.09.028>). To our knowledge few studies or none have made considering two criteria, two algorithms <http://dx.doi.org/10.1016/j.rse.2017.09.028> and two platforms, giving sometimes complicate patterns of comparisons between all these different cases or situations. Furthermore, the authors have not found any other comparison between MODIS and sun photometers in the Caribbean Basin and only two studies conducted on islands at different latitudes and regions appear in the literature. In spite of the differences found between the different areas of study, we have carried out the comparison with our results and this has been incorporated in the text, at the end of section 3.1.

- Lastly, the comparison of AERONET and MODIS AODs is a routine task thus, the results may not be that interesting to a wider audience. The most interesting part of the paper is the broadband AOD thus, the authors should discuss it in more detail. For example, it would be interesting to see the time series of BAOD from the four sites: how they compare with each other and with AERONET and MODIS. And if there are clear differences during some periods, it would be interesting to read what is causing the differences.

Answer: The opinion of the authors is that for the present paper time series does not provide better information than the one provided by the statistics already reported, but this is just a result, because as mentioned this Caribbean area has not been analyzed before in detail (the mixing of land and ocean water areas is a big challenge for the retrieval algorithms) and this area is very interesting for regional climatological studies. Our current national research project is to determine the climatology of AOD for Cuba from MODIS: the AOD and AE climatology for Camaguey and the BAOD climatology for Camagüey, Topes de Collantes, Jovellanos and La Fe. It includes the analysis of the respective AOD, AE and BAOD time series and their trends. Those results will be reported in future publication and here we report the climatology given by MODIS and its comparison with the others two series of BAOD and Photometer. The article is already long enough and it is focus on MODIS data, not on the characteristics of the other time series of data. But they serve for an interesting and necessary comparison.

Consequently, the manuscript should be thoroughly revised to clarify the content and to make it more interesting to the readers.

Answer: We think we have followed this recommendation making a thorough revision of the paper.

My specific comments are given below:

GENERAL ANSWER: The text of the manuscript has been substantially modified in the introduction and, mainly, in the result section. Therefore some of these responses have a minor contribution in the text now, or no longer make sense.

P2, Abstract: The reported results should be given with more details and numerical values.

Corrected: The abstract was rewritten including more details and numerical values.

P2, 48: Results improve in comparison to what?

Corrected: This section was removed of the article because is out of the focus of MODIS comparison.

P2, 51: I understand what you mean with “extending backward in time AOD estimates” but it sounds grammatically confusing.

Corrected: That part of the sentence was change to ...”*for producing historical AOD estimates where series of DNI measurements are available.*”

P3, 57: You mention that aerosols have a small mass but compared to what? Gases have even smaller masses and they have even larger effects on the climate.

Corrected: The reviewer is right; the aerosols mass is not relevant for the research described in the paper. The sentence has been changed to ...” *Atmospheric aerosols play an important role in weather and climate.*”

P3, 59: “chemical Earth’s processes” → chemical processes, modified this sentence

Corrected.

P3, 70: comes → goes

Corrected.

P3, 78: Antuña → Antuña-Marrero

Corrected.

P4, 104: accumulate → have accumulated

Corrected.

P4, 108: Regions visually → *Modified*

Corrected.

P5, 112: improving the signal → Modified

Corrected.

P5, 134: What is considered as moderate or high AOD? Please provide a numerical value.

Corrected. The sentence reads now *“However, for the DB algorithm AE skill increases for moderate or high AOD aerosol loadings, AOD > 0.3 (Sayer et al., 2013).”*

P5, 137: Please explain in more detail how the AE is calculated in the traditional version.

Corrected. The sentence reads now: *“The enhanced Deep Blue algorithm methodology for deriving the AE in Collection 6 is the same than in Collection 5. It uses the Ångström power law and the AOD values at 412, 470 and 650 nm. Under non-vegetated surfaces AE is derived using the AOD from pair 412/470 nm. For vegetated surfaces AE is derived from the 470/650 nm pair. In the case of a surface with mixed vegetated and non-vegetated areas AOD values at the three wavelengths area used together to derive the AE (Hsu et al., 2013).”*

P6, 140-143: I don't think this information is needed in the manuscript.

Corrected. The first sentence of the paragraph was erased. The following sentence changed and now reads, *“The Camagüey sun photometer, installed under an agreement between the University of Valladolid (UVA), Spain, and the Meteorological Institute of Cuba (INSMET) for joint aerosols research, contributes to the Aerosol Robotic Network (AERONET) of NASA (Antuña et al., 2012).”*

P6, 144: What do you mean with replacement? Do you mean the annual calibration of the instruments or was the cimel replaced with another one? Please clarify.

Corrected. Yes, the Cimel is replaced by a fresh calibrated one after '1-year' of measurements (standards of quality in AERONET). Now the sentence reads, *“Although the annual replacement of the instrument by a calibrated one, sent from Valladolid to Camagüey, confronted multiple delays”...*

P6, 155: Is the selected wavelength range closest to the wavelength range used in the DB retrievals?

Answer: Yes. The AE from AERONET is derived with the pair 440 – 675 nm and the DB AE is derived using the pairs 412 - 470 nm for non-vegetated surfaces; the pair 470 - 650 nm for non-vegetated or the two pairs for mixed non-vegetated and vegetated surfaces.

P6, 158: Please clarify what you mean with an observation here. Is it an observation at a specific time at all possible wavelengths or are all the wavelengths calculated separately?

Corrected. The sentence is now: *“It consisted of 29,940 single observations of AOD (340 to 1640nm) and AE_{SP} .”*

P6, 159: You are using the Ångström power law so please reference it accordingly.

Corrected. The sentence is now: *“Applying the Ångström power law we converted the single sun photometer AOD measurements at 500 nm wavelength to AOD at 550nm, (AOD_{SP}) making use of the AE_{SP} from the same measurement.”*

P6, 166: What do you mean with “cloudiness equal or less than one”? Usually cloudiness is given with values ranging from 0 to 1, 0 being cloud-free and 1 being completely cloudy.

Corrected. The sentence is now: *“We combined the cloud-free conditions, selecting DNI measurements under cloud cover equal or less than 1/10 of the sky with the cloud-free condition in the line of sight to the sun.”*

P7, 167: “That-free”. What does it mean? Please explain here in detail how the AOD is calculated from the pyrheliometer observations.

Corrected. The sentence is now: *“The cloud-free condition in the line of sight to the sun is satisfied selecting DNI measurements with a clear line of sight between the pyrheliometer and a region of 5° around the sun (GOAC, 2010).”*

P7, 180: Why is the monthly mean PW calculated differently for Camagüey than for the other sites? How large difference in the BAOD could this change cause? It would be clearer and more robust to use the same method for each site.

Answer: According to table 3 in Gueymard, (1998) for PW = 5 cm with an error of $\pm 20\%$ in the PW value, the magnitude of the possible absolute error in BAOD is between 0.0145 and 0.0325. The first value is estimated for an instrumental error of $\pm 0.5\%$ and the second for $\pm 3\%$.

We used PW from sunphotometer at Camagüey because of its lower error than PW from reanalysis data. At the other 3 sites we have only PW from reanalysis data. The differences between monthly mean PW from sun photometer and reanalysis at Camagüey (estimated for 2008 to 2015) are in the order of 1% for the wet season (November to April) and 8% in the rainy season (May to October). Then the magnitudes of the possible error in BAOD produced by the PW differences between the sun photometer and the reanalysis are inside the estimated total error in the determination of the BAOD, 10^{-2} .

P7, 185: “enough amount of satellite” → enough satellite

Corrected.

P7, 186: Why is Cuba different from the other regions? Are there more clouds or something else?

Corrected: The difference we are referring to is the areal extension of Cuba (the case of the insular countries) compared with continental regions. Two sentences were included after the first sentence of this paragraph: *“The reason in general is the little areal extension of islands. In addition, in the case of Cuba its particular narrow latitudinal, elongated longitudinal extensions and the vicinity of the sea makes the MODIS L3 product not suitable for climatological studies.”*

P7, 187: To my knowledge, 2 data is typically used when comparing with AERONET observations. L3 is used in model comparisons and climatological analysis.

Corrected: We modified the sentence to express clearly that we are referring to the climatology. The following sentence have been included after the former one: *“In that sense is absolutely necessary to validate the single MODIS L2 with the single sun photometer measurements.”*

P7, 188: Which methodology are you referring to?

Answer: We are referring to the methodology to maximize the number of pairs of single observations without any repeated observation. In addition, the sentence was modified: *“We designed and applied a methodology for maximizing the available pairs of MODIS L2 and sun photometer AOD and AE measurements coincident in space and time avoiding the duplicate use of any of them.”*

P8, 215: As I mentioned in the general comments, the exclusion of the analysis regarding individual measurements would make the manuscript easier to follow.

Answer: We do not agree. The comparison of the individual measurements is necessary to determine the real differences between the single MODIS L2 products and the sun photometer measurements in Cuba.

P9, 243: As you mention in the text, “daily mean” is not the best term for the calculated values. Maybe collocated mean values or something like that would be better.

Corrected: The term “daily mean” was replaced by “collocated daily mean”

P9, 247: Is there a minimum number requirement for the MODIS and AERONET observations? Sayer et al. (2014) required only single observations from both instruments but other studies have used lower limits ranging from 2 to 5 (e.g. Petrenko et al. (2012)). I would prefer the usage of some lower limit (e.g. at least 3 observations from MODIS and 2 from AERONET). Of course the selection of these limits affects the number of overpasses available for analysis so you have to select in a way that you do not throw away too much data but at the same time, you only compare representative observations.

Answer: We required only single observations as in Sayer et al., (2014) for the single observations. For calculating daily mean we required at least 2 sun photometer observation and 2 from MODIS. In section 2.4.1 we added the sentence: *“At least two single AOD_{SP} and two single AOD_t (AOD_a) measurements were required to calculate the average”*. About this point, different authors select different criteria as in Bennouna et al., (2011, 2013). These two

references were added in the new version of the manuscript.

P9, 248: Did you limit the AE comparison to cases with moderate or high AOD? I think you should because the MODIS AE's are only usable in those cases.

Answer: In figure 3 may be appreciated that low AOD values predominate, at least for the spatio-temporal coincident MODIS and sun photometer observations. In the case of the coincident measurements of the AE, after eliminating the cases with 1.5 and 1.8 AE values (columns 4 to 6 on table 6) and also eliminating the cases with $AOD \leq 0.3$ we ended with 29 cases for Terra and 10 cases for AQUA. The statistics are below:

	AE _{ta}
RMSE	0.89491
MAE	0.73562
BIAS	-0.41833
R	-0.71978
Cases	39

P10, 262: This is a confusing sentence. You should explain here that EE_DT is defined relative to AERONET AOD and is therefore independent of the MODIS retrievals.

Corrected: Now reads *“We used the EE_{DT} expression in equation (2) for estimating also the uncertainty when the DB algorithm is applied. The purpose is to allow comparing the performance of DB and DT algorithms directly (Sayer et al., 2014).”*

P11, 278-279: I wasn't able to follow this sentence

Corrected: *All this part of results section has been modified substantially.*

P11, 284: Can you really say that the monthly values will also be good because the daily values are good? In addition to the accuracy of the daily means, the quality of the monthly means depends on the temporal sampling within the months. For example, if you have 5 accurate daily means from a month but all 5 values are from the first week of the month, will the monthly mean be representative? When you calculate monthly averages you should also consider the distribution of the daily means within the months. If the temporal coverage is poor, the monthly mean will not be that reliable. Consequently, the authors should explain in text in detail how they calculated the monthly means and they should use some kind of a lower limit for the daily means before monthly means are calculated.

Answer: The sentence on P11, Line 284 says: *“From the results described above it is evident that the monthly means AOD_t and AOD_a derived using the DT algorithm agree better with the AOD_{SP} than the ones derived using the DB algorithm”*. We do not say that the monthly values will also be good because the daily values are good.

We agree that it will better to apply strict climatological procedures for conducting the AOD comparisons. However, the available sun photometer and the pyrhemeters measurements in Cuba do not have homogeneous time distribution allowing complying with those climatological procedures for the comparisons. To deal with these data limitations we are deriving simultaneously the climatology the AOD from the sun photometer for Camaguey and the BAOD and MODIS climatology for the four pyrhemetric stations.

P11, 290: This section could able be omitted.

Answer: We do not agree. The comparison of the individual measurements is necessary to determine the real differences between the single MODIS L2 products and the sun photometer measurements in Cuba.

P12, 305: What does the work “single” refer to in the title?

Corrected: It is now: *“Monthly means observation.”*

We also realized we have been using the terms “single” and “individual” for the same type of observations. We unified the terminology using now only the term “single”.

P12, 319: You should check if sampling could explain the peak. In any case, some explanation for the feature would be welcome.

Answer: We did it. We replaced the sentence: *We have not explanation for it.* with the following paragraph: *“In the table S2, for the DT algorithm, we can see that the number of cases of the AOD_{ta} from March to April drops a 55 %. However, something similar happens for the DB algorithm in table S1, with the number of cases of the AOD_{ta} dropping from March to April a 61 %. Then the sampling could not be attributed as the cause of the peaks in RMSE and MAE for the DT algorithm. We plan to revisit this feature in future studies.”*

P12, 330: What could explain this feature? Is it related to the number of points in each month?

Answer: The number of points could not explain the fact that for both DB and DT the magnitude of R is equal or lower than 0.5 on December and January. From December to March the number of cases remain over 150 for both DB and DT, while the rest of the year the number of cases are equal or lower than 90 (except for DT in August). Then if the number of cases is the cause we should expect for February and March values of R lower than 0.5 and that did not happen both for DB and for DT.

P12, 331: This is surprising result as the correlation coefficients are the lowest during the months with the highest fractions. What could explain this contradiction?

Answer: We agree this is a surprising result. We have no explanation for it for now.

P13, 337: well → better

Corrected.

P13, 351: I think this analysis should also be done using daily means instead of individual observations.

Answer: We followed the reviewer suggestion. The results for the Collocated daily means, excluding MODIS AE values of 1.5 & 1.8 were added to table 6.

Taking into account the statistics for this new set of results we re-wrote the discussion of table 6, which reads now: *“Statistics on table 6 for the single observations, both considering and excluding AE_t and AE_a equal to 1.5 or 1.8 show high values of RMSE, MAE and BIAS. These results in addition to the values of R, below 0.5, evidence big differences between the AE from both instruments. Similar results are in the case of the collocated daily mean both considering and excluding AE_t and AE_a equal to 1.5 or 1.8. The comparison showed the low quantitative skill of the AE_t and AE_a for this site providing numeric magnitudes of it. One factor contributing to this result is that the AE from MODIS has large uncertainty in low-AOD conditions, because the AE is a gradient between two small numbers (Wagner and Silva, 2008). Another factor could be the poor performance that the DB algorithm showed in the comparison with AODSP.”*

P13, 355: 1S → S2

Corrected.

P14, 365: As you have DNI measurements only once an hour, you could modify the coincidence criteria to average a couple of measurements even though both of them are not within the one-hour time window. That might provide you with more comparable observations.

Answer: That is an option. However, we decided to remain the one hour time window.

P14, 368: The combination of the sites works only if all the sites have similar aerosol populations. Otherwise the combination might mask some site specific features and, in the worst case, lead to erroneous conclusions. Are the aerosols the same at each site?

Answer: Very few aerosols studies exist in Cuba. The unique aerosol characterization among the four stations used in the present research has been conducted in Camaguey. In addition, the statistics for the individual stations will not be robust because of the few pyrhelimeter and MODIS coincident cases at the individual stations. We will do that in the near future. We are at the beginning of the data rescue of the actinometrical observations conducted before 2010 in Jovellanos and before 2011 at La Fe, both extending far before Terra's record.

P14, 370: Why did you leave out the days with high AOD? Are they cloud contaminated?

Answer: Yes. We changed the sentence to: *“In addition, we did not considered the very few cases with values of BAOD > 0.5, around 1 %, of all the cases, **to avoid the possibility of an inadvertent cloud contamination.**”*

P14, 376: Why the DB retrievals match better with BAOD than DT retrievals. It was the opposite with the AERONET data. What about monthly comparisons between MODIS and BAOD?

Answer: We have no answer for this fact. We verified the calculations and found no errors. Because the hourly time step of the DNI measurements the BAOD have a low level of coincidence with MODIS observations as is shown in table 8. In addition, between May and October the clear sky conditions are less than the 10% of the available solar radiation measurements. Hence, the number of cases for monthly statistics of the coincident BAOD and MODIS measurements is very small for the statistics between May and October.

P14, 381: I would suggest to change the places of the sections 3.3 and 3.4. It would be clearer if the BAODs would be compared first with ground-based and then with space borne measurements.

Corrected, but we have removed the comparison between BAOD and sun-photometer, because the paper is focused on the comparison of MODIS and ground-based instruments.

Corrected.

P15, 401: There isn't much discussion regarding the results. How do these findings compare with other studies done in this region/with similar methods?

Answer: The authors have not found any other comparison between MODIS and sun photometers in the Caribbean Basin and only two conducted on islands at different latitudes and regions. A comparison with former regional results for North and South America, have been added.

I would also like to see the long BAOD time-series from these sites and how they compare with the AERONET and MODIS time-series. Those results would make the manuscript more interesting to a wider audience.

Answer: The opinion of the authors is that for the present paper time series does not provide better information than the one provided by the statistics already reported. The current research project is producing the climatology of the AOD for Cuba from MODIS; the AOD and AE climatology for Camaguey and the BAOD climatology for Camagüey, Topes de Collantes, Jovellanos and La Fe. It includes the analysis of the respective AOD, AE and BAOD time series and their trends. Those results will be reported in a publication.

P15, 402: Please include numerical values in the conclusions to make it more robust and clear.

Answer: Numerical results have been included in the conclusions.

P26, Fig 3: Please include the error envelopes in the plots. Density plots would make it easier to see where most of the observations are (see for example Fig. 5 in Petrenko et al. (2012)) and you should limit the axis range to 0.0-0.6 to remove unnecessary empty space.

Corrected: The new figure 3 contains density plots, with axes ranges between 0 and 0.6. In addition, figure 6 is now a density plot. In both figures the least squares linear fit is also shown and drawn, together with the number of cases.

P28, Fig 5: Shouldn't these values be collocated? Now the AERONET data seems to have over two times more points. Collocated values would enable a more meaningful comparison.

Corrected: The new figure 5 shows the frequency distribution of Ångström Exponents only for coincident sun photometer and Terra and Aqua values. The same distribution but for sun photometer and Terra and sun photometer and Aqua separately are shown in figure S4, added in the supplements