ANSWERES TO THE REVIEWERS:

"Comparison of aerosol optical depth from satellite (MODIS), Sun photometer and pyrheliometer 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 pyrheliometer 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 pyrheliometer 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 ± 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 ± 0.5 % and the second for ± 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 <= 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 pyrheliometers 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 pyrheliometric 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 AODta 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 AODta 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, ead 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 pyrheliometer 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 firs 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.

P15, 392: 2S → S2

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

Anonymous Referee #2

Received and published: 24 November 2017

This manuscript focuses on the comparison of aerosol optical depth (AOD) retrieved using satellite (MODIS) and ground-based instruments (sun photometer and pyrheliometer) in Cuba. This study draws conclusions about the different MODIS aerosol algorithms (Dark target and Deep Blue) for deriving aerosols on oceans and land, as well as, the distinct retrievals between the different sensors onboard Terra and Aqua platforms.

An interesting aspect of this paper is the potential to use pyrheliometer measurements as a reliable source for aerosol characterization in the absence of sun photometer data, allowing for the reconstruction of AOD time series under such circumstances. It is a notable contribution to extend the existing AOD series in the Caribbean region, a key zone for studying dust transport.

However, the paper needs major modifications before being published.

GENERAL COMMENTS:

- The use of English is poor. I would strongly encourage the authors to have the paper checked by a native English speaker. There quite a lot of grammar prob- lems, mistakes with figure numbers and general imprecisions which make the paper quite difficult to read and understand.

Answer: The manuscript has been revised extensively by a Professional Translator of English native language. Apart, as recommended the paper has been modified considerably in order to be improved scientifically, mainly in the section of results. Also the objective of the paper is clearly exposed.

- From the information given in the introduction, I understand there are no previous studies in scientific journals about the AOD series extracted from the Camagüey sun photometer, and in Cuba in general. If so, the AOD series presented in Figure 4 (a) is the first AOD series derived from sun photometry published in Cuba, and not enough discussion has been carried out on this important result. On the contrary, notable efforts have been devoted to the superficial and less interesting discussion on the AOD extracted from MODIS. Under this circumstance, a non-existing AOD time series can hardly be extended backwards in time, as is stated in both the Abstract and in the Introduction alike. I strongly recommend the authors reconsider the objective of this publication, placing emphasis on the AOD retrieval by the sun photometer and the Broadband AOD (BAOD) from the pyrheliometer (both at Camagüey). MODIS comparison should be used once the complete AOD series in Cuba has been published and evaluated.

Answer: AOD data series by sunphotometer 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. **See also the answers below.**

The systematic lack of high-impact references in the manuscript is very concerning. Despite the fact there are published few papers in the literature aimed at the aerosol characterization in Cuba, there are many examples at other sites around the world to enrich the methodology and the discussion section as well. A reader could have the impression that this type of analysis has been only performed in Cuba.

Answer: Some more references concerning MODIS (or other sensors) aerosol studies in different areas of the world have been now added in the manuscripts (i.e., Papadimas et al., 2009; Mishchenko, et al., 2010; Kahn et al., 2011; Bennouna et al., 2011, 2013; Witte et al., 2011; Gkikas et al., 2013; 2015; Levy et al., 2015). 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 been 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. The authors have not found any other comparison between MODIS and sun photometers in the Caribbean and only two conducted on islands at different latitudes and regions. This has been discussed at the end of Section 3.1.

- Despite being the most relevant contribution to the paper, the pyrheliometer description is missing. Therefore, please include at least some information about pyrheliometers spectral response, field of view (FOV) and calibration.

- Apparently, four pyrheliometers have been used in this study. However, only one of them (the one at Camagüey) has been used in the discussion. Please clarify the source of these discrepancies. If these three instruments don't provide reliable results, please do not include any mention of them in the paper.

Corrected: In answer to the two comments above the paragraph was erased and replaced by the section: *"2.3.1 Direct normal irradiance measurements."* where the pyrheliometers used in Cuban stations are described and the process of manual measurements and computerized processing are briefly described, pointing to the appropriated references. Also the information about the pyrheliometer FOV and its estimated level of error are provided.

In addition the term "pyrheliometer" was replaced in the paper by *" broadband pyrheliometer"*

- Is the inclusion of single measurements in the discussion section really important? Personally, I am quite confused with the results section. Reducing the amount of approaches will improve the readability of the paper considerably.

Answer: 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

A new version of Figure 1 has been included to highlight the reasons for using L2 MODIS data instead 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:"

We also rewrote the first paragraph of section: "2.4 Coincidence criteria for MODIS and Sun photometer measurements: "

- As I mentioned previously, the FOV of the pyrheliometer used in the present study is missing in the text but it is expected to be significantly different to the FOV of the sun photometer. Please include discussion on how to reconcile the two different pieces of information and the possible impact of the scattering radiation effect on pyrheliometer measurements as a result of the wider FOV.

Answer: The pyrheliometer FOV was included in the text. A paragraph was added at the end of section 2.3.2 describing the effect of the circumsolar radiation and our decision of not using DNI observations for the large solar zenith angles.

- The BAOD retrieval method is not described adequately. Equations and information about how the different terms have been calculated need to be included. García et al. (2015) is not an appropriate reference in this context.

Corrected: The reference (Garcia et al., 2015) was erased. The section *"2.3.2 BOAD retrieval method."* Was included in the text. It describes the main retrieval equation and the parameterized variables. In addition, the main assumptions are described. The reader is referred to the original paper for details on the methods origin and assumptions.

Regarding the BAOD uncertainty estimation, if we look at the methodology presented in Gueymard et al. (1998), the total uncertainty in BAOD can conceptually be evaluated taking into account three sources of error (modelling, atmospheric inputs and experimental errors). I strongly suggest the authors perform a more rigorous estimation of the BAOD uncertainty.

Answer: According to table 3 in Gueymard, (1998) for PW = 5 cm with an error of ± 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 ± 0.5 % and the second for ± 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}.

SPECIFIC COMMENTS:

P2, Abstract: Please quantify the main results including some numbers in the Abstract.

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

P3, .57: Is the small mass of aerosols an important issue related to the role of atmospheric constituents in weather and 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, . 78: Antuña-Marrero et al. (2016) does not seem an adequate reference.

Answer: We consider that is an adequate reference because it describes the aerosol research conducted at Camaguey. Nevertheless, we added the URL http://www.goac.cu/uva/ to provide additional information on this subject.

P5, .117-123: I think this MODIS calculus chain is not relevant in this manuscript.

Answer: In the author's opinion, considering the broad and diverse audience of this journal, at least a simple explanation of the MODIS calculus chain is necessary.

P5, .129-131: This information is missing in the Introduction and would be better in the introductory part.

Corrected: The following sentence was modified and moved to the introduction: *"We used the combination of both Terra and Aqua and DB and DT algorithms to evaluate the reliability of the satellite AOD and AE retrievals for selecting the most appropriate data set to derive the climatology of both aerosol parameters in Cuba."*.

P6, .140-147: It does not seem relevant to me for this study.

Corrected: The sentence was erased. The following was modified: "*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, .148-155: Information about sun photometer nominal wavelengths is required.

Corrected: The following sentence was added: *"In general, Cimel sun photometers nominal wavelengths are 340, 380, 440, 500, 675, 870, 935, 1020 and 1640 nm. In some cases, the 1640 nm is replaced by a 1240 nm."*

P6, .159: Please refer to Angstrom Law and reference this law 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. L. 159: Please, include in this section the information required about PWV calculation using the sun photometer.

Answer: We consider it is not necessary to include in the paper the information required about PWV calculation using the sun photometer. We neither include information on how reanalysis derives PWV. The PWV is used to derive the BAOD it is not subject of the comparison. References are provided.

P6. l. 161: Please, clarify the method and include equations as well.

Corrected: The section *"2.3.2 BOAD retrieval method."* Was included in the text. It describes the main retrieval equation and the parameterized variables. In addition, the main assumptions are described. The reader is referred to the original paper for details on the methods origin and assumptions.

P7. l. 167: What does "That-free" mean? Is it a typo?

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).”*

P.7, .179-183: This is not the place to describe the PWV retrieval using sun photometry. In addition, García et al. (2015) does not seem an adequate reference for this methodology.

Answer: We are sorry but we do not agree with this comment. This is the right place for this explanation, because we are describing how we derived the PWV to be used in the algorithm described by Gueymard (1998) to derive BAOD. We already did this as it is described in García et al. (2015)

P7, . 182: Is Barja et al. (2015) the only reference for this type of analysis?

Answer: Yes, it is the only reference about deriving PWV from reanalysis for Cuba. It includes a comparison of those PWV with the ones measured by sun photometer and GPS at Camagüey.

P7, . 182-183: Gueymard et al. (1998) pointed to instrumental errors and PWV estimation as the main limiting factors of this method. So, the uncertainty of this type of methodology is linked to the uncertainty on these factors. Please include details on these sources of error.

Answer: According to table 3 in Gueymard, (1998) for PW = 5 cm with an error of ± 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 ± 0.5 % and the second for ± 3 %.

We used PW from sun photometer 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, . 185-187: It sounds better in the Introduction. Take into account that many references in the literature using the MODIS Level 2 in these types of comparisons exist. Please remove this sentence.

Corrected: The sentence “.In response to it, we used the MODIS L2 product instead of L3 used commonly for this type of studies.” Has been erased.

We consider the paragraph should remain in this section. In addition, we modified the whole paragraph to express clearly the goals we pursue: “*Obtaining enough satellite measurements for climatological studies at insular states represent a challenge with respect to the typical amount of data available over continental regions, like US, Europe and China for example. 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. In response to it, we plan to use the MODIS L2 product to produce the aerosols climatology for Cuba instead of L3 used commonly for this type of studies. In that sense is absolutely necessary to validate the single MODIS L2 with the single sun photometer measurements.*”

P8, . 208: Why these two periods?

Corrected: There was a typo regarding the first period. It is 2001-2015 and not 2011-2015; it was corrected. The sentence was rewritten for clarity: *“It shows the amount of data available or the entire period 2001 to 2015, when pyrheliometer measurements at Camagüey are available and 2008 to 2014, the period of the available sun photometer measurements.”*

P12, . 315-319: What about the maximum in summer?

Answer: We added the description of the statistics for the summer: *“In summer, RMSE and MAE show their maximum values associated to the maximum values of the AOD resulting from the arrival of Saharan dust to Cuba transported across the Atlantic. The BIAS is negative in summer for both Terra and Aqua AOD, showing the fact that AODt and AODa measurements have higher magnitudes than AODSP.*

P12, . 315-323: Figure 3 > Figure 4? Please revise figure numbers and table captions.

Corrected: The captions were corrected and the figure revised.

P. 17, . 461: This is not a reference but an URL.

Corrected: The URL was referred directly in the text and eliminated from the reference list.

Figures 3 and 6: Please add diagonal lines. I also suggest including some statistics in the figures. Mixing tables and figures could help to improve comprehension.

Corrected. Figures 3 and 6 contains now the density plots. The least squares linear fit is also shown and drawn, together with the number of cases.

Comparison of aerosol optical depth from satellite (MODIS), ~~Sun~~sun photometer and broadband pyrheliometer ground-based ~~measurements~~observations in Cuba.

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Abstract~~:~~

~~In the present study, we report the first comparison of the aerosol properties measured with sun photometer at Camagüey, Cuba, with the MODerate resolution Imaging Spectroradiometer (MODIS) instruments on Terra and Aqua satellites. We compared the aerosol optical depth at 550 nm (AOD) and the Ångström Exponent (AE) from the sun photometer for the period 2008 to 2014 with the same variables measured by both MODIS instruments, that are spatially and temporally coincident. The comparison includes AOD derived with both Deep Blue (DB) and Dark Target (DT) algorithms from MODIS Collection 6. The AOD derived with DT algorithm for Terra and Aqua agrees better with AOD from the sun photometer than the AOD derived with DB. Additionally there is little difference between AOD from both satellite instruments, when they are compared with sun photometer AOD, allowing to combine AOD from Terra and Aqua for more comprehensive climatological statistics. The comparison of the AE showed similar results with reports in the literature about the little skills of the current DT and DB algorithms for its retrieval. In addition, we report the comparison of the broadband AOD (BAOD) from pyrheliometer measurements located at Camagüey site and other three meteorological stations along Cuba, with AOD measurements from the sun photometer and from MODIS onboard Terra and Aqua. The comparison of the BAOD from the four sites as a whole with coincident AOD from MODIS onboard Terra and Aqua showed similar results than the ones of the comparison between the sun photometer AOD and the AOD from the two satellite instruments. In the comparison between the BAOD and the AOD at each one of the eight individual sun photometer wavelengths, the results improve in the spectral range 400 to 675 nm, with the best result at 500 nm. The BAOD typical uncertainty ranges from 0.04 to 0.06 at this band. The results from the BAOD comparisons demonstrate its reliability for characterizing AOD at sites with no sun photometer and for extending backward in time AOD estimates.~~

In the present study, we report the first comparison between the aerosol optical depth (AOD) and Angstrom exponent (AE) of the MODerate resolution Imaging Spectroradiometer (MODIS) instruments on the Terra(AOD_t) and Aqua(AOD_a) satellites and those measured using a sun photometer at Camagüey, Cuba, for the period 2008 to 2014. The comparison of spatially and

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temporally coincident Terra and Aqua data includes AOD derived with both Deep Blue (DB) and Dark Target (DT) algorithms from MODIS Collection 6. Combined Terra and Aqua (AOD_{ta}) data were also considered. Assuming an interval of ±30 minutes around the time-overpass and the area of 25 km around the site of the sun photometer, two collocated coincident criteria were taken: individual pairs of observations and both spatial and temporal mean values, the latter of which we call collocated daily means. The usual statistics (BIAS, MAE, RMSE) together with linear regression analysis are used for this comparison. Results show very similar values for the two criteria. For collocated daily means, the DT algorithm generally displays similar behavior for AOD_t, AOD_a, AOD_{ta} compared to AOD_{SP} with lower values for the statistics and higher homogeneity than the DB algorithm. Root mean square errors (RMSE) of 0.060 and 0.062 were obtained for Terra and Aqua daily means with the DT algorithm, and 0.084 and 0.065 for the DB algorithm, respectively. MAE follows the same patterns. Although BIAS for both Terra and Aqua daily means presents positive and negative values, those of the DT algorithm are lower than the DB algorithm. Combined AOD_{ta} data also give lower values of these three statistical indicators for the DT algorithm. Both algorithms present good correlations for comparing AOD_t, AOD_a, and AOD_{ta} with AODSP. In general, linear correlations for both algorithms are good, although the DT algorithm yields better figures, giving slopes of 0.96 for Terra, 0.96 for Aqua and 0.96 for Terra+Aqua compared to the DB algorithm which has slope values of 1.07, 0.9, 0.99, thus displaying greater variability. Comparison with the AE showed similar results to those reported in the literature concerning the two algorithms' capacity for retrieval. A comparison between broadband AOD (BAOD) from broadband pyrheliometer observations at the Camagüey site and three other meteorological stations in Cuba and AOD observations from MODIS on board Terra and Aqua show a poor correlation with slopes below 0.3, with the exception of Terra (0.38) for

Comentado [JCAM1]: Creo que es necesario aqui y un poco mas abajo para que no se confunda con la single observations

both algorithms. Aqua(Terra) showed RMSE values of 0.073(0.080) and 0.088(0.087) for the DB and DT algorithms. As expected, RMSE values are higher than those from the MODIS/sun photometer comparison, although they are in the same order of magnitude. Results from the BAOD, derived from solar radiation measurements, demonstrate its reliability to describe AOD climatology at sites with no sun photometer and to produce historical AOD series estimates.

KEY WORDS: ~~Atmosphere, Remote~~atmosphere, remote sensing, ~~Aerosols~~aerosols, Aerosol ~~optical depth~~Optical Depth (AOD), Broadband Aerosol optical depth (BAOD), AERONET, MODIS

Comentado [JCAM2]: La frase "BAOD radiation measurements" era incorrecta

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1. Introduction~~:~~

~~Although atmospheric~~Atmospheric aerosols ~~have a small mass, they~~ play an important role in weather and climate~~.~~ (IPPC 2013). Depending on the physical ~~and~~ /chemical and optical properties of ~~the aerosol, its~~atmospheric aerosols together with their origin and ~~its~~ spatial and temporal distribution, they can affect the Earth's radiative ~~transfer,~~budget, as well as dynamic, biogeochemical and chemical ~~Earth's~~ processes (Knippertz and Stuut, 2014; Seinfeld and Pandis, 2016). ~~Atmospheric aerosols have~~All of these processes play a ~~strong effect on the atmospheric latent heating spatial heterogeneity and the atmospheric radiative transfer (IPCC, 2013).~~key role at a global and regional scale due to the high spatio-temporal variability of aerosol properties. Aerosols can also affect the biosphere and, in particular, humans in several ways~~. For~~: for example, ~~in the case of~~ the Saharan dust transported to America across the Atlantic~~, it~~ supplies nutrients to the Amazon forest (Swap et al., 1992; Yu et al., 2015). Moreover, in the Caribbean, in addition to ~~the locally originated~~ aerosols of local origin, dust makes the ~~aerosol~~ amount ~~to~~of aerosol exceed ~~the~~ air quality standards associated to human health ~~effects~~ (Prospero and Lamb, 2003; Prospero et al., 2014). The great variability of Saharan dust transported to the Caribbean basin has been documented using long-term ~~measurements~~observations in Barbados (Prospero and Lamb, 2003; Prospero and Mayol-Bracero, 2013) and more recently ~~measurements~~ in Miami, Guadeloupe and Cayenne (Prospero et al., 2014). ~~The earliest attempt to measure the~~The Caribbean region is thus of great importance for aerosol studies due to its low aerosol background, which helps aerosol transport studies (Kaufman et al., 2005; Denjean et al., 2016; Velasco et al., 2018). One difficulty, however, is that it is an area where land and water make up a mixed pixel when remote satellite aerosol studies are carried out.

In order to improve calculations of aerosol climatology for Cuban land areas, which remains ongoing, we compared aerosol ground-based observations and available satellite data, as

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a first step towards assessing this climatology. This involves a comparison between all the available Camagüey sun photometer aerosol optical depth (AOD) data and the BAOD provided by solar radiation measurements with the series of AOD (550 nm) from the MODerate resolution Imaging Spectroradiometer (MODIS) instruments on board the Terra (2001 to 2015) and Aqua (2002 to 2015) satellites. Selected observations were those spatially and temporally collocated between satellite instruments and ground-based sites. In addition to the aerosol load given by the AOD, we also evaluated the Ångström exponent (AE) as a parameter providing information about particle size for MODIS and sun photometer data.

One of the challenges we faced was the low amount of potential coincident AOD and AE from MODIS and the Sun photometer. The same is true for AOD from MODIS and broadband pyrheliometer derived BAOD, in both cases due to existing gaps in the ground-based time series and also because this area is strongly affected by clouds (mainly partially cloud cover). In order to maximize the number of satellite and surface measurement pairs, we used primary AOD and AE L2 products without any averaging as well as combined AOD and AE from Terra and Aqua MODIS sensors as a whole dataset. We also used Deep Blue (DB) and Dark Target (DT) algorithms to evaluate the reliability of satellite AOD and AE retrievals to select the most appropriate data set to derive the climatology of both AOD/AE aerosol parameters in Cuba.

The earliest attempt to measure aerosol optical properties at ground level in Cuba ~~registered~~recorded in a scientific publication~~, comes~~ dates back to 1988~~. Using a Linke Feussner pyrheliometer, direct normal irradiance (DNI) measurements were conducted in Havana between 1977 and 1985.The~~ (Martinez, 1988) where the Linke turbidity factor and the Ångström ß turbidity coefficient were ~~calculated (Martinez, 1988). Results were limited because of the fact that the Linke turbidity factor represents the combined turbidity of aerosols, water vapor and NO_2, while the Ångström turbidity coefficient could only be determined if the Ångström Exponent is assumed a priori.~~derived from solar direct normal irradiance (DNI)

Comentado [JCAM3]: El "so as" es muy difuso. El "to" es preciso pues en este caso es preciso apuntar a la selección.

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measurements. Twenty years later, a cooperation agreement between scientific institutions ~~of~~in Spain and Cuba~~, allowed the installation of~~ enabled a Cimel CE-318 sun photometer to be installed at Camagüey (Cuba) and ~~its inclusion~~for it to be included in the Aerosol Robotic Network (AERONET, Holben et al., 1998). ~~-~~Several aerosol studies have been conducted using the Aerosol Optical Depth (AOD) and AE ~~observations~~ from Camagüey's sun photometer observations (see, Antuña-Marrero et al~~,~~., 2016~~).~~ ; http://www.goac.cu/uva/).

Broadband pyrheliometric DNI observations allow the Broadband Aerosol Optical Depth (BAOD) ~~estimates complement~~to be determined, which complements sun photometer aerosol ~~measurements~~observations at Camagüey~~ but also provide~~, and provides aerosol information at three other ~~three~~ locations in Cuba. The main purpose of determining BAOD is to ~~provide~~offer information ~~about the~~concerning aerosol variability ~~of aerosols along~~over the island, also making it ~~also~~ possible to extend ~~the~~ aerosol records back in time. ~~Pyrheliometric DNI measurements allow the BAOD retrieval.~~ The first BAOD calculations used for~~ the~~ DNI measurement were conducted at Camagüey under clear sky conditions for the period 1985-2007 using Gueymard's (1998) improved parameterizations (Fonte and Antuña, 2011). ~~-~~García et al. (2015) ~~made use of~~used this kind of DNI ~~measurements but~~observation for a longer period (1981-2013~~).~~) and compared this BAOD to sun-photometer AOD data. They used observations under the clear line of sight between the broadband pyrheliometer and a region of 5° around the Sun, as well as improved climatological values of the integrated water vapor.

This comparative analysis does not aim to be a validation study of the MODIS sensor since many works during the long history of the MODIS sensor on the Terra and Aqua platforms have sought to improve its features (these include: Kaufman et al., 1997a, b; Tanré et al., 1997; Remer et al., 2002, 2005, 2006; Hsu, et al., 2004,2006, 2013; Levy et al., 2007; 2009; 2010, 2013, 2015;

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Sayer et al., 2013, 2014; https://darktarget.gsfc.nasa.gov/atbd/overview). However, compared to other areas of the world, no studies have been reported in the Caribbean region and in Cuba in particular (Papadimas et al., 2009; Mishchenko, et al., 2010; Kahn et al., 2011; Bennouna et al., 2011, 2013; Witte et al., 2011; Gkikas et al., 2013; 2015; Levy et al., 2015). ~~In advance of the aerosol climatology for Cuba land areas, already under development, we have conducted a comparison of aerosol ground-based measurements and the available satellite data. It consists of the comparison among all available Camagüey's sun photometer AOD (500 nm) and AE, and the BAOD measurements at four Cuban locations, with the series of AOD (550 nm) and AE from the MODerate resolution Imaging Spectroradiometer (MODIS) instruments onboard Terra (2001 to 2015) and Aqua (2002 to 2015) satellites. Selected observations were the ones spatially and temporally collocated between the satellite instruments and the ground-based sites. One of the challenges we faced was the low amount of potential coincident AOD and AE from MODIS and Sun photometer. The same is true for AOD from MODIS and pyrheliometer BAOD, in both cases because of existing gaps in the ground-based time series. In order to maximize the number of satellite and surface measurement pairs, we used the primary AOD and AE L2 products without any averaging and the combined AOD and AE from Terra and Aqua MODIS sensors as a whole dataset.~~

As mentioned, our aim is to establish reliable aerosol climatology in Cuba based on satellite and ground-based instruments. By making a detailed comparison of similarities and differences between available data sets, the present work seeks to make a contribution to said aim.

The article is structured as follows. Section 2 begins with the description of the datasets, followed by the explanation of the coincidence criteria between the ~~MODIS~~ AOD and AE MODIS L2 products and the same two variables from the sun photometer~~, as well as the MODIS AOD L2 products~~ and broadband pyrheliometer BAOD. This section ends with the explanation of the ~~statistics and the~~ statistical ~~methods~~indices used. Section 3 ~~shows the~~ is composed of various sections designed to explain and discuss the large volume of results to emerge from the comparison given by taking two different retrieval AOD aerosol algorithms, for both the Terra and ~~discussion, followed by~~ Aqua

Comentado [JCAM4]: No he encontrado en la literature ninguna comparacion de MODIS con estaciones de AERONET en el Caribe

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platforms, with the sun photometer and BAOD. Section 4 contains a summary ~~and~~of the conclusions~~ in section 4~~.

2. Materials and Methods~~:~~

2.1 *MODIS satellite instruments*~~:~~

The twin MODIS instruments ~~onboard~~on board the Terra and Aqua satellites ~~accumulate more than~~have accumulated over 15 years of ~~measurements~~observations of several atmospheric parameters, including AOD at several wavelengths and the AE parameter, the two most common parameters ~~to characterize the~~for describing atmospheric aerosol optical properties. ~~Depending~~Based on the assumptions about the properties of the Earth's surface and the aerosol type expected over these surfaces, the MODIS Atmosphere team developed three algorithms for ~~the~~ processing ~~of~~ MODIS ~~measurements~~observations (Levy et al., 2013). Regions which appear visually "dark" from ~~the~~ space, ~~named~~referred to as Dark Target (DT), include the algorithm assumptions for vegetated land surfaces (Kaufman et al., ~~1997~~1997a, b) and for remote ocean regions (Tanré et al., 1997). The third algorithm, called the Deep Blue (DB) algorithm, includes assumptions for surfaces which are visually "bright" from space and ~~makes use of the~~uses near-UV wavelengths (DB band near 410 nm). Under these conditions, the DB band provides a better signal than the visible wavelengths, improving the ~~signal~~information content for aerosol retrievals (Hsu et al., 2004; 2006) due to lower surface albedo at this short wavelength. Levy et al. (2013) ~~provides~~provide a detailed explanation of basic MODIS ~~basic~~ retrieval concepts and ~~the~~ improvements ~~of~~to the DT algorithm in Collection 6 for aerosol products. In addition, Hsu et al. (2013) ~~makes~~give a detailed explanation of the DB algorithm improvements in Collection 6.

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Following Levy et al. (2013~~)~~), we summarize the MODIS calculus chain. MODIS Level 0 (L0) is the basic data file~~,~~ containing ~~the~~ raw ~~measurements~~observations from the sensors. ~~Measurements~~Observations grouped in ~~5 minutes~~five-minute swath scans (called granules) are Level 1A (L1A), which after calibration becomes Level 1B (L1B). L1B data feed the MODIS geophysical retrieval algorithms, generating the ~~very~~ primary geophysical observations, which include AOD and AE, designated Level 2 (L2). ~~It~~This is followed ~~in the calculus chain by the~~by Level 3 (L3), consisting of daily and monthly statistics of ~~the~~ geophysical products, in 1º x 1º latitude\longitude grid boxes. L2 aerosol products are stored in the ~~files~~ MOD04 (Terra) and MYD04 (Aqua~~).~~) files.

We selected AOD at 550 nm from MODIS (both on Terra and Aqua satellites) Collection 6, L2 data level derived using the two algorithms; DB for land with the highest data quality (Quality flag = 2, 3) and DT for land, corrected (Quality flag = 3). In addition, we selected the AE retrieved over land from the DB algorithm~~, because~~ using the corresponding pairs of AOD values (412/470 nm or 470/650 nm) with the highest quality (Quality flag = 2, 3), since the DT algorithm only retrieves the AE over the ocean (Table B1 in Levy et al., 2013). ~~We only selected the AE for the cases of high quality AOD at 550nm from DB (Quality flag = 2, 3).~~ Table 1 lists the aerosol products used in the present study. ~~The purpose of using the combination both satellites and DB and DT was to evaluate the reliability of the satellite AOD and AE retrievals for selecting the most appropriate data set to derive the climatology of both aerosol parameters in Cuba.~~

~~It~~At a global scale, it has been established ~~the fact~~that~~, at global scale,~~ using the DT algorithm over land, MODIS-retrieved aerosol size parameters ~~using DT algorithm over land show little~~evidence poor quantitative ~~skill, in particular the~~capacity, particularly AE (e.g., Levy et al., 2010; Mielonen et al., 2011). However, for the DB algorithm, AE ~~skill~~capacity increases for moderate or high aerosol loadings, AOD > 0.3 (Sayer et al., 2013). ~~Then we~~We therefore decided to conduct the comparison

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between the AE from the MODIS ~~(from~~ DB~~)~~ algorithm and the AE from the ~~Camagüey's Sun~~Camagüey sun photometer ~~for estimating~~to estimate its uncertainty. ~~It should be noted that in Collection 6 the~~ The enhanced ~~Deep Blue algorithm has three options to calculate the AE: the traditional Deep Blue~~DB algorithm ~~(412 nm), if the surface~~ methodology for deriving AE in Collection 6 is ~~vegetated~~ the same as in Collection 5. It uses the Ångström power law and AOD values at 412, 470~~/~~ and 650 nm ~~pair; if the surface is a mixture of~~. 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, ~~it uses all 3~~ AE is derived using the AOD at the three wavelengths ~~together.~~mentioned (Hsu et al., 2013).

2.2 *Camagüey AERONET ~~Sun~~sun-photometer~~:~~*

~~In 2007,~~The Camagüey sun photometer, installed thanks to an agreement between the University of Valladolid (UVA), Spain, and the Meteorological Institute of Cuba (INSMET) ~~signed an agreement for conducting~~for joint ~~long-term~~ aerosol research~~. Under this agreement, the Grupo de Óptica Atmosférica from UVA (GOA-UVA) provided a Cimel CE318 sun photometer to the Grupo de Óptica Atmosférica de Camagüey (GOAC-INSMET). The Camagüey sun photometer~~, contributes to the NASA Aerosol Robotic Network (AERONET) ~~of NASA~~ (Antuña et al., 2012). ~~Although the annual~~Annual replacement of the instrument ~~confronted multiple delays in~~ for one calibrated, sent from Valladolid to Camagüey, encountered numerous transportation and customs delays, causing gaps in the observation series. However, the collected series of ~~measurements represents~~observations does represent a valuable dataset of ~~the~~ aerosol columnar optical properties in the Caribbean, ~~allowing~~enabling GOAC-INSMET and GOA-UVA to conduct preliminary aerosol research (Antuña-Marrero et al, 2016).

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The AERONET Cimel ~~Sun~~sun photometers have been conducting aerosol ~~measurements~~observations at ~~9~~nine spectral narrow ~~bands during more than~~band filters for over two decades, producing spectral AOD and column effective particle properties (Holben et al., 1998). In general, Cimel sun photometer nominal wavelengths are 340, 380, 440, 500, 675, 870, 935, 1020 and 1640 nm. In some cases, the 1640 nm is replaced by a 1240 nm. Its processing algorithm, based on the Beer-Lambert-Bouguer law, allows ~~the determination of~~ spectral ~~AOD~~OD values at ~~a level of~~an uncertainty level of approximately ~~of~~ 0.01 to 0.02 to be determined (Holben et al., 1998; Eck et al., 1999). Because of this low level of uncertainty, AERONET AOD ~~measurements~~observations commonly serve as reference values ("ground truth") ~~for the validation of~~to validate AOD measured by other remote sensing sensors (Zhao et al., 2002). AERONET AE are derived for five different wavelength intervals; 340-440 nm, 380-500 nm, 440-675 nm, 440-870 nm and 500-870 nm. In the present study, the ~~AE~~ selected AE is the one in the ~~range~~ 440-675 nm range (AE_{SP}).

We used ~~Camagüey's~~Camagüey sun photometer Level 2.0 data as processed by AERONET, i.e.~~.~~, cloud screened and quality-assured (Smirnov et al., 2000), covering the period from 7 October ~~7th,~~ 2008 to 1 August ~~1st,~~ 2014. ~~It~~This consisted of 29,940 ~~observations of~~single AOD (340 to 1640nm) and AE_{SP}~~. We~~ observations. Applying the Ångström power law, we converted ~~the individual~~single sun photometer AOD ~~measurements~~observations at 500 nm wavelength to AOD at 550nm, (AOD_{SP}) using the AE_{SP} from the same measurement:

$$AOD_{SP} = AOD_{500}\cancel{\left(\frac{\lambda_{550}}{\lambda_{500}}\right)^{-\alpha}}\left(\frac{\lambda_{550}}{\lambda_{500}}\right)^{-AE_{SP}} \qquad (1)$$

~~where α is the AE_{SP}.~~

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2.3 *Solar direct irradiance measurements and derived Broadband ~~aerosol optical depth~~ Aerosol Optical Depth(BAOD~~):~~)*

Four actinometrical stations belonging to the “Diagnostic Service ~~of the~~for Solar Radiation in Cuba~~”,~~,” provided the DNI ~~measurements~~observations used to derive the BAOD (Antuña et al., 2008; 2011). Table 2 lists the WMO code of the four stations, the geographical location and the number of observations available for the periods at each station. Figure 1 shows the geographical location of the four stations.~~; GOAC, 2016). The method for determining the BAOD relays on a set of parameterizations of the most relevant extinction processes modulating the transfer of shortwave radiation in the absence of clouds~~ The stations are equipped with Yanishevsky manual broadband solar radiation instruments supplied between the 1970s and 1980s by the Hydrometeorological Service of the Soviet Union. The Yanishevski broadband pyrheliometer is the M-3 model, a thermo-battery system with a 5º field of view connected to an analogic galvanometer, GSA-1MA or GSA-1MB model (GGO, 1957).

Calibrations of all the actinometrical instruments are conducted periodically by comparison with a master broadband pyrheliometer and a master pyranometer. Trained observers perform hourly manual observations from sunset to sunrise, following the standard methodologies and quality control procedures established for this set of instruments (GGO, 1957). Once manual measurement is conducted and recorded in a notebook designed for the purpose, all the measurement information is digitized using Actino version 2.0 software (Estevan, 2010; Antuña et al., 2008) of the “Diagnostic Service of the Broadband Aerosol & Clouds Optical Depth for Cuba” (http://www.goac.cu/eoc/), a public service provided by GOAC. The software includes a robust quality control of input data, its processing and output quality control (Antuña et al., 2011). Because of the ageing of the Soviet era instruments, the magnitude of the error associated to the broadband pyrheliometers currently operating in Cuba is estimated to be around 10 %.

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Based on the model parameterization of solar broadband irradiances, the integrated aerosol optical depth δ$_a$, BAOD, can be obtained using equation (2), where direct normal solar irradiance (DNI) is measured and the remaining variables are determined independently (Gueymard, 1998~~;~~ ~~Garcia et al.,~~).

$$\delta_a = \left(\frac{1}{m_a}\right)\left[ln\left(\frac{E_{0n}}{DNI}\right) - m_R\delta_c - m_w\delta_w - m_{nt}\delta_{nt}\right] \qquad (2)$$

The individual atmospheric processes considered are: Rayleigh scattering, absorption by ozone (O_3), stratospheric and tropospheric nitrogen dioxide (NO_2), uniformly mixed gases, water vapor, and extinction (mostly scattering) by aerosols. The variables in equation (2) are: optical air mass of aerosols (m_a), Rayleigh scattering, uniformed mixed gases, O_3 absorption and stratospheric NO_2 (m_R), water vapor (m_w) and tropospheric NO_2 (m_{nt}) and similarly the corresponding broadband optical depths δ. The method makes a series of assumptions, i.e., Bouguer's law; in the strict sense that it is only valid for monochromatic radiation and is applied to define broadband transmittance. For a detailed description of the derivation of equation (2) and the parameterization of the variables, see Gueymard, (1998), and Fonte and Antuña (2012) and García et al. (2015~~). We combined the~~) for the method's application to our data.

In order to avoid cloud~~-free conditions, selecting DNI measurements under cloudiness equal or less than 1~~ contamination in BAOD retrieval, we used only DNI observations with the cloud-free condition in the line of sight to the sun~~. That free condition is satisfied selecting DNI measurements~~, in other words with a clear line of sight between the broadband pyrheliometer and a region of 5° around the sun (GOAC, 2010). ~~Table 2 lists the WMO code of the four stations, its geographical location and the available number of measurements for the periods available at each station.~~ Furthermore, to avoid errors associated with high elevation zenith angles, causing larger air masses, DNI observations performed at 6:00 and 18:00

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Local Time (LT) were not used in the present study. ~~Figure 1 shows the geographical location of the four stations.~~

The main errors of the method ~~to determine the~~for determining BAOD are associated to ~~the~~ instrumental ~~error~~errors and the error ~~in the estimation of~~when estimating the precipitable water (PW) component (Gueymard, 2013). In the first case, in order to ~~guarantee~~ensure the quality of the solar radiation dataset from the four actinometrical stations used in this study, including DNI, they are regularly subject ~~of~~to a two-step quality control (Estevan et al., 2012). The first step applies the standard procedures designed for ~~the~~ Yanishevski type actinometrical instruments ~~type Yanishevski by~~from the former Soviet Hydro-Meteorological Service (Kirilov et al., 1957). ~~The data passing~~Data that pass this quality procedure are then ~~the subject of the second step, which evaluation follows the strictest~~evaluated following the standards set by the Baseline Solar Radiation Network - BSRN (Ohmura 1998, Long and Shi, 2006; 2008; Estevan et al., 2012).

The size of the field of view of the broadband pyrheliometers is another potential source of error since, in certain cases, circumsolar radiation causes more radiation to be measured than expected. In such cases, the effect is an underestimation of BAOD. Nevertheless, this effect is low in general, except in specific conditions such as large air masses, in the presence of high aerosol loads or of large-particle aerosols (Gueymard, 1998).

Monthly mean ~~water vapor AOD calculations, necessary for the BAOD retrieval, used monthly mean~~ PW values at the four actinometrical stations~~.~~ were used as input to derive monthly mean δ_w values (Gueymard, 1998). For Camagüey, we calculated the monthly mean PW values from the sun photometer PW ~~measurements~~observations from 2008 to 2014 (~~Garcia~~García et al., 2015). For each ~~one~~ of the ~~other~~ three other stations, we calculated the monthly mean PW values using the vertical integrated water vapor (kg m^{-2}) from spatially coincident ERA-Interim reanalysis ~~from~~between

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1979 ~~to~~and 2013 (Barja et al., 2015). ~~The~~Taking into account all the above-mentioned errors, the total uncertainty of the method used ~~for the~~to determine BAOD ~~determination~~ is in the order of 10^{-2} (Gueymard, 1998).

2.4 *Coincidence criteria for MODIS and Sun photometer ~~measurements:~~observations*

Obtaining ~~enough amount of~~ sufficient AOD satellite ~~measurements~~observations over land for climatological studies ~~at~~in insular ~~states represent~~ areas poses a challenge ~~with respect~~when compared to the ~~typical~~ amount of data usually available over continental regions~~, like~~ such as the US, Europe ~~and China for example.~~ or China. The reason tends to be the small size of the islands. In the case of Cuba, its particular narrow latitudinal and elongated longitudinal extension combined with its irregular coasts renders the MODIS L3 product unsuitable for climatological studies. As can be seen in Figure 1, most of the 1º by 1º grid cells consist of both land and sea areas, resulting from the merging AOD measured over the two surfaces. The red grid cell in Figure 1 is an example of the limitations of MODIS L3 products to represent land areas in the case of Cuba. In response to ~~it~~this, we ~~used~~plan to use the MODIS L2 product ~~instead of L3 used~~to produce aerosol climatology for Cuba rather than L3, which is commonly used for this type of studies. In this regard, it is vital to validate the single observations from MODIS L2 with the single sun photometer observations. We designed and applied a ~~methodology for maximizing~~method to maximize the available pairs of MODIS L2 ~~measurements~~and sun photometer AOD and AE observations coincident in space and time ~~with the sun photometer measurements.~~, avoiding duplicating the use of any of them. Additionally, ~~to try~~in an effort to increase the amount of data, we tested the differences between Terra and Aqua L2 MODIS AOD and AE ~~measurements~~observations in order to determine the possible combination of both Terra and Aqua ~~AOD and AE measurements~~ in a ~~unique~~single dataset.

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Hereinafter, AOD$_t$, AOD$_a$, AOD$_{ta}$ and AOD$_{SP}$ will denote spatio-~~temporally~~temporal AOD from collocated MODIS (Terra, Aqua and Terra + Aqua) and AERONET sun photometer data, respectively. ~~All the~~Unless otherwise indicated, “AOD” ~~references will be~~refers to ~~the~~ AOD at 550 nm wavelength~~, unless otherwise indicated.~~. Similarly, AE from Terra, Aqua and Terra + Aqua derived using only the DB algorithm~~,~~ will be denoted as AE$_t$, AE$_a$ and AE$_{ta}$.

~~Because of~~Given the challenges ~~of~~arising from the ~~low~~small amount of potential coincident spatial and temporal AOD$_t$ ~~(~~and AOD$_a$~~)~~ with AOD$_{SP}$ and BAOD, ~~and of AE$_t$ (AE$_a$) with AE$_{SP}$,~~as explained above, we used MODIS L2 data to maximize the amount of available MODIS ~~measurements~~observations for ~~the~~ comparison. Hereinafter, we ~~named those measurements~~call these observations “single observation values”; using the same denomination for the instantaneous sun photometer ~~measurements~~observations on each day and for ~~the~~ hourly broadband pyrheliometer ~~measurements.~~ observations. Another way to increase the amount of data was to combine AOD$_t$ and AOD$_a$ (AOD$_{ta}$) for ~~the~~ comparison with AOD$_{SP}$ and BAOD~~; and the combined AE$_t$ and AE$_a$ (AE$_{ta}$) for the comparison with AE$_{SP}$.~~. In these cases, different ~~measurements~~observations of AOD$_{SP}$ and BAOD match AOD$_t$ and AOD$_a$ because the time difference established for coincidence (± 30 min) is lower than the difference between the Terra and Aqua daily overpass times.

~~The spatial~~Spatial coincidence criteria ~~was granted~~were guaranteed by selecting all the AOD$_t$ and AOD$_a$ measured inside the 25 km radius around the sun photometer site for the ~~entire~~whole data period ~~of data~~ from each satellite sensor. ~~-~~Table 3 shows the amount of spatial coincident information for non-negative AOD$_t$ and AOD$_a$ values. It shows the amount of data available ~~or~~for the ~~entire~~whole period ~~2011~~2001 to 2015, when broadband pyrheliometer observations at Camagüey are available, and ~~for~~ 2008 to 2014, the period of ~~the~~ available sun photometer ~~measurements. The available measurements from Terra~~ observations. There are at least twice ~~the number of measurements~~as

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many available observations from Terra as from Aqua for ~~both~~the two periods~~, causing the same balance of measurements with the sun photometer as it will be shown below.~~ . The ~~higher amount~~greater number of available data from Terra ~~with respect~~compared to Aqua is associated to the different overpass times of ~~both~~the two satellites over Cuba. Figure 2 shows that Terra overpasses occur in the ~~middle~~mid to late morning before convective activity begins, while the Aqua overpasses take place in the early afternoon when convection has already ~~began~~begun, causing a higher ~~amount~~number of observations to be discarded in AOD retrievals due to ~~the~~cloud presence~~ of clouds~~.

2.4.1 Collocated “*Single observation*” *values*~~:~~ *and “daily mean” values*

All Aqua and Terra overpass times in a radius of 25 km around Camagüey for the periods 2001 to 2015 (Terra) and 2002 to 2015 (Aqua) are shown ~~on figure~~in Figure 2. Overpass times, defined by the maximum and minimum values of all the 25 km spatially coincident MODIS ~~measurements~~observations, are 10:12 ~~-~~– 11:49 (LT) for Terra and 12:47 – 14:20 (LT) for Aqua. In addition, ~~figure~~Figure 2 shows the diurnal frequency of sun photometer ~~measurements~~observations from 2008 to 2014~~. Also~~, and the diurnal frequency of the BAOD ~~measurements~~observations for Camagüey for the period 1981 to 2015. Note that the BAOD histogram shows only hourly frequency values, ~~because~~since that is the time interval between the manual pyrheliometric ~~measurements~~observations.

For each day, we compared the corresponding time of each ~~individual~~single sun photometer measurement with the time of each ~~individual~~single AOD$_t$ and AOD$_a$ ~~measurements the same day~~observation located in a radius of 25 km around the sun photometer site (an area of almost 2,000 km^2) and in the time window of ± 30 minutes between both ~~measurements.~~ types of observations. The former ~~process of~~ selection process includes, for each satellite, the ~~values of~~ AOD$_t$ and AOD$_a$ values derived both with the DB and DT processing algorithms separately, producing four

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independent bulk datasets, two for Aqua and two for Terra~~, coincident spatially inside 25 km radius around the sun photometer location, an area of almost 2,000 km^2. Then we~~. We then identified four different cases of ~~daily coincident~~matching data per day in the bulk coincident datasets. The first consisted of days with only one AOD$_{SP}$ value and one AOD$_t$ (AOD$_a$) coincident value~~. The~~, and the second, only one AOD$_{SP}$ value coincident with multiple AOD$_t$ (AOD$_a$) values each day. In the third case, only one AOD$_t$ (AOD$_a$) value~~, coincide~~ coincided with multiple AOD$_{SP}$ values. Finally, the fourth case consisted of multiple AOD$_{SP}$ values coincident with multiple AOD$_t$ (AOD$_a$) values.

~~The selection of the coincident~~Coincident cases were then selected for ~~the~~ comparison~~ was then conducted~~, case by case. In the first ~~case~~instance, we selected all ~~the~~ cases. In the second case, because of the MODIS instruments spatiotemporal sampling geometry, ~~the~~time differences ~~in time~~ between ~~the~~ MODIS and sun photometer ~~measurements~~observations are in the order of one minute. ~~Then~~As a result, only the ~~criteria~~criterion of the minimum distance between the positions of the AOD$_t$ (AOD$_a$) and the sun photometer was applied to determine the pair of coincident values, ~~thus granting no~~therefore not allowing any repeated AOD$_{SP}$ and AOD$_t$ (AOD$_a$) values ~~being~~to be selected. ~~In the third case because~~Since it consists of only one AOD$_t$ (AOD$_a$) measurement and multiple AOD$_{SP}$ ~~measurements,~~ observations, in the third case the distance is the same~~,~~; hence the ~~criteria of~~ selection criteria was the minimum of the time differences between AOD$_{SP}$ and AOD$_t$ (AOD$_a$) ~~measurements.~~ observations. The fourth case, the most complicated~~ one~~, allowed ~~the application of~~ both criteria to be applied; the minimum in distance and time. ~~We tested the influence of the order of application of both criteria and it produced no~~No differences in the amount of coincident data~~.~~

~~**2.4.2 *Daily mean values***~~ were found when testing whether the order in ~~***the ± 30 minute interval around MODIS overpass time:***~~which the two criteria were applied had any impact.

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Another approach~~-~~, the most commonly used for ~~the~~ comparison ~~of AOD_{SP} and AOD_t (AOD_a) measurements consists of time averages of~~(Bennouna et al., 2011; Sayer et al., 2014), involves the average of all the AOD_{SP} values in the interval of ± 30 minutes ~~with respect to~~ compared to MODIS instrument overpass time (note that AOD_t and AOD_a averages are really the daily values of MODIS ~~instruments overpass time. We averaged the AOD_t and AOD_a measurements~~) located in a radius of 25 km around the sun photometer ~~site for the time interval of ± 30 minutes around the Terra (Aqua) overpass time respectively for the same day (Sayer et al., 2014).~~ . At least two single AOD_{SP} and two single AOD_t (AOD_a) observations were required to calculate the spatio-temporal average. We applied a similar approach to calculate collocated daily means ~~AE_A~~AE_{SP}, AE_t and AE_a. ~~Then for each one of those days we calculated the daily mean AOD_{SP} for the time interval of ± 30 minutes around the Terra (Aqua) overpass time respectively.~~

The procedures described above generated a series of collocated daily means of AOD_{SP} ~~vs.~~versus AOD_t (AOD_a) and AE_{SP} vs. AE_t (AE_a). ~~Combining~~Hence, by combining the former generated series of AOD (AE) for Terra and Aqua we produced the coincident (Terra + Aqua ~~daily means~~) dataset. ~~We followed a similar procedure for the AE coincident Terra + Aqua dataset. The term~~The term *collocated daily mean AOD* will be used hereinafter although it ~~does not represent exactly~~should be stressed that this approach reduces the number of observations generated by virtually a ~~daily average. It refers only to an hourly average centered~~third.

After explaining the coincidence criteria adopted here, it is well known that this type of comparison shows major differences depending on the spatial and or temporal resolution taken for the MODIS ~~overpass time~~sensor in relation to the ground-based instruments used (Santese et al., 2007; Levy et al., 2009; Bennouna et al., 2011, 2013). The justification for using a "single observations" dataset and a "collocated daily means" dataset separately to analyze this comparison is based on: a) the characteristics of the surface area under study, with nearby areas of water and land; b) the difference concerning how cloud cover affects data during the overpass time of the

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Terra and Aqua platforms; and c) the possibility of including the largest amount of data; d) the fact that only single observations can be compared in the case of BAOD pyrheliometer measurements.

2.5 *Statistics*

The statistics used in the present study are ~~the ones~~those commonly used (e.g., Sayer et al., 2014). ~~They~~These are the root mean ~~squared~~square error (RMSE), mean absolute error (MAE), median bias (BIAS), the Pearson linear correlation coefficient (R), the number of coincident MODIS and sun photometer cases (Cases) and the fraction (f) of the MODIS/AERONET AOD retrievals in agreement within the expected uncertainty. ~~The expected~~ Expected uncertainty, defined as a one standard deviation confidence interval~~, appears~~ entails the sum of the absolute and relative AOD errors. Usually referred to as "expected error, EE", it was applied in ~~the~~ accordance with equation ~~2~~3 (Sayer et al., 2014~~):~~).

$$EE_{DT} = \pm(0.05 + 0.15\,AOD) \qquad (\cancel{2}3)$$

~~We used AOD_t (AOD_a) expected uncertainty defined in equation 2, determined for the DT algorithm, also for estimating the uncertainty of AOD_t (AOD_a) when the DT algorithm~~The aim is ~~applied,~~ to ~~allow~~compare the performance of the DB and DT ~~to be compared more~~algorithms directly (Sayer et al., 2014).

~~The RMSE, MAE, BIAS, R and f~~ All of these statistical indicators were evaluated for the ~~complete~~whole set of ~~coincident~~collocated AOD_t, AOD_a, AOD_{ta} with AOD_{SP}~~; AOD_t, AOD_a, AOD_{ta} with~~, and BAOD ~~and BAOD with AOD_{SP}~~; AE_t, AE_a, AE_{ta} with AE_{SP}~~. In addition, we evaluated those statistics at monthly scales for the comparison of AOD_{SP} with AOD_t, AOD_a, AOD_{ta}, and BAOD. In addition, we calculated the~~; as well as time frequencies (Figure 2) and histograms of ~~the magnitudes of AOD_t, AOD_a, AOD_{ta}, AOD_{SP}, BAOD, AE_t AE_a,~~ these quantities. We also evaluated these statistics on a monthly scale for the AOD values~~**AE_{ta}** and AE_{SP} measurements~~.

3. Results and Discussion~~:~~.

Comentado [JCAM6]: Igual que mas arriba, el BAOD no es medicion de radiacion

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This section is divided into four subsections. In the first subsection, we analyze in detail the main results from comparing the AOD satellite MODIS sensors and the sun photometer data given by the statistical indicators and linear correlations, as a result of taking two different criteria, two different retrieval AOD aerosol algorithms both for the Terra and Aqua platforms. Section 3.2 analyzes the same type of results but under the perspective of monthly values since they represent the climatology of AOD and the associated uncertainties. Section 3.3 shows AE behavior and Section 3.4 analyzes the comparison of satellite MODIS data in relation to broadband aerosol optical depth from solar radiation.

3.1 *Comparison of AOD retrievals from sun photometer and MODIS satellite instruments.*

~~3.1.1 *Daily means*~~

~~Figure 3 shows the scatter plot of the daily means AOD values from the sun photometer and Terra (Aqua) MODIS instruments for DB and DT algorithms. Table 4 shows the statistics of the comparison of daily mean AOD_t (AOD_a) with AOD_{SP}. For AOD_t RMSE and MAE are lower for the DT than for DB algorithm. In addition, the magnitude of the BIAS is lower for DT than for DB and its sign is the same for both DT and DB. The sign and magnitude of the BIAS for DB demonstrate that the daily mean AOD_t from DB algorithm are larger than the daily mean AOD_{SP}. However, in the case of DT the low BIAS shows that there are not predominant higher values between the daily mean AOD_t from DT algorithm and AOD_{SP}. Up to 80% of AOD_t values derived with DT are inside the expected error margins, while this statistic decreased to 66% for DB. The correlation coefficient R shows no differences between DT and DB and f shows a value of 80% for DT, decreasing to 76 % for DB. In the case of AOD_a, RMSE and MAE show almost no difference for DB and DT while the BIAS is negative for DB and positive for DT, with lower absolute value for DT as in the case of AOD_t.~~

~~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. In addition, the similar values of the statistics for both AOD_t and AOD_a derived with DT support the combination of the monthly mean AOD_{ta} in a unique dataset for studies ranging from daily to climatological temporal scales. The last two columns in table 4 report~~

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~~the statistics for such combined AOD_{ta} dataset. As expected, the DT algorithm shows better agreement between combined AOD_{ta} dataset with AOD_{SP} than DB.~~

~~**3.1.2 *Single observation values***~~

~~The results of the comparison of the single observations measurements of AOD_t (AOD_a) with AOD_{SP} are in table 5. The magnitudes of the statistics on table 5 are, in general, similar to the results shown in table 4 for the comparison of the daily means. The single observations AOD_t derived with DT also shows better results than the ones derived with DB but that is not the case for AOD_a. The BIAS shows that DB algorithm also produces higher values of the single observations mean AOD_t (AOD_a) than the single observations AOD_{SP} values. On the other side DT produces lower values of the single observations mean AOD_t (AOD_a) than the individual AOD_{SP} values. The absolute magnitude of the overestimation produced by DB is higher than the underestimation produced by DT. The AOD_t and AOD_a derived with DT show higher percent values inside the expected error margins than the same variables derived using DB.~~

~~The similitude of the statistics for DT both for AOD_t and for AOD_a, also adds the intra-daily temporal scale to the already determined range of temporal scales from the comparison of daily means AOD_t and AOD_a with AOD_{SP}. The last two columns on table 5 report the statistics for the comparison of the single observations values of the combined AOD_{ta} dataset with the single observations values of AOD_{SP}. Its values are quite similar to the ones on table 4 for the daily mean AOD_t (AOD_a) comparison with AOD_{SP}.~~

As explained, we selected MODIS AOD_t (AOD_a) and sun photometer AOD_{SP} data based on two different criteria for their comparison. Results are shown in Tables 4 and 5, corresponding to collocated daily means and single observations, respectively. The values of all the statistics of these two tables are extraordinarily similar, with analogous behavior for the different algorithm and platforms. In truth, no substantial differences are found. It must be noted that Table 4 for collocated daily means contains a third less data than Table 5 based on single observations. In contrast, however, the latter data have a higher associated error than daily mean data. This result cannot be foreseen a priori but clearly demonstrates that either criterion may be taken, since the result is basically the same.

Comentado [JCAM7]: Aui estan cambiado el nombre del orden de las tablas respect a las que aparecen en el texto.

Taking Table 5 together with Figure 3 of collocated daily mean values, we then analyze the different behavior of the two algorithms for the Terra and Aqua platforms, when AOD_t (AOD_a) from satellite are compared with the sun photometer, AOD_{SP}. Figure 3 shows the density plots of the collocated daily mean AOD values from the sun photometer versus those of MODIS instruments for Terra, Aqua and combined, for DB (top plots) and DT (bottom plots) algorithms. The least squares linear fit lines and equations are also shown in the figure while the correlation coefficients (R values) are in Table 5. In general, the plots show that low loading aerosols predominate and that scatter increases for higher aerosol loadings, with a slight overestimation of AOD_t (AOD_a) satellite data compared to AOD_{SP}. In all cases, the slopes are between 1 and 0.9 and the intercepts are in the order of 10^{-2} (with lower values for the DT algorithm), showing very good values of these parameters for Terra and Aqua for both the DT and DB algorithms.

Figure 3 shows that the DT algorithm displays generally better behavior than the DB algorithm. The DT algorithm evidences more unified behavior as can be seen for the slope values (0.96 for both Aqua and Terra) while DB changes, giving a value above 1 (1.069) for Terra and below 1 for Aqua (0.901). However, these differences are not very relevant since both algorithms give almost identical R values, and the difference appears for the platforms, with higher values for Aqua than for Terra (~0.78 and ~0.73, respectively). A compensation effect can be observed when data are combined, since in this case the slope of the DB algorithm is closer to 1 than the DT algorithm, although the intercept is higher (closer to 0 for DT algorithm). For combined data, the two algorithms show a more similar behavior than for separate Aqua or Terra results. Analyzing Table 5, the magnitudes of the RMSE, MAE, BIAS and f statistics are lower for the DT than for the DB algorithm (see the higher values of DB for Terra, column 1, and the more similar values in the other columns). As mentioned, the values of these four parameters show that the DT algorithm presents a more unified behavior for both platforms than the DB, which has similar values for Aqua but which change significantly for Terra.

Although the statistical numbers in the comparison depend on the area under study, comparisons between areas are always possible. A recent validation of MODIS Collection 6 AOD_a (Aqua), derived using the DB algorithm, with AOD_{SP} from six AERONET stations in Central/South America (CSA) and seven in Eastern North America (ENA) was reported by Sayer et al. (2013). The number of pairs of collocated MODIS and AERONET daily averaged observations for CSA (ENA) was 3,032 (4155). Sun photometer data were averaged within the 30 minute MODIS overpass time and MODIS data were averaged in the 25 km radius around the sun photometer site, which makes the comparison appropriate. We selected the BIAS and R statistics in Table 1, which were defined as in the present study (Sayer et al., 2013).

We compare those statistics with the ones given in Tables 4 and 5, calculated for Camagüey. The BIAS for the CSA (ENA) stations is -0.016 (0.0094), although those of Camagüey for both single observations and collocated daily means are (-0.027 and -0.033), thus showing higher values for Camagüey and similar signs for CSA and the opposite for ENA. R values for Camagüey for single observations and collocated daily means are 0.82 and 0.79, respectively, lower by around 10 % (5 %) than the R values of 0.96 (0.86) for the CSA (ENA). However, it should be noted that the number of cases used for the statistics at Camagüey was 419 for single observation and 169 for collocated daily means, representing 6 % and 14 % of the 3,032 cases used in the cited study. In addition, none of the stations in the CSA (ENA) regions were located in the Caribbean, but south and north (Sayer, 2018). Despite the significant difference in the amount of cases used in both studies and the location of the six stations, results show reasonable agreement.

~~3.1.3~~ ***Monthly*** ~~***single observations.***~~

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3.2 ~~Figure 4 shows the monthly~~ ***means values and statistics***

Given the close similarity in the results from single observations and collocated daily means data, it seems reasonable to evaluate monthly mean values based on only one of them, i.e., for the collocated daily means data. Figure 4 shows the monthly means (based on the mean of each month for every year of the measured period) and the statistics resulting from the comparison between AOD_{SP} and AOD_{ta} for both the DB and DT algorithms. –Tables S1 and S2 (see supplementary material) also illustrate this comparison although they add separate information for Terra and Aqua (see supplementary material). In Figure 4a~~ shows~~, the multiannual monthly means from the combined AOD_{ta} ~~with AOD_{SP} when the MODIS DB and DT algorithm are used. We combined the two coincident sets of measurements of AOD_{t} coincident with AOD_{SP} and from AOD_{a} coincident with AOD_{SP} to produce the combined AOD_{ta} with AOD_{SP} dataset. Similarly, the coincident Camagüey's sun photometer dataset AOD_{SP} was generated from the union of both individually coincident AOD_{SP} datasets with AOD_{a} and AOD_{t}, which were independent as it was explained above, because the differences in overpass time between Terra and Aqua is higher than the time difference established for coincidence (± 30 min). Monthly mean AOD_{ta} derived with DT algorithm shows~~and AOD_{SP} for both the MODIS DB and DT algorithm are shown, providing an initial overview of aerosol AOD climatology in Camaguey. It can also be seen that the DT algorithm gives the best match with monthly mean AOD_{SP}.

The monthly RMSE and MAE plots~~, on figures 3b~~ in Figures 4b and ~~3c,~~4c generally show increases~~ in general~~, with the increase ~~of the AOD_{ta} for the DB algorithm.~~in the AOD_{ta} for the DT algorithm and also for the DB algorithm, the exception being the minimum in April for the DT algorithm (this means greater differences between satellite and sunphotometer in summer than in winter). These results are consistent with the fact that ~~the~~ AOD uncertainty depends on the AOD itself (see eq. ~~2). The~~ 3) and greater AOD variability in summer. The AOD_{ta} peaks for the DT algorithm in March in both RMSE and MAE are also present ~~also~~ in the ~~RMSE and MAE~~ results for

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AOD$_t$ and AOD$_a$, separately, and the amount of cases available for the statistics is among the highest of all the months seen ~~on tables S1 and S2 (see supplement 01). We have no explanation for it.~~ in Tables S1 and S2 (see supplementary material). In Table S2, for the DT algorithm, we can see that the number of cases of AOD$_{ta}$ from March to April drops by 55 %. However, something similar happens for the DB algorithm in Table S1, with the number of AOD$_{ta}$ cases falling from March to April by 61 %. Sampling cannot therefore be seen as the cause of the RMSE and MAE peaks for the DT algorithm. We plan to revisit this feature in future studies. In summer, RMSE and MAE show their maximum values associated to the maximum values of the AOD resulting from Saharan dust reaching Cuba from across the Atlantic. The BIAS is negative in summer for both Terra and Aqua AOD, showing that AOD$_t$ and AOD$_a$ observations have higher magnitudes than AOD$_{SP}$.

Tabulated results of the comparison between AOD$_t$, AOD$_a$ and AOD$_{ta}$ with AOD$_{SP}$ ~~at~~on a monthly scale~~, showing~~ also show better results for ~~DT, table~~the DB (see Table S1~~,~~) than for ~~DB, table S2, both on supplement tables.~~ the DT (Table S2) algorithm. Here, we ~~will~~only discuss ~~only~~ the results of the joint AOD$_{ta}$ dataset using both the DT and DB algorithms ~~for the retrievals.~~

. In ~~figures 3d~~Figures 4d, the BIAS for the DT algorithm is positive from December to May, a period of the year with predominant lower ~~values of~~ AOD$_{ta}$ and AOD$_{SP}$~~.~~ values. During this period, AOD$_{ta}$ underestimates ~~the~~ AOD$_{SP}$. ~~Then the~~ BIAS then becomes negative from June to November, which is ~~the period of the year~~ when ~~the arrival of~~ Saharan dust ~~to~~reaches the Caribbean ~~basin occur.~~ basins. At the same time, the BIAS of the AOD$_{ta}$ derived with the DB algorithm is negative for the whole year, with higher absolute values ~~magnitudes~~ than ~~the ones~~those from the DT algorithm.

The correlation coefficient, R, ~~on figure~~in Figure 4e is the ~~statistics showing~~ statistic which shows almost the same agreement for the DB and DT algorithm. However, the DT shows a higher

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number of R-values bearing higher magnitudes. R magnitudes remain over 0.5 almost the whole year ~~around~~round except in December and January when lower AOD values occur.

~~The~~Figure 4f shows the fraction of the AOD$_{ta}$ (f~~) shown on figure 4f,~~), in agreement with AOD$_{SP}$ within the expected uncertainty, ~~shows~~showing its higher values over 80 % from November to January, in general for both algorithms. This is the period of the year with the ~~lower~~lowest monthly mean values of both AOD$_{ta}$ and AOD$_{SP}$. During the rest of the year, including the period of the Saharan dust arrivals, it shows its ~~lower~~lowest values between 60 % and 75 % for the DT algorithm while values for DB ~~values~~ below 50 % occur in four of the ~~month~~months between June and October. The ~~blue~~ discontinuous blue line at f = 68 % denotes a one standard deviation confidence interval, selected ~~for the definition of~~to describe EE. The f values ~~of f~~ above that value mean the algorithm works ~~well~~better than expected. All the statistics demonstrate that the DT algorithm performs better than the DB for the region of study. However, the lowest R values for those months with the highest f values would seem to be contradictory. At present, we have no explanation for this.

~~3.2~~3.3 *Comparison of Ångström Exponent by sun photometer and MODIS satellite instruments:*

Figure 5 shows the frequency distribution of the coincident AE$_{SP}$ ~~as well as~~with both AE$_t$ and AE$_a$~~. We used the AE$_a$ and AE$_t$ derived~~ using the DB algorithm ~~measured~~, as explained. As can be seen in ~~a radius of 25 km around~~ the literature, the Ångström Exponent varies between 0 and 2. Our Ångström Exponent data obtained from the AERONET sun photometer ~~for the whole 2001 – 2015 period (2002 - 2015 in the case of Aqua). A maximum~~ measurements are within this range with a wide and smooth frequency ~~for both AE$_t$ and AE$_a$ appears for the~~ distribution of values ~~of~~ and with a not well-defined maximum in the range 1.2 and 1.6. Neither AE$_t$ nor AE$_a$ present any real distribution shape

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because there are practically no values below 1, with most being around $AE = 1.5$, followed by a ~~secondary~~second maximum at $AE = 1.8$. The first~~ of them~~, 1.5, is a regional default value for AE_t and AE_a (Hsu et al., 2013; Sayer et al., 2013) assumed by the DB algorithm in the case of low AOD values (AOD_t or $AOD_a < 0.2$~~) because of the lack of information on this parameter. ~~). The second~~ one~~ is associated with the fact that the AE_t and AE_a values allowed by the aerosol optical models in Collection 6 are constrained between 0 and 1.8 to avoid unrealistic values (Sayer et al., 2013).

Table 6 shows the results of the comparison of coincident AE_t~~ and~~, AE_a ~~measurements in radius of 25 km around the Camagüey's sun photometer~~and AE_{ta} with E_{SP}. For both single observations and ~~± 30 minutes with AE_{SP} measurements. We classified the AE from~~collocated daily mean data the statistics were calculated for the two options: the ~~two MODIS instruments and the sun photometer coincident~~first including all values ~~in three groups. The first one considers the daily individual coincident AE_t, AE_a with AE_{SP}. The ~~and the second ~~one excludes from the ~~excluding cases with AE=1.5 and 1.8. The statistics in Table 6 for all values present similar values considering those derived by single observation or for collocated daily ~~individual coincident AE_t and AE_a~~mean values as expected once we know the results for AOD, although similar values also appear for Terra and Aqua (no clear distinction appears between Terra and Aqua). These statistics present very high values if compared with ~~AE_{SP} the cases of AE_t and AE_a equal to 1.5 or 1.8 value. The third one compares ~~those shown for AOD. Obviously, the R correlation coefficient presents very low values, which are below 0.5 (the poor correlation is observed in the ~~daily mean values of daily individual coincident AE_t and AE_a with AE_{SP}, including the cases of~~scatter plots similar to those in Figure 6, not shown here). Excluding AE_t and AE_a values equal to 1.5 or 1.8 ~~values. We took into account also the combined coincident AE_{ta} with AE_{SP} for the three cases.~~

~~Scatter plots are in figure 1S in the supplements. Statistics on table 6 for the three cases the RMSE, MAE and~~entails no substantial difference, only lower BIAS ~~statistics are in the same order of magnitudes. In addition, the magnitude of R is below 0.5 and negative for the three cases. The~~values. Overall, the results of the

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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 ~~AERONET has large~~the MODIS DB algorithm displays great uncertainty ~~in~~for low-AOD conditions, ~~because the~~since AE is obtained as a gradient between two small AOD numbers (Wagner and Silva, 2008).~~ Another factor could be the poor performance that the DB algorithm showed in the comparison with AOD$_{SP}$.~~

3.~~3~~4 Comparison of AOD between MODIS products and BAOD for the four Cuban actinometrical stations.

Two main facts limit the number of available BAOD values coincident in time with AOD$_t$ and AOD$_a$~~. The~~: the hourly time step between manual DNI ~~measurements conducted hourly used to derive BAOD;~~observations and the required condition ~~for these measurements to take place under~~of a clear line of sight between the pyrheliometer and a region of 5° around the Sun. Consequently, only one BAOD measurement could coincide each day with AOD$_t$, and another ~~one ~~with AOD$_a$ ~~because of~~given the time coincidence criteria. ~~ ~~Table 7 ~~list~~lists the number of coincident AOD$_t$, AOD$_a$, AOD$_{ta}$ ~~measurements~~observations in space and time with BAOD both for the DB and ~~for ~~DT algorithms for each ~~one ~~of the actinometrical stations. ~~ Because~~Since the amount of coincident ~~measurements~~observations at each station is low, we decided to combine all the pairs of ~~AOD$_{TE}$~~AOD$_t$, AOD$_a$ and AOD$_{ta}$ coincident with BAOD in the four sites together in order to conduct the comparison. ~~ ~~In addition, we did not ~~considered~~consider the very few cases with values of BAOD > 0.~~5~~6, around 1 ~~%,~~% of all ~~the ~~cases, so as to avoid the possibility of inadvertent cloud contamination.

Table 8 contains almost the same statistics used in previous comparison satellite-sun photometer data (see Table 4 and 5), both for the DB and for DT algorithms for the four actinometrical stations together. ~~ The scatter plot of the BAOD vs. AOD$_t$, AOD$_a$, and AOD$_{ta}$ appears in figure 6, ~~The only statistic not included in ~~table~~Table 8 is f, the fraction of the MODIS/AERONET AOD retrievals in agreement within the expected uncertainty, because such uncertainty ~~has ~~still has to be

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established for BAOD. We highlighted the best performing algorithm in bold for each ~~one~~ of the statistics. The AOD_a derived with the DB algorithm performs better than the other three combinations of AOD_t, AOD_a, for DT and DB ~~according~~ in accordance with all ~~the~~ four statistics, except for ~~the~~ BIAS, where the best performing is still the DB algorithm, but for AOD_t. However, in general and taking into account the low number of data and the fact that we have single observations, the RMSE, MAE and BIAS for AOD_t, AOD_a, AOD_{ta} derived with both DB and DT algorithms remain in the same order of magnitude~~.~~ as earlier Tables 4 and 5, with the exception of the low values of the correlation coefficient R. The BIAS shows ~~an~~ almost similar behavior except for its best performing value. This different behavior of algorithms and platforms with respect to the earlier results of Table 4-5 is clearly shown by Figure 6 where the scatter plots of the BAOD vs. AOD_t, AOD_a, and AOD_{ta} are depicted. What is clear is the poor correlation given by the very low values of the slope with respect to the value 1 and also the relatively high values of the intercept in relation to 0, and hence the resulting low values of the R coefficient. BAOD shows a high uncertainty for low values of AOD (below 2, see this range over the X axis in the plots) which are those prevalent in this area (l).

~~3.4 Comparing BAOD from actinometrical data and sun photometer:~~

~~Theoretical studies have shown that the best agreement between BAOD and AOD_{SP} occurs at the wavelengths about 700 nm (Blanchet, 1982; Molineaux et al., 1998). In addition, the Molineaux et al., (1998)~~

4. Conclusions

This study ~~reports an empirical validation finding that measured BAOD and AOD at 700 nm had similar values. We found no literature reports about BAOD validations with AOD_{SP} at each one of the AERONET sun photometer wavelengths.~~

~~At Camagüey, using the 715 coincident measurements (± 30 minutes) of BAOD and AOD_{SP} in the period from 2008 to 2013, we calculated the coefficients of determination (R^2) between BAOD and AOD_{SP} at each sun photometer wavelength. Results showed the higher values of R^2 (about 0.45) at 675 and 500 nm (Garcia~~addresses

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Comentado [JCAM8]: ?Que significa?

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~~et al., 2015).~~ ~~The comparison we report here includes those same BAOD and AOD$_{SP}$ at each sun photometer wavelengths plus 162 pairs of coincident measurements from 2014.~~

~~Table 9 shows the statistics of the comparison between BAOD with AOD$_{SP}$ at the eight wavelengths measured in Camagüey. Corresponding scatter plots are in figure 2S in the supplements. The amount of cases is the same at all wavelengths with the exception of 1640 nm. Two out of six CIMEL sun photometers employed at Camagüey site between 2008 and 2014 had a 1240 nm channel instead of the most common 1640 nm. At 500 nm R^2 is 0.48 (R = 0.69) while at 675 nm and 400 nm wavelengths the R^2 has the same value of 0.46 (R = 0.68), very similar among the three wavelengths and with the results reported by Garcia et al., (2015) with a slightly less data. However, the other three statistics show notorious differences. The best performing value for each statistic is in bold, belonging to the 500 nm wavelength follow by the 675 nm and 440 nm in that order. After this comparison, we can estimate the uncertainty of the BAOD to be about 0.04 larger than the sun photometer uncertainty, i.e. 0.06 in total and the best correspondence takes place at the 500nm wavelength.~~

~~4. Summary and conclusions~~

~~The study address~~ the comparisons of different sources of AOD and AE from ground-based sun photometer (AERONET level 2.0 data), MODIS instruments (Terra, Aqua, and Terra + Aqua) and retrievals from direct normal solar irradiance observations in Cuba ~~for a long period. Results~~. Although this type of comparison ~~between~~shows important differences depending on the spatial and temporal ~~coincident daily mean values in the ± 30 minutes interval around~~ resolution of MODIS ~~overpass time AOD$_{SP}$ vs. AOD$_t$ and AOD$_a$ show better performance for the Dark Target (DT) algorithm. We found little differences between AOD$_t$ and AOD$_a$ justifying the combination of AOD$_t$ and AOD$_a$ measurements in one dataset. When we conducted the comparison between daily individual spatial and temporal coincident AOD$_{SP}$ vs. AOD$_t$ and AOD$_a$ we found similar results. For both spatial and temporal coincident daily means and daily individual observations of AOD$_{SP}$ vs. AOD$_t$ and AOD$_a$, the correlation coefficient R is equal or higher than 0.70 for Deep Blue (DB) and DT algorithms. However, the most notorious result is the fact that the portion of AOD$_t$ and AOD$_a$ values within the expected error margins (0.05±0.15·AOD) is higher for DT than for DB both when we used single observations and daily means values. That is an important criterion to take into account for the selection of the AOD$_t$ and AOD$_a$ data to calculate the aerosol climatology over Cuba~~and ground-based instruments, justification for using a

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single observations dataset and collocated daily means data set separately to analyze this comparison here is based on the characteristics of the surface area under study, with nearby stretches of water and land. Another reason is the difference with regard to how cloud cover at the overpass time of the Terra and Aqua platforms affect the aerosols observations. Despite the different number of observations given by the two selected criteria, the overall results shown by the statistics are very similar and show alike patterns, which are therefore equal from the analysis perspective.

~~The statistical evaluation of multiannual monthly means of the daily individual coincident AOD$_{ta}$ and AOD$_{SP}$ reveals~~The results of the comparison between spatial and temporal coincident single observations and collocated daily means of AOD$_{SP}$ vs. AOD$_{t}$ (AOD$_{a}$) show better performance for the Dark Target (DT) algorithm. Furthermore, we found small differences between AOD$_{t}$ and AOD$_{a}$, thus justifying the combination of these observations in a single dataset, and thereby improving the behavior of both algorithms. Evaluation of multiannual monthly means of collocated daily mean AOD$_{ta}$ reveals better agreement with AOD$_{SP}$ for the DT algorithm and a clear overestimation for the DT algorithm, corroborated by the statistics. Statistics show a direct relation between the RMSE and MAE values and the monthly mean values of AOD$_{ta}$. The BIAS and fraction of data within the uncertainty margins (f) show an inverse relation with the monthly mean values of AOD$_{ta}$. The f magnitudes reveal that both the DB and DT algorithms work better than expected between November and January with f magnitudes of around 80 %. However, for the rest of the year, f remains around a confidence interval of one standard deviation (f = 68 %) for the DT algorithm, while f falls well below this level for several months for the DB, showing that the DT algorithm gives better results than the DB for Camagüey.

~~Daily mean~~The Ångström exponents AE$_{t}$, AE$_{a}$ and AE$_{ta}$ do not show ~~a~~ good agreement with ~~daily mean and daily individual~~the spatial and temporal coincident AE$_{SP}$ values~~. This result corroborates~~

Comentado [JCAM9]: La coverture nubosa no afecta al “overpass” sini a las observaciones de aerosoles

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when the default–1.5 and the constraint-1.8 values are or are not considered. Those results corroborate the limitation of the MODIS derived AE in general.

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In the comparison of BAOD vs. AOD_t, AOD_a, AOD_{ta} ~~the AOD_a~~, the errors are generally of the same order of magnitude ~~than~~as the average values~~, in general. ~~. It is ~~noteworthy that for the AOD satellite products~~noticeable that the statistics are similar for the sun photometer AOD and the BAOD~~.~~ for the AOD satellite products. This result ~~points out~~highlights the potential of BAOD ~~to be~~as a reliable source of aerosol information ~~in the places lacking~~for climatological studies in areas that lack a sun photometer or any other surface measurement.~~ This conclusion is reinforced by the results of the comparison of BAOD with AOD_{SP} at all the eight individual sun photometer wavelengths, showing better agreement in the spectral bands between 400 and 675 nm with the better result at 500 nm and typical uncertainty about 0.04-0.06 in this spectral range.~~

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Tables:

Table 1: Aerosol products from the MODIS Collection 6 dataset used in the present study

Product	Description
Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimate	Deep Blue AOT at 0.55 micron for land with higher quality data (Quality flag=2,3)
Deep_Blue_Angstrom_Exponent_Land	Deep Blue Angstrom Exponent for land with all quality data (Quality flag=1,2,3)
Optical_Depth_Land_And_Ocean	AOT at 0.55 micron for both ocean (Average) (Quality flag=1,2,3) and land (corrected) (Quality flag=3)

Table 2: Information about ~~the~~ Cuban actinometrical stations operating under the Solar Radiation Diagnostic Service (SRDS). Available ~~BAOD~~ number of BAOD observations included in column 6 and the period ~~they cover~~covered in the last column.

Code	Station Name	Latitude	Longitude	Height (m)	No. Obs.	Period
78355	Camagüey (CMW)	21.42	-77.85	122 m	2495	2001-2015
78330	Jovellanos (JVN)	22.80	-81.14	23 m	1182	2010-2015

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78342	Topes de Collantes (TPC)	21.92	-80.02	766 m	1358	2011-2015
78321	Santa Fé (LFE)	21.73	-82.77	32 m	1756	2011-2015

Table 3: ~~Available~~Number of available non-negative AOD$_a$, AOD$_t$, AE$_a$ and AE$_t$ ~~and AE$_a$~~data spatially coincident with the Camagüey ~~sun photometer~~sunphotometer in a radius of 25 km for each retrieval ~~algorithms~~algorithm, DB and DT~~. The entire~~ for the whole period 2001-2015~~ is shown,~~ as well as the period 2008-2014, when sunphotometer data, AOD$_{SP}$ and AE$_{SP}$, are available~~, 2008-2014.~~.

Period	**2001-2015**			**2008-2014**		
Algorithm	**DB**		**DT**	**DB**		**DT**
Parameter	**AOD**	**AE**	**AOD**	**AOD**	**AE**	**AOD**
Terra	6884	8111	6311	3418	4024	3166
Aqua	2445	3909	2869	1329	1534	2093

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Table 4: Statistics of the comparison between collocated daily means of AOD_t ~~(~~and AOD_a~~)~~ with AOD_{SP}~~. In addition, the statistics for the comparison between~~ and the combined AOD_{ta} ~~with AOD_{SP} is shown in the last two columns~~.

	AOD_{SP} vs. AOD_t		AOD_{SP} vs. AOD_a		AOD_{SP} vs. AOD_{ta}	
	DB	**DT**	**DB**	**DT**	**DB**	**DT**
RMSE	0.084	0.060	0.065	0.062	0.078	0.061
MAE	0.062	0.045	0.046	0.047	0.056	0.046
BIAS	-0.053	-0.001	-0.033	0.006	-0.046	0.002
R	0.730	0.729	0.785	0.779	0.741	0.753
f	0.656	0.803	0.763	0.795	0.694	0.800
Cases	311	335	169	254	480	589

Table 5: Statistics of the comparison between collocated single observation of AOD_t and AOD_a with AOD_{SP} and combined AOD_{ta}.

	AOD_{SP} vs. AOD_t		AOD_{SP} vs. AOD_a		AOD_{SP} vs. AOD_{ta}	
	DB	**DT**	**DB**	**DT**	**DB**	**DT**
RMSE	0.081	0.061	0.063	0.064	0.076	0.062
MAE	0.059	0.046	0.044	0.050	0.054	0.047
BIAS	-0.048	0.007	-0.027	0.017	-0.042	0.010
R	0.716	0.701	0.817	0.794	0.744	0.742
f	0.664	0.773	0.773	0.784	0.699	0.777
Cases	880	900	419	500	1299	1400

Table 6: Statistics of the comparison between AE_t, AE_a and AE_{ta} with AE_{SP} for single observations and daily mean values.

	Single observations			**Single observations (Except AE 1.5 & 1.8)**			~~**Daily Means**~~**Collocated daily means**			**Collocated daily means (Except AE 1.5 & 1.8)**		
	AE_t	AE_a	AE_{ta}	AE_t	AE_a	AE_{ta}	AE_t	AE_a	AE_{ta}	AE_t	AE_a	AE_{ta}
RMSE	0.637	0.692	0.658	0.575	0.609	0.587	0.637	0.659	0.645	0.548	0.578	0.561
MAE	0.494	0.553	0.516	0.446	0.496	0.464	0.490	0.512	0.498	0.431	0.466	0.445
BIAS	-0.327	-0.337	-0.331	-0.129	-0.101	-0.119	-0.398	-0.384	-0.393	-0.189	-0.139	-0.167
R	-0.187	-0.426	-0.272	-0.191	-0.444	-0.269	-0.259	-0.414	-0.308	-0.124	-0.400	-0.236

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Cases	615	374	989	353	189	542	311	169	480	172	120	292

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Table 7: Number of coincident cases of AOD$_t$, AOD$_a$, AOD$_{ta}$ with BAOD both for the DB and for DT algorithms.

Station:	**BAOD vs. AOD$_t$**		**BAOD vs. AOD$_a$**		**BAOD vs. AOD$_{ta}$**	
	DB	**DT**	**DB**	**DT**	**DB**	**DT**
Camagüey	166	171	66	79	232	250
Topes de Collantes	112	138	49	76	161	214
Jovellanos	65	65	35	34	100	99
La Fe	34	66	46	85	80	151
All combined	377	440	196	274	573	714

Table 8: Statistics ~~for~~of the comparison between the single observations of BAOD ~~measured~~ at the four actinometrical stations coincident in space and time with the single observation (L2) of AOD$_t$, AOD$_a$ and AOD$_{ta}$. In bold, the values of best agreement.

	Camagüey, La Fe, Topes de Collantes & Jovellanos					
	BAOD vs. AOD$_t$		**BAOD vs. AOD$_a$**		**BAOD vs. AOD$_{ta}$**	
	DB	**DT**	**DB**	**DT**	**DB**	**DT**
RMSE	0.080	0.087	**0.073**	0.088	0.078	0.088
MAE	0.055	0.063	**0.048**	0.066	0.052	0.064
BIAS	**0.001**	0.027	0.014	0.049	0.005	0.035
R	0.455	0.325	**0.501**	0.417	0.468	0.355
Cases	373	436	191	268	564	704

~~Table 9: Statistics for the comparison between the single observations time coincident BAOD and AOD$_{SP}$ at all wavelengths measured by the sun photometer at Camagüey. In bold are the best performing value for each statistic.~~

~~**BAOD vs. AOD$_{SP}$(λ)**~~	~~**1640 nm**~~	~~**1020 nm**~~	~~**870 nm**~~	~~**675 nm**~~	~~**500 nm**~~	~~**440 nm**~~	~~**380 nm**~~	~~**340 nm**~~
~~**RMSE**~~	~~0.072~~	~~0.071~~	~~0.057~~	~~0.048~~	~~**0.044**~~	~~0.056~~	~~0.081~~	~~0.102~~
~~**MAE**~~	~~0.062~~	~~0.060~~	~~0.046~~	~~0.037~~	~~**0.030**~~	~~0.040~~	~~0.059~~	~~0.076~~
~~**BIAS**~~	~~0.060~~	~~0.059~~	~~0.043~~	~~0.032~~	~~**-0.002**~~	~~-0.022~~	~~-0.049~~	~~-0.068~~
~~**R**~~	~~0.46~~	~~0.59~~	~~0.65~~	~~0.68~~	~~**0.69**~~	~~0.68~~	~~0.67~~	~~0.65~~
~~**Cases**~~	~~490~~	~~877~~	~~877~~	~~877~~	~~**877**~~	~~877~~	~~877~~	~~877~~

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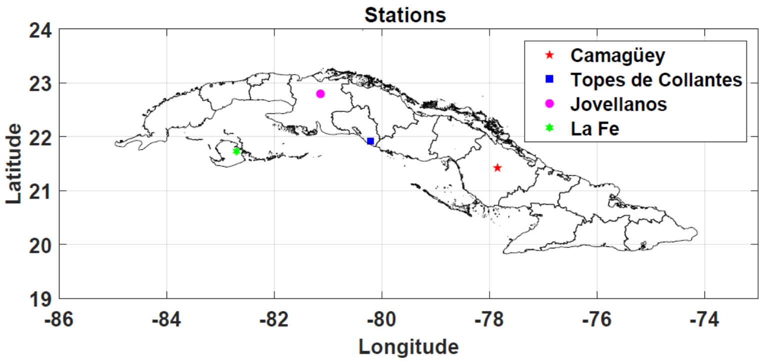

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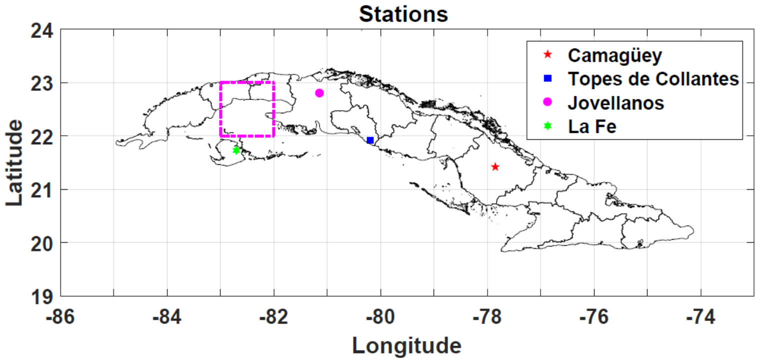

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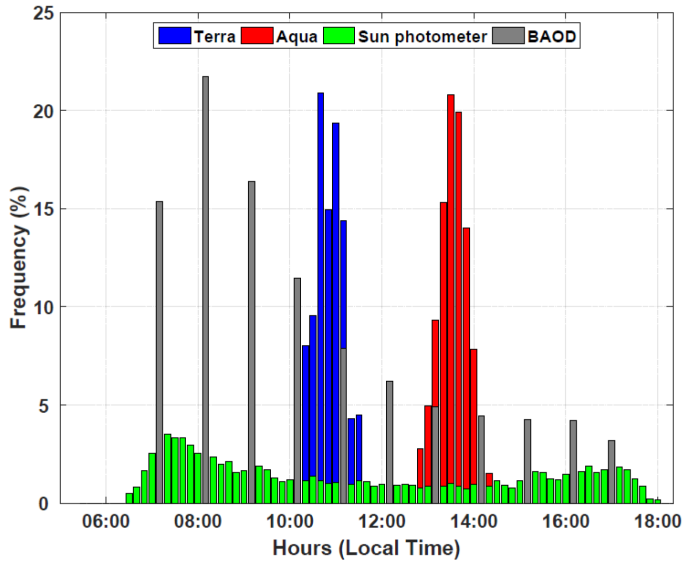
Figure 1: Map of Cuba locating the stations where the sun photometer and the four broadband pyrheliometer ~~measurements~~observations are conducted.



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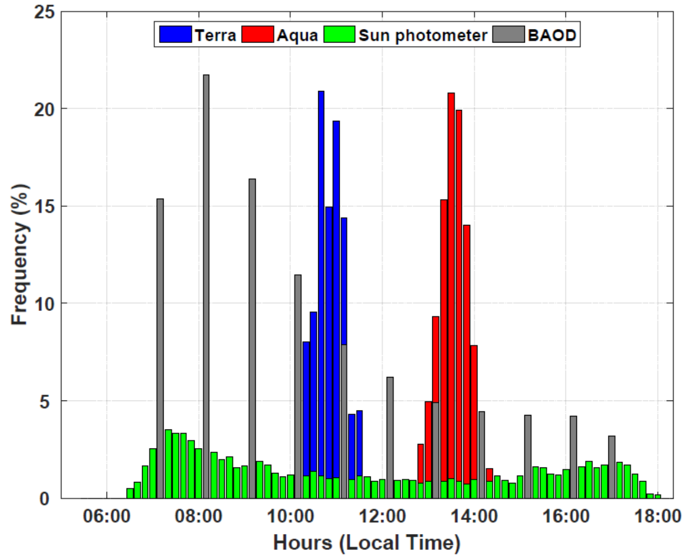

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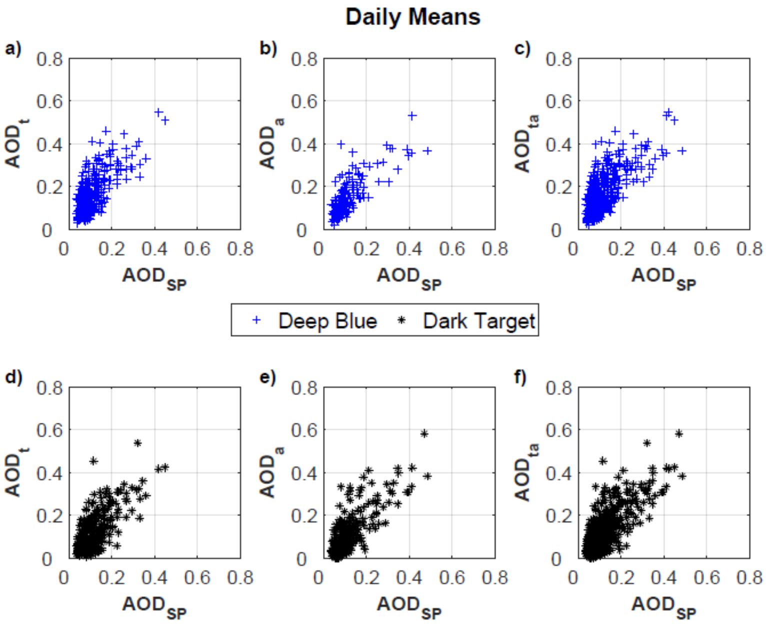
Figure 2: Frequencies of the time of the day (Local Time) ~~the~~overpass of Terra and Aqua (blue and red respectively) ~~overpass~~ Camagüey's sun photometer site in a radius of 25 km for the period 2001 to 2015. In green the time frequencies for the Camagüey's sun photometer ~~measurements~~observations in the period 2008 to 2014. In addition, the time frequencies for the direct radiation ~~measurements~~observations used to calculate the BAOD. The bar width is 10 minutes for Terra, Aqua and the sun photometer and 1 hour for the BAOD.



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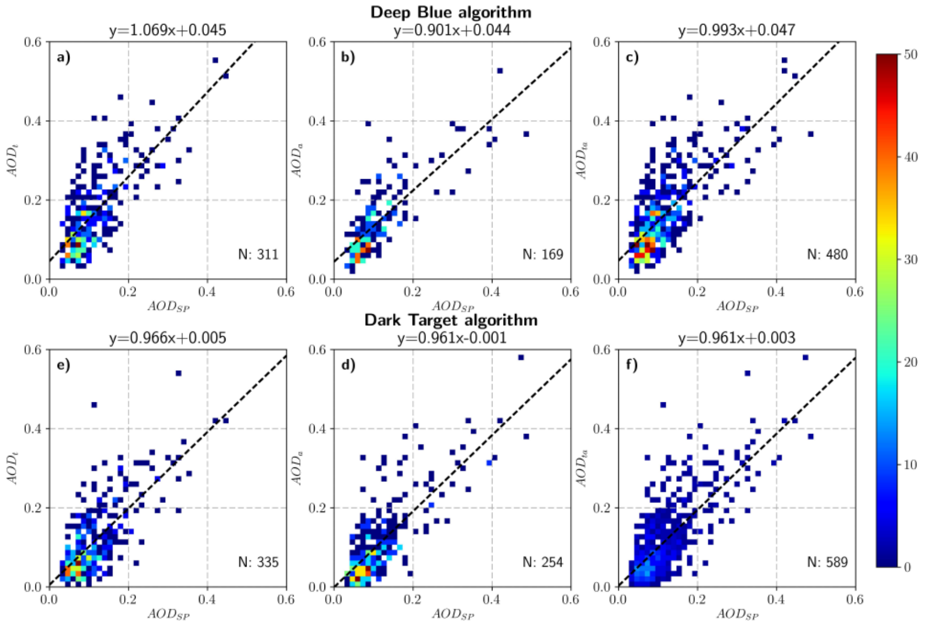

Figure 3: ~~Daily~~Collocated "daily mean" density scatter plots of the coincident AOD ~~measurements~~observations from the sun photometer and Terra and Aqua MODIS instruments for DB and DT algorithms.: a) to c) ~~Daily means of the~~ AOD$_{SP}$ vs AOD$_t$, AOD$_a$ ~~-~~and AOD$_{ta}$ respectively for DB algorithm; d) to f) Idem for DT algorithm. The data density is represented by the color scale, showing the number of data points located in a particular area of the plot. Linear regression is given by the black discontinuous line and the corresponding equation. The number of data points appears in the right bottom.

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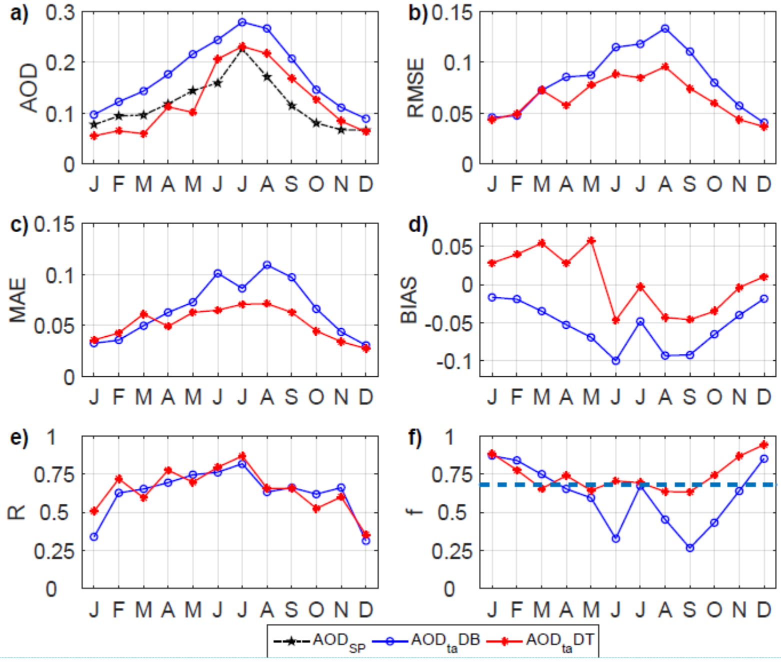

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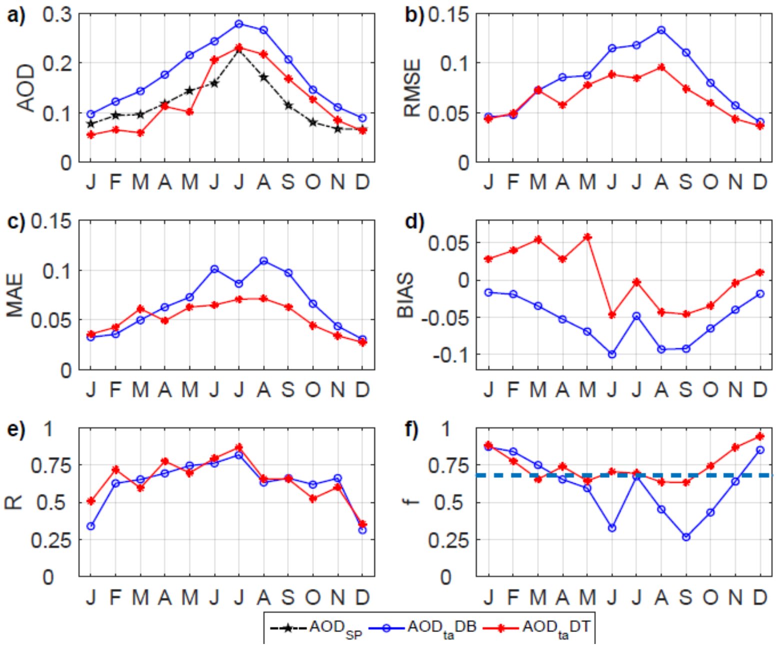

Figure 4: Monthly means and statistics (RMSE, MAE…….) resulting from the comparison between AOD_{SP} and AOD_{ta} for both DB and DT algorithms: a) Monthly means of the AOD_{SP} and AOD_{ta} for both DB and DT algorithms; b) RMSE for the comparison between AOD_{SP} and AOD_{ta} for both DB and DT algorithms; c) Idem for MAE~~;~~, d) ~~Idem~~ for BIAS~~;~~, e) ~~Idem~~ for R~~;~~ and f) ~~Idem~~ for f. The blue discontinuous line at f= 68 % represent one standard deviation confidence interval for the EE ~~expression~~indicator.

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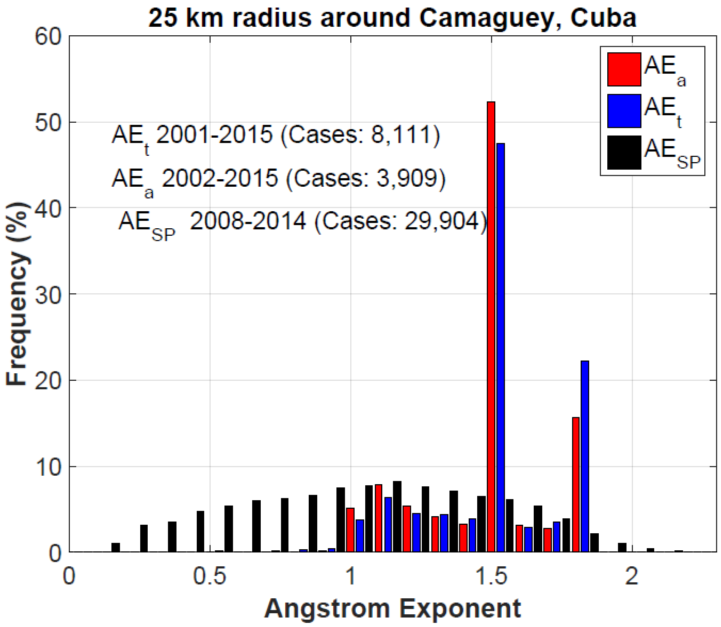

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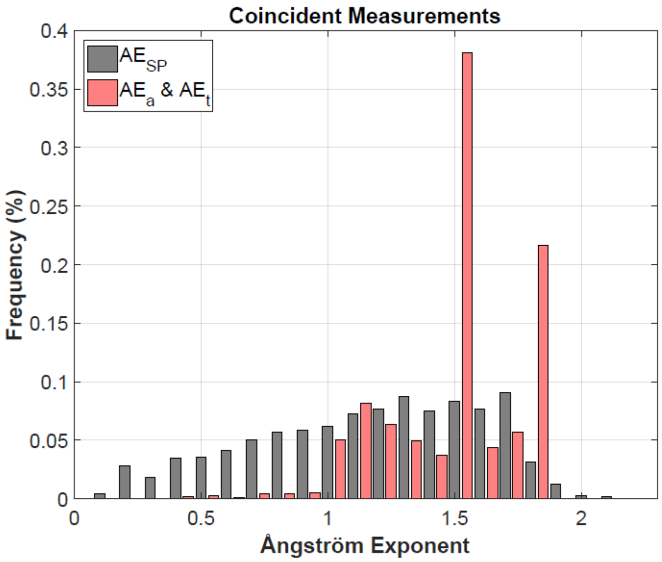

Figure 5: Frequency distribution of the ~~AE_t, AE_a~~Angstrom exponent (AE) values ~~for all~~ from both MODIS instruments Terra and Aqua and the ~~available values~~sun photometer coincident ~~within a~~ in ± 30 minutes and 25 km radius around Camagüey. ~~Also included all the AE_{SP} values.~~

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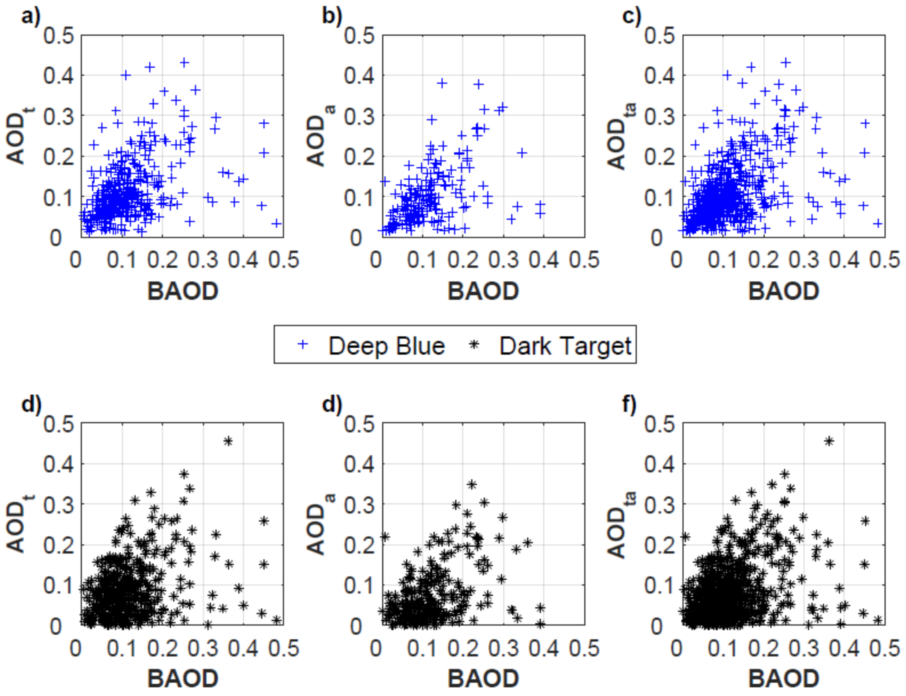

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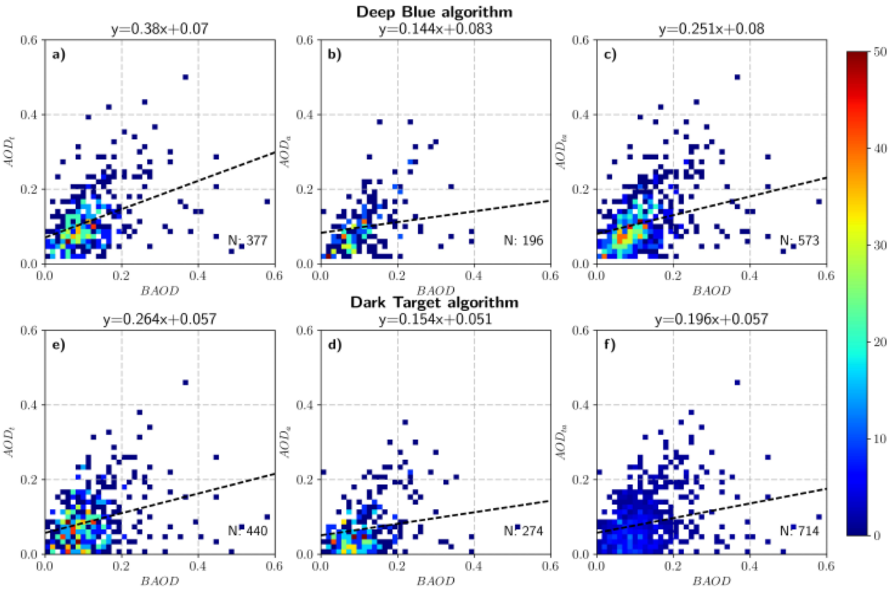

Figure 6: Single observations density scatter plots of the coincident BAOD ~~measurements~~observations from the broadband pyrheliometer and Terra and Aqua MODIS instruments for DB and DT algorithms.: a) to c) BAOD vs. AOD_t , AOD_a and AOD_{ta} respectively for DB algorithm; d) to f) Idem for DT algorithm. The data density is represented by the color scale, showing the number of data points located in a particular area of the plot. Linear regression line is shown by the black discontinuous line and the corresponding equation. The number of data points appears in the right bottom.

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