Climatology of Aerosol Optical Depth at Mid-Continental US Site: Ground-based Observations

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ABSTRACT

The total aerosol burden in the atmosphere is typically represented by aerosol optical depth (AOD). To capture important and climate-relevant signatures of the aerosol burden, such as year-to-year and seasonal variability, continuous multi-year AOD observations are required. For more than two decades, these observations have been performed at the mid-continental Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Central Facility (CF) using ground-based passive remote sensing. The partially overlapping and fragmentary AOD records at the ARM SGP CF have been provided by four individual instruments, namely two co-located (C1 and E13) Multifilter Rotating Shadowband Radiometers (MFRSRs), a Normal Incidence Multifilter Radiometer (NIMFR), and a Cimel Sunphotometer (CSPHOT). Since these individual records are sporadic with instrument- and time-dependent data quality, development of a continuous multi-year high-quality AOD dataset is a challenging task. In this work, an initial development of a continuous 20-year (1997-2017) high-quality AOD product is introduced. The development involves (1) incorporation of the available data quality information and delivery of the historical time series of AOD with high quality from four individual instruments, (2) comparison of multiple AOD retrievals to identify potential instrument-related issues and/or retrieval problems, and (3) merging these individual time series, generation of a two-decade continuous climatology of high-quality AOD and reporting of the uncertainty estimations of the merged product.

Keywords: ground-based passive remote sensing, individual and combined measurements of aerosol optical depth (AOD), Quality Control (QC) tests, Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) Central Facility, Mid-Continental US site, multi-year climatology

1. INTRODUCTION

Long-term records of aerosol optical depth (AOD) provide important observational constrains for understanding the aerosol-induced changes of the Earth's radiation budget[1-2] and for evaluating model predictions of these changes[3-4]. However, obtaining multi-year AOD records in a continuous fashion is very problematic mostly because of relatively short lifetime of instruments (in the order of several years). The required upgrades and/or replacements of instruments associated with their degradation can be responsible for substantial gaps (on the order of several days or even months) in the obtained discontinuous records. Moreover, the degradation of instruments can be responsible for considerable changes in the instrument calibration with time, and thus for potential data quality changes.

Since continuous AOD records on a time scale of decades are needed to narrow down the uncertainties of aerosol radiative impacts[5-6], decadal measurements of AOD are the focus of several programs and agencies, such as the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM; http://www.arm.gov) Program and the National Aeronautics and Space Administration (NASA; https://www.nasa.gov). Here, we consider an initial development of a continuous multi-year (1997-2017) high-quality AOD dataset by merging four individual records obtained from the ARM- and NASA-supported ground-based measurements at the mid-continental ARM Southern Great Plains (SGP) Central Facility (CF)[7]. Our initial development also involves estimation of uncertainties of the merged product.

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2. INSTRUMENTS

For more than two decades, AOD observations have been performed at the ARM SGP CF using ground-based passive remote sensing. The partially overlapping and fragmentary AOD records have been provided by four individual instruments (**Figure 1**), namely two co-located (C1 and E13) Multifilter Rotating Shadowband Radiometers (MFRSRs), a Normal Incidence Multifilter Radiometer (NIMFR), and a Cimel Sunphotometer (CSPHOT). The first three instruments (MFRSR C1, MFRSR E13 and NIMFR) are supported by the ARM Program (http://www.arm.gov/instruments), while CSPHOT is part of the NASA-supported Aerosol Robotic Network (AERONET; http://aeronet.gsfc.nasa.gov/) and is jointly supported by ARM and NASA.

A review of the MFRSR and NIMFR (**Figure 1**), their calibration and cloud screening are given by Michalsky et al. (2010)[8]. The MFRSR measures total and diffuse solar irradiances at six narrowband wavelength channels centered at 0.415, 0.5, 0.615, 0.673, 0.870 and 0.94μm. These quantities are used to obtain the spectral values of the direct solar irradiance. The NIMFR is narrow field-of-view (FOV) Sun-tracking radiometer and measures the direct solar irradiance at the same six narrow spectral bands. Note that the MFRSR and NIMFR have the same receiver and their calibration is based on the same Langley field technique[8]. The direct irradiance in turn is applied to derive AOD.

A review of the CSPHOT (**Figure 1**), its calibration and cloud screening are given by Holben et al., (2001)[9]. CSPHOT is narrow FOV Sun-tracking radiometer and measures the direct solar irradiance at eight (0.34, 0.38, 0.44, 0.5, 0.67, 0.87, 0.94, and 1,020 μm) narrow spectral bands. Calibration of the field instrument (CSPHOT) at the ARM SGP CF is based on intercomparison with reference instruments, which are typically recalibrated at Mauna Loa Observatory (MLO) with low and stable AOD. The direct irradiance in turn is applied to derive AOD[9]. To ensure high data quality, the latest version (version 3) of Level 2.0 data is used in our study. This version represents cloud screened and quality-assured data.

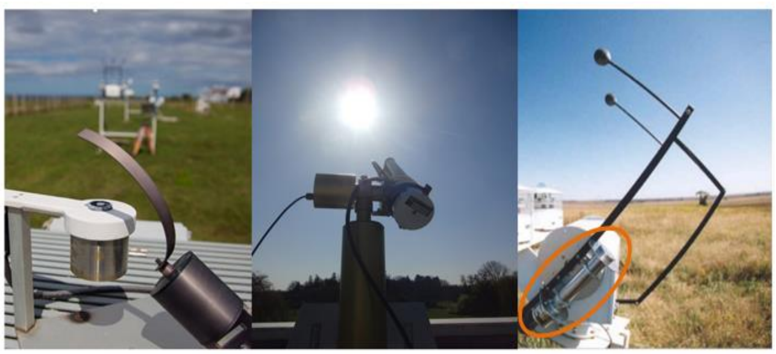

Figure 1. Images of three ground-based instruments for measuring AOD at the ARM SGP CF: MFRSR (left), CSPHOT (center) and NIMFR (right).

3. APPROACH

Here we introduce a three-step approach with a focus on development of a continuous multi-year (1997-2017) high-quality AOD dataset. The introduced approach can be considered as an extension of the method introduced previously by Michalsky et al. (2010)[8]. The extension includes (1) enhanced flexibility, (2) longer period and (3) possibility to offer the uncertainty of the merged data. Here are objectives of three main steps:

- Provide historical time series of AOD with high quality from four individual instruments.
- Compare multiple AOD retrievals to identify potential instrument/retrieval problems.
- Merge individual time series of AOD and generate a two-decade climatology of high-quality AOD and estimate uncertainty of the merged product.

The following sections highlight these three steps, provide several important details and discuss the initial results.

4. RESULTS

Let us start with the first step. It involves application of the Quality Control (QC) variables that are embedded in the data files for three instruments: two MFRSRs (C1 and E13) and NIMFR. We apply the *automated* QC tests from these variables to remove "incorrect" and "suspect" data from our analysis. Note that the term "incorrect" indicates that the AOD values are inaccurate and should not be used, while the term "suspect" indicates that the AOD values are exhibiting some indication of an underlying issue and additional screening is required (https://www.arm.gov/data/data-quality-program/).

The automated QC tests are very useful for analysis of multi-year records. However, these tests occasionally were not able to detect several dates with "incorrect" and "suspect" data. Thus, we applied *manual* inspection in addition to automated QC tests to filter out these infrequent dates from the collected MFRSR and NIMFR records. Based on our investigation, we remove several dates with small negative AODs (represent "incorrect" data) and dates where the NIMFR was not operated correctly (represent "suspect" data). Joint application of the automated QC tests and manual inspection of the collected MFRSR/NIMFR data results in the required selection of "valid dates" (**Figure 2**). The term "valid date" defines a date that has at least one AOD after removing data that fail the automating QC tests and the manual inspection. The fraction of "valid dates" shows its strong dependence on the instrument and period of interest. For 2013, for example, this fraction is about 30% and 65% for the NIMFR and MFRSR (both C1 and E13) data, respectively. However, for 2012, these fractions are about 70% and comparable for these three instruments (**Figure 2**). This fraction is typically smaller than 70% for all years considered here and for all four instruments. Both observational conditions (e.g., presence of clouds) and the instrument-related data quality issues are responsible, at least in part, for the obtained fractions (**Figure 2**).

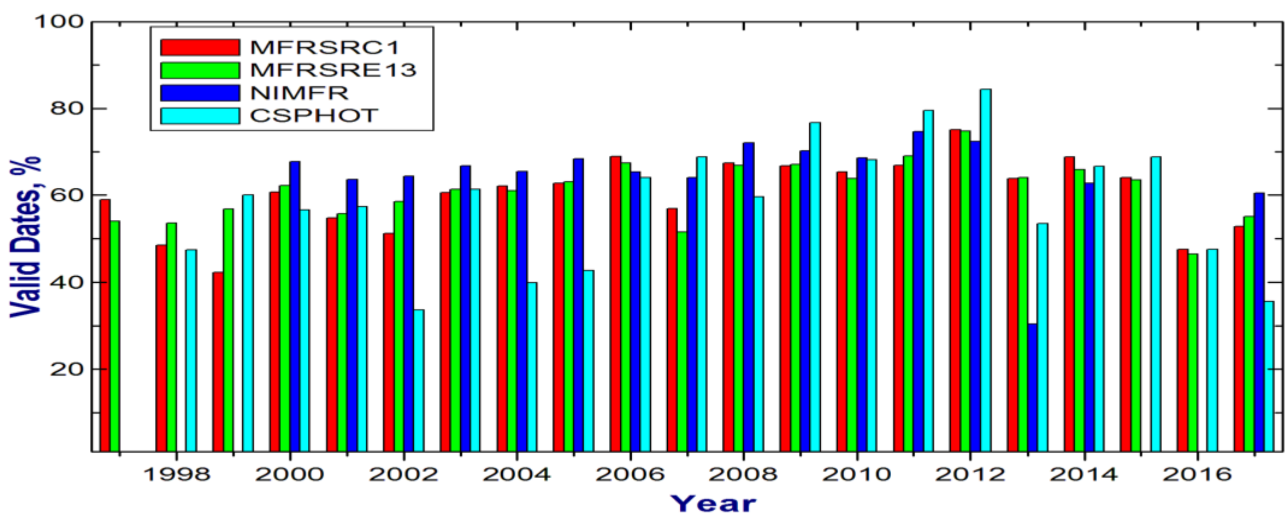

Figure 2. Fraction of valid dates for a given instrument (colored bars). For MFRSR/NIMFR, this fraction is a ratio of "Number of Valid Dates" to "Total Dates Available". For CSPHOT, this fraction is a ratio "Total Dates Available"/365 for non-leap years and "Total Dates Available"/366 for leap years.

The "valid dates" information obtained for four individual instruments (**Figure 2**) defines both the frequency and durations of "gaps" in the corresponding time series of daily averaged AODs (**Figure 3**). The latter are calculated from coincident times for the instruments on each date. There are three main reasons for the observed "gaps": (1) degradation/upgrade of instruments, (2) data quality issues and (3) different cloud screening methods (MFRSR/NIMFR vs. CSPHOT) aimed to address the challenging issues associated with the cloud contamination. It should be emphasized that the cloud screening methods developed for the MFRSR/NIMFR[10] and CSPHOT[11] data are based on the analysis of total optical depth and its temporal variability. Large variability of the total optical depth is a good indicator for the presence of clouds, which typically have inhomogeneous spatial and temporal structure. It should be mentioned that this spatial and temporal inhomogeneity of the total optical depth is more pronounced for shallow cumuli with complex and variable geometry. However, the developed cloud screening methods implement different sampling strategy to quantify this variability: three short samples separated by 30s for the CSPHOT data[11] and longer (e.g., 5-min) samples for the MFRSR/NIMFR data[10].

In the second step, time series obtained for four instruments show comparable seasonal changes of individual AODs (**Figure 3**). These changes are characterized by large AODs observed during summer and small AODs during winter. Similar seasonal changes of AOD at the SGP CF have been demonstrated previously[8] for a shorter period. To assess the level of agreement between AODs obtained from four different instruments, we generate the corresponding scatterplots for the daily averaged AODs (**Figure 4**). Note that calculations of the daily averaged AODs involve coincident AODs only. The generated scatterplots illustrate clearly that the AODs obtained from four different instruments are very comparable: the points cluster more tightly around the 1:1 line. The scatterplots also include the basis statistics of the AOD comparison. These statistics are comparable as well. For example, small biases (smaller than 0.01) and close to unity slope (>0.97) are obtained for three pairs of instruments considered here (**Figure 4**).

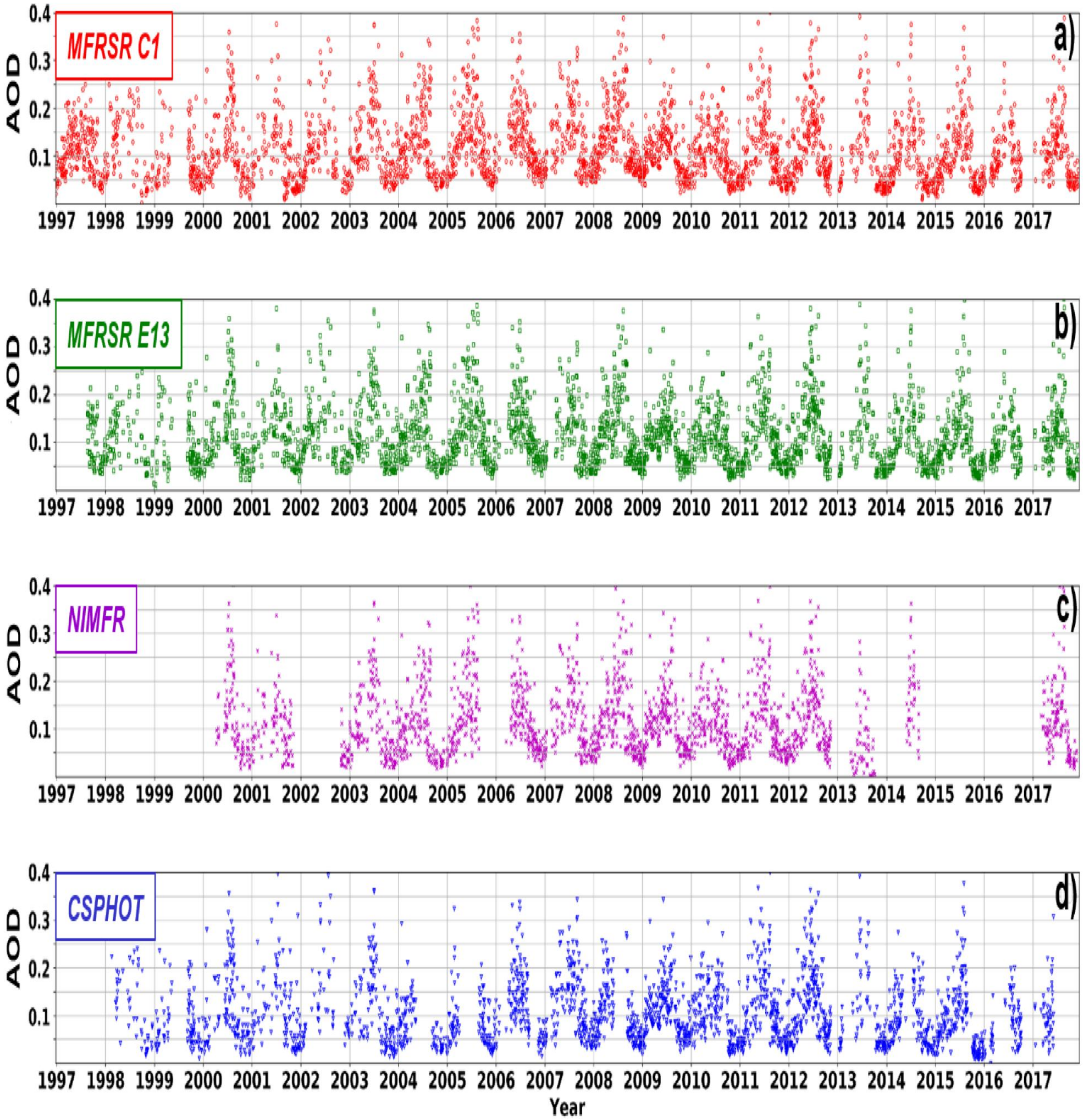

Figure 3. Time series of daily averaged AOD at 500 nm wavelength obtained from 4 instruments for 20-year period (1997-2017): MFRSR C1 (a), MFRSR E13 (b), NIMFR (c), and CSPHOT (d).

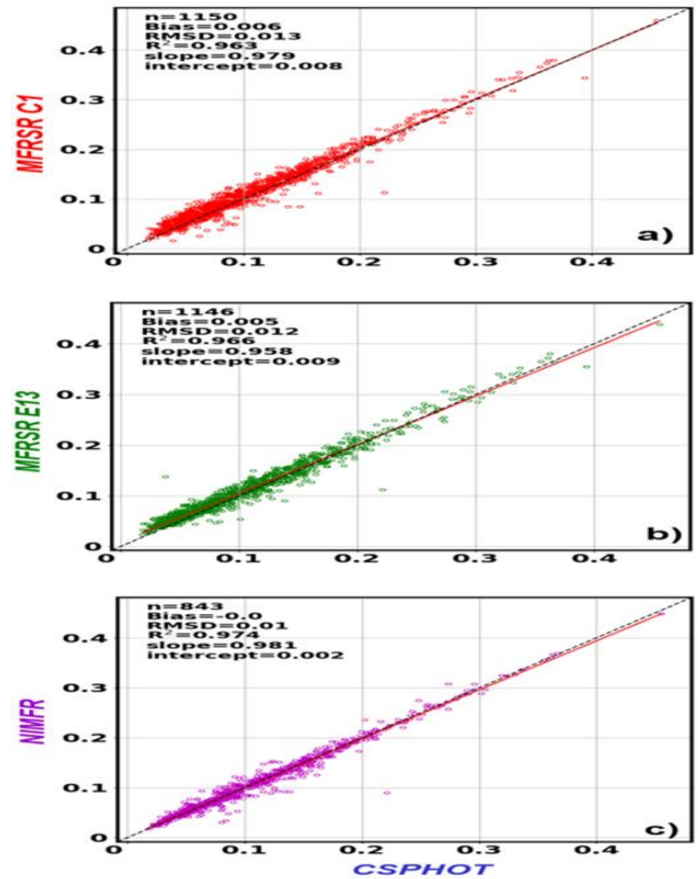

Figure 4. Scatterplot of daily averaged AOD at 500 nm wavelength obtained from CSPHOT (horizontal axis) and 3 instruments (vertical axes) for 20-year period (1997-2017): MFRSR C1 (a), MFRSR E13 (b) and NIMFR (c).

Let us highlight our ongoing work on the third step. We are working on incorporating available AODs and providing the best combined estimate using the weighted sum of coincident individual AODs:

$$AOD_{CE} = \sum_i \omega_i AOD_i \Big/ \sum_i \omega_i \,,\; i = 1,\ldots,N \tag{1}$$

where N is the number of available AODs (up to 4) and the weightings are inversely proportional to the square of the standard errors. In general, more credits (or larger weightings) should be given to more accurate measurements. It could be expected that the accuracy is time-dependent. For example, AODs obtained from the same instrument after "recent" and "old" calibration/upgrade likely would have smaller and larger errors, respectively. Also, AODs obtained from the NIMFR and CSPHOT data could have preference over AODs obtained from the MFRSR data due to lack of necessary cosine correction for the NIMFR and CSPHOT measurements. The initial version of the best combined estimate (Eq. 1) assumes that these errors are fixed and the same (0.02) for all individual AODs. In other words, individual AODs are treated with the same importance. In this case, the standard error of the weighted sum is $\sqrt{(0.02)^2/N}$. Also, the initial version sets high (1 min) temporal resolution for the weighted sum and does not involve an interpolation over short gaps where individual AODs are not available for a period of interest. The standard error and standard deviation of the weighted sum ($N \geq 2$) and the corresponding AOD range (the highest value minus the lowest value; $N \geq 2$) are all considered as estimations of the uncertainty of the best combined estimate, AOD_{CE} .

5. SUMMARY

Continuous high-quality records of aerosol optical depth (AOD) on a time scale of decades are required for climate-related studies. Moreover, uncertainty estimations of these records are another challenging demand of these studies with growing important outcomes. The multi-year AOD measurements at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Central Facility have been provided by four ground-based instruments, namely two co-located (C1 and E13) Multifilter Rotating Shadowband Radiometers (MFRSRs), a Normal Incidence Multifilter Radiometer (NIMFR), and a Cimel Sunphotometer (CSPHOT). However, the individual time series of AOD are sporadic with instrument- and time-dependent data quality. Here we introduce a three-step approach with focus on development of a continuous 20-year (1997-2017) high-quality AOD product and illustrate early results obtained for the first two steps. The first step incorporates the available data quality information and offers the historical time series of AOD with high quality from four individual instruments. In particular, joint application of the automated quality control tests and manual inspection results in removal of "incorrect" and "suspect" data from of the collected multi-year MFRSR/NIMFR datasets. The second step compares multiple AOD retrievals to identify potential instrument-related issues and/or retrieval problems. The ongoing work on the third step is aimed at merging these individual time series, generating a two-decade continuous climatology of high-quality AOD and providing uncertainty estimations of the merged product.

Acknowledgments

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