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Quality Control Aerosol Optical Depth Value-Added Product Report

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Acronyms and Abbreviations

AERONET	Aerosol Robotic Network
AOD	aerosol optical depth
ARM	Atmospheric Radiation Measurement
CDF	cumulative distribution function
CF	Central Facility
CSPHOT	Cimel sunphotometer
EF	Extended Facility
MFRSR	multifilter rotating shadowband radiometer
NASA	National Aeronautics and Space Administration
NIMFR	normal incidence multifilter radiometer
QC	quality control
QCAOD	Quality Control Aerosol Optical Depth Value-Added Product
SGP	Southern Great Plains
StDv	standard deviation
VAP	value-added product

Contents

Figures

Tables

1.0 Introduction

Four aerosol optical depth (AOD) products are offered by four collocated ground-based instruments deployed at the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility's Southern Great Plains (SGP) observatory (SGP Central Facility 1 [C1] and Extended Facility 13 [E13]) for more than two decades. Two of these instruments, the multifilter rotating shadowband radiometers (MFRSRs C1 and E13), are sensors with horizontal hemispherical receivers shaded by rotating shadowbands (Hodges and Michalsky 2016). The other two instruments, the normal incidence multifilter radiometer (NIMFR; Hodges and Michalsky 2016) and the Cimel sunphotometer (CSPHOT; Gregory 2011), are sensors with a sun-pointing design. The CSPHOT is part of the National Aeronautics and Space Administration (NASA) Aerosol Robotic Network (AERONET; Holben et al. 1998) and CSPHOT operation and scheduling differs from operation of the ARM-supported radiometers. The distinct designs of these four instruments and types of data processing determine the instrument-dependent continuity, quality, and resolution of the corresponding AOD products.

The four AOD products outlined above are used as input for the Quality Control Aerosol Optical Depth (QCAOD) Value-Added Product (VAP). The main goal of the QCAOD VAP is to generate a combined AOD with high quality, enhanced continuity, and fine temporal resolution. An initial generation of the combined AOD at two wavelengths (500 and 870 nm) with 1-min resolution is performed for a 21-yr period (1997−2018). This generation addresses major challenges associated with varying data quality and resolution mismatch of the individual AOD products. Also, uncertainty assessment of the combined AOD is made and its relevance for user-specified needs is discussed.

AODs offered by the ARM-supported measurements (two MFRSRs and NIMFR) incorporate the automated quality control (QC) tests. Only "good" data indicated by these tests (two MFRSRs and NIMFR) are used for generation of the combined AOD. Also, this generation involves "quality-assured" (Level 2.0) CSPHOT data provided by the most recent AERONET-supported Version 3 (V3), which has an improved cloud screening in comparison with its predecessor (Giles at al. 2019).

The automated QC tests are very useful for preliminary analysis of data quality. However, these tests occasionally are unable to detect "incorrect" data. For example, several NIMFR AODs, which successfully passed the automated QC tests, can exceed substantially those provided by the other three instruments (Figure 1). These "incorrect" NIMFR AODs (e.g., summer of 2003) have a weak spectral dependence, which likely indicates cloud contamination.

Figure 1 also reveals that the individual time series have gaps, which are likely associated with the instrument-dependent data quality issues and the required upgrades and replacements of the ground-based instruments. Duration of these gaps is instrument-dependent and can be substantial (from several weeks to several months). The NIMFR AOD record with many detached parts has the longest durations of gaps (up to several years) compared with the AOD time series offered by the other three instruments. In contrast, the MFRSR AOD records show the best continuity.

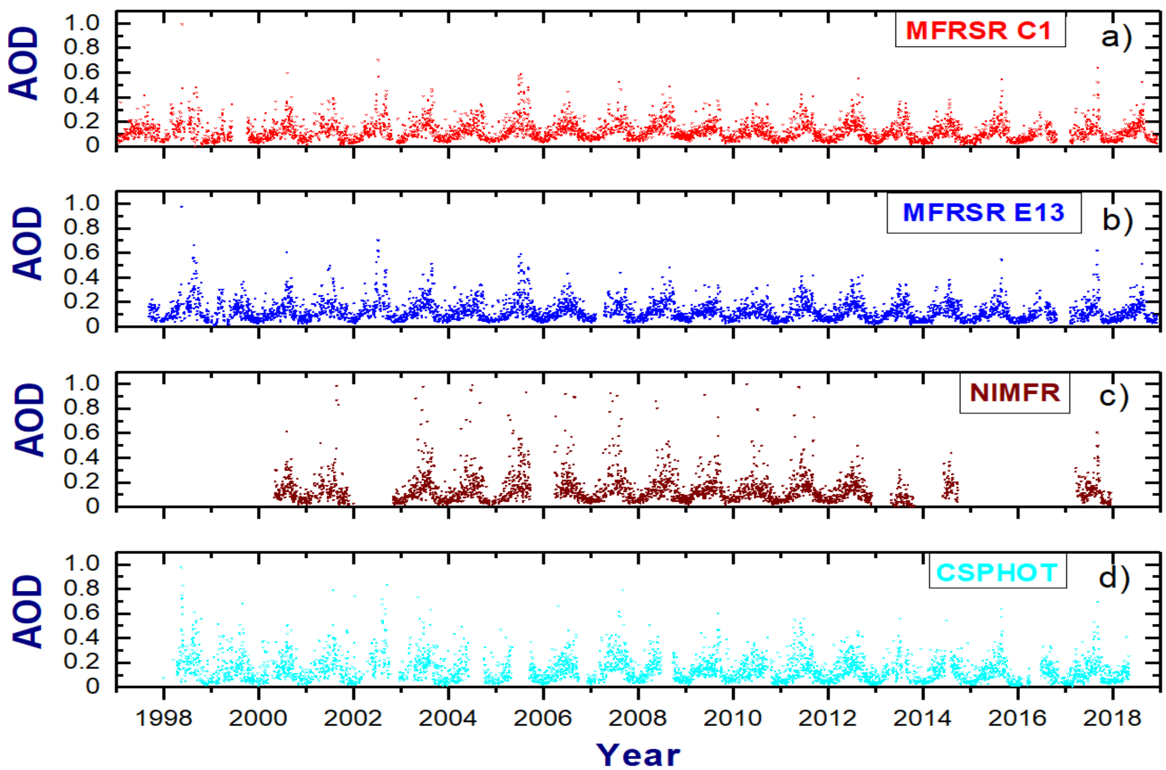

Figure 1. Time series of daily-averaged AOD at 500-nm wavelength obtained from four ground-based instruments for a 21-yr period (1997-2018): MFRSR C1 (a), MFRSR E13 (b), NIMFR (c), and CSPHOT (d). The included time series exhibit similar seasonal patterns with large and small AOD values during summer and winter, respectively. Note that the strong seasonal variability of AOD at the SGP site has been documented previously (e.g., Michalsky et al. 2010).

2.0 Algorithm and Methodology

The combined (or best-estimate) AOD is calculated by retrieving AOD measurements at 500 nm and 870 nm wavelengths from the four input sources. Then, each AOD measurement is averaged to a 1-min time scale. For a given minute, the average AOD value is calculated from 0 seconds (inclusive) to 60 seconds (exclusive). During the averaging, any time sample with the following is not used for averaging:

1. a non-zero quality control (QC) value
2. AOD value is less than 0
3. AOD value is greater than 1.

If no valid time samples are within the 1-min time period, the averaged AOD value is set to the missing value (-9999). After the AOD measurements are averaged to a 1-min scale, the combined AOD value is then calculated for each minute and wavelength.

For each minute, the combined AOD value for a given wavelength is calculated by taking the average of the AOD measurements from the four 1-min averaged input sources. If one of these sources has a non-zero QC value, the AOD value is not used in the average. For the ground-based instruments considered here, this number can change from 2 (AODs are available from two instruments only) up to 4 (AODs are available from all instruments). If there are no good AOD values for a given minute, the combined AOD is set to the missing value (-9999). An AOD value is considered good if the corresponding QC value is zero.

In addition, the four 1-min averaged inputs (500-nm AOD values) are compared against each other. There are six pairs of these four inputs. For each pair, the VAP finds the time periods where its inputs have good QC. Then, a linear regression is performed for these periods. The VAP then provides the slope, root mean square deviation, and the mean bias from the linear regression.

3.0 Input Data

The four input datastreams for the QCAOD VAP are:

- MFRSR instrument located at SGP C1 (sgpmfrsraod1michC1.c1)
- MFRSR instrument located at SGP E13 (sgpmfrsraod1michE13.c1)
- NIMFR instrument located at SGP C1 (nimfraod1michC1.c1)
- AERONET v3 from SGP C1 (sgpcsphotaodfiltqav3C1.a1).

The 500-nm and 870-nm AOD measurements are retrieved from each the datastreams, along with their associated QC variables (qc_*).

4.0 Output Data

The output of the QCAOD VAP is the qcaod.c1 datastream. This datastream contains the four 1-min averaged 500-nm and 870-nm AOD values and the combined 500-nm and 870-nm AOD values. The complete list of output variables is provided in Appendix A. The combined 500-nm AOD for a 21-year period is shown in Figure 2. The unscreened “incorrect” NIMFR AODs (Figure 1c) are responsible for occasional “incorrect” values of the combined AOD (Figure 2).

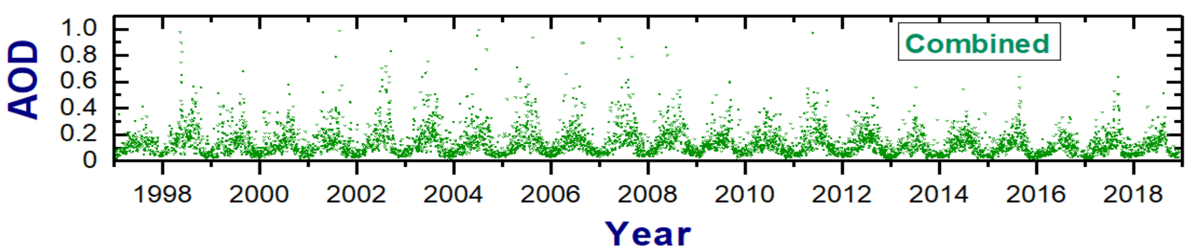

Figure 2. Daily-averaged combined AOD obtained from four individual AODs (Figure 1).

Figure 3 is an example of the combined 500-nm AOD and its four individual components for a given day (May 11, 2008). This example defines a “favorable” case where all four individual AODs are assessable and the spread between them is quite small (about 0.02 or less). To ease visual comparison of the combined and individual AODs, this example represents a “zoom in” version of their diurnal changes by selecting a narrow (3-h) temporal window. As expected, the combined AOD is located between two individual AODs with largest and smallest values and its diurnal changes follow those of the individual AODs.

Good visual agreement between individual time series (Figure 3) is supported by the basic statistics provided by the linear regressions applied to six pairs of the four individual AODs (Table 1). The six pairs are defined as follows:

1. MFRSR C1 versus CSPHOT
2. MFRSR E13 versus CSPHOT
3. NIMFR versus CSPHOT
4. MFRSR C1 versus NIMFR
5. MFRSR E13 versus NIMFR) and
6. MFRSR E13 versus MFRSR C1.

For example, the square of correlation coefficient (R^2) exceeds 0.92 for all pairs (Table 1). The slope is relatively small (~0.8) and large (~1.0) for the first three and last three pairs, respectively (Table 1). It should be emphasized that sample size for the first three pairs ($N \leq 44$) is about 10 times smaller than that for the last three pairs ($N \leq 438$). Therefore, the difference between slopes obtained for the first and last three pairs can be attributed, at least in part, to the substantial difference between sample sizes.

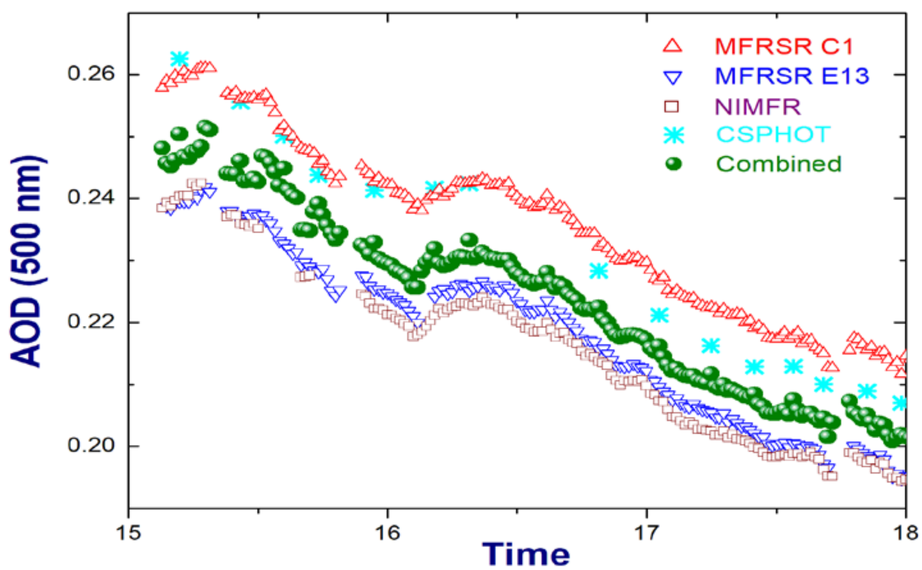

Figure 3. Example of time series of the combined AOD (green) and its four individual components (red, blue, wine, and cyan) during 3-h period for a given day (May 11, 2008).

Table 1. Parameters of linear regressions obtained for six AOD pairs for a given day (May 11, 2008): number of points (N), square of correlation coefficient (R^2), slope, and mean difference (bias).

AOD pair	N	R^2	Slope	Bias
1	44	0.952	0.845	0.007
2	38	0.989	0.796	-0.011
3	34	0.986	0.810	-0.013
4	382	0.926	1.01	0.02
5	355	0.984	0.986	0.002
6	438	0.943	1.044	0.019

Both range and standard deviation (StDv) of the combined AOD are calculated for describing its temporal variability. The latter can be viewed as an uncertainty of the combined AOD. Large (>0.05) values of the calculated StDv represent rare events (~ 3% of time) (Figure 4) that include days with occasional "incorrect" AODs (Figure 2). An appropriate selection of the StDv threshold can remove them easily. For example, by choosing a small (0.01) threshold, one can preserve the distinct seasonal pattern of the combined AOD (Figure 2) but eliminate days with "incorrect" AODs. It should be emphasized that the StDv (or uncertainty) of the combined AOD does not exceed the prescribed uncertainties (0.01-0.02) of the individual AODs for the majority of cases (~ 90% of time) (Figure 4). Different applications of the combined AOD may have different user-specified requirements in terms of acceptable uncertainty. Statistics of the StDv (Figure 4) offer an opportunity to accomplish these goals.

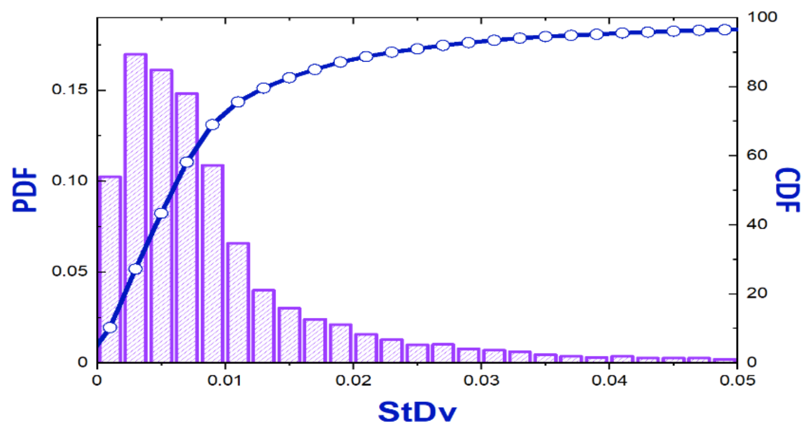

Figure 4. Frequency and cumulative distribution function (CDF) of the daily-averaged combined AOD as a function of the standard deviation (StDv).

Figure 5 contrasts temporal coverages obtained for both individual and combined AODs and demonstrates two important points. First, coverage of the combined AOD is comparable with those obtained for two MFRSR AODs, mostly due to their greater continuity compared to AODs provided by the other two (NIMFR and CSPHOT) instruments (Figure 1). Second, coverage of the combined AOD is substantially greater than that for the NIMFR AOD and for the CSPHOT AOD. This coverage difference is about 80% and 40% for the NIMFR AOD and CSPHOT AOD, respectively. Several factors, such as large gaps in the NIMFR AOD and CSPHOT AOD data sets, and their partial overlaps (Figure 1), impact this difference.

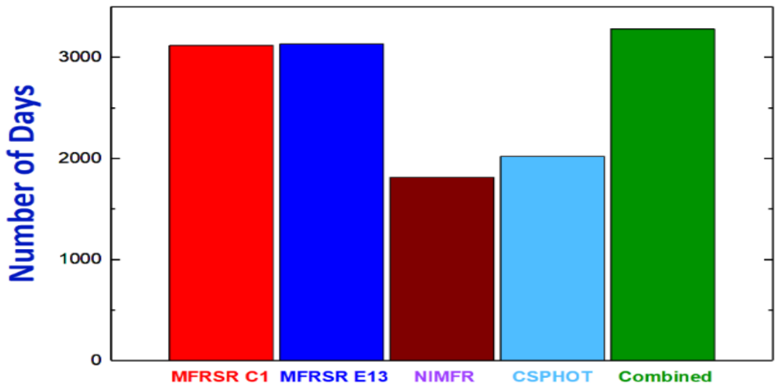

Figure 5. Number of days (or temporal coverage) for the combined AOD and its four components obtained for a small (0.01) value of the StDv threshold.

Tables 2 and 3 illustrate level of agreement between individual AODs as a function of the StDv threshold and include six pairs of four individual AODs. The obtained statistics suggest that the small (e.g., ≤ 0.02) spectrally independent StDv threshold can be used to pick up days where all individual AODs are consistent with each other. Certainly, the required level of agreement between individual AODs depends on user-specified needs and an appropriate selection of the StDv threshold can address these needs. Such selection could include a wavelength-dependent threshold and/or its normalized version if needed.

Table 2. Parameters of linear regressions obtained for six pairs of daily-averaged AODs at 500-nm wavelength for a 21-year period (1997-2018) and small (0.01) value of the StDv threshold: number of days (N), square of correlation coefficient (R^2), slope, and mean difference (bias). The AOD pairs are the same from Table 1.

AOD pair	N	R^2	Slope	Bias
1	2184	0.973	0.967	-0.003
2	2201	0.974	0.949	-0.002
3	1363	0.981	0.973	0.003
4	1727	0.986	0.997	-0.007
5	1721	0.988	0.992	-0.005
6	3006	0.989	0.978	0.001

Table 3. The same as Table 2, except for different value (0.02) of the StDv threshold.

AOD pair	N	R^2	Slope	Bias
1	2865	0.951	0.942	-0.001
2	2890	0.950	0.920	0.001
3	1860	0.953	0.950	0.005
4	2302	0.979	1.000	-0.008
5	2299	0.981	0.991	-0.006
6	3812	0.984	0.972	0.001

5.0 Summary

An initial version of the QCAOD VAP generates the combined AOD at two wavelengths (500 and 870 nm) with high temporal resolution (1-min) for a 21-yr period (1997-2018) by merging available individual AOD products. These products are provided by four ground-based instruments (MFRSR C1, MFRSR E13, NIMFR, and CSPHOT) deployed at the ARM SGP observatory (C1 and E13). However, filling the data gaps with unavailable individual AODs is not considered. This initial version also provides uncertainty of the combined AOD. This uncertainty information would be beneficial for a wide range of cross-cutting applications, such as an effective screening of occasional events with poor-quality data and identification of periods where individual AOD products are in a good agreement. Contrasting the combined AOD and its individual components reveals that the combined AOD has an extended temporal coverage (e.g., up to 40% relative to the CSPHOT AOD), while uncertainty of the combined AOD does not exceed the prescribed uncertainties (0.01-0.02) of the individual AODs for the majority of cases (~ 90% of time). Thus, the generated combined AOD preserves the advantages of the individual AODs (high data quality) and reduces their disadvantages (detached parts of the data time series).

6.0 References

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Appendix A

Datastream Variables

Below is a table of the qcaod.c1 datastream variables and descriptions. Variable names in bold are the primary variables of the datatream.

Table 4. Datastream variables and descriptions.

Variable name (dimension)	Description
aod_cimel_500 (time)	Aerosol Optical Depth at 500 nm from the csphotaodfiltqav3.a1 datastream.
aod_cimel_500_goodfraction (time)	Metric goodfraction for field aod_cimel_500.
aod_cimel_870 (time)	Aerosol Optical Depth at 870 nm from the csphotaodfiltqav3.a1datastream.
aod_cimel_870_goodfraction (time)	Metric goodfraction for field aod_cimel_870.
aod_nimfr_500 (time)	Aerosol Optical Depth at 500 nm from the nimfraod1mich.c1 datastream.
aod_nimfr_500_goodfraction (time)	Metric goodfraction for field aod_nimfr_500.
qc_aod_nimfr_500 (time)	Quality check results on field: Aerosol Optical Depth at 500 nm from the nimfraod1mich.c1 datastream.
aod_nimfr_870 (time)	Aerosol Optical Depth at 870 nm from the nimfraod1mich.c1 datastream.
aod_nimfr_870_goodfraction (time)	Metric goodfraction for field aod_nimfr_870.
qc_aod_nimfr_870 (time)	Quality check results on field: Aerosol Optical Depth at 870 nm from the nimfraod1mich.c1 datastream.
aod_mfrsr_E13_500 (time)	Aerosol Optical Depth at 500 nm from the mfrsraod1mich.c1 datastream at the E13 site.
aod_mfrsr_E13_500_goodfraction (time)	Metric goodfraction for field aod_mfrsr_E13_500.
qc_aod_mfrsr_E13_500 (time)	Quality check results on field: Aerosol Optical Depth at 500 nm from the mfrsraod1mich.c1 datastream at the E13 site.
aod_mfrsr_E13_870 (time)	Aerosol Optical Depth at 870 nm from the mfrsraod1mich.c1 datastream at the E13 site.
aod_mfrsr_E13_870_goodfraction (time)	Metric goodfraction for field aod_mfrsr_E13_870.
qc_aod_mfrsr_E13_870 (time)	Quality check results on field: Aerosol Optical Depth at 870 nm from the mfrsraod1mich.c1 datastream at the E13 site.
aod_mfrsr_C1_500 (time)	Aerosol Optical Depth at 500 nm from the mfrsraod1mich.c1 datastream at the SGP C1 site.

Variable name (dimension)	Description
aod_mfrsr_C1_500_goodfraction (time)	Metric goodfraction for field aod_mfrsr_C1_500.
qc_aod_mfrsr_C1_500 (time)	Quality check results on field: Aerosol Optical Depth at 500 nm from the mfrsraod1mich.c datastream at the SGP C1 site.
aod_mfrsr_C1_870 (time)	Aerosol Optical Depth at 870 nm from the mfrsraod1mich.c1 datastream at the SGP C1 site.
aod_mfrsr_C1_870_goodfraction (time)	Metric goodfraction for field aod_mfrsr_C1_870.
qc_aod_mfrsr_C1_870 (time)	Quality check results on field: Aerosol Optical Depth at 870 nm from the mfrsraod1mich.c datastream at the SGP C1 site
aod_be_500 (time)	AOD best estimate at 500 nm. Mean of any AOD points considered good.
qc_aod_be_500(time)	Quality check results on field: AOD best estimate at 500 nm. Mean of any AOD points considered good.
aod_be_500_random_uncertainty (time)	Standard deviation of data points used in aod_be_500 when 2 or more measurements available. Standard value of 0.02 when 1 AOD variable used.
aod_be_500_quadrature_uncertainty (time)	Quadrature of uncertainty values used in aod_be_500.
aod_be_500_range (time)	Range of AOD values (max-min) used in aod_be_500.
aod_be_500_source (time)	Source for field: AOD best estimate at 500 nm. Mean of any AOD points considered good.
aod_be_870 (time)	AOD best estimate at 870 nm. Mean of any AOD points considered good.
qc_aod_be_870 (time)	Quality check results on field: AOD best estimate at 870 nm. Mean of any AOD points considered good.
aod_be_870_random_uncertainty (time)	Standard deviation of data points used in aod_be_870 when 2 or more measurements available. Standard value of 0.02 when 1 AOD variable used.
aod_be_870_quadrature_uncertainty (time)	Quadrature of uncertainty values used in aod_be_870
aod_be_870_range (time)	Range of AOD values (max-min) used in aod_be_870
aod_be_870_source (time)	Source for field: AOD best estimate at 870 nm. Mean of any AOD points considered good.
daily_RMSD_500 (ncomparisons)	Root mean square deviation between two variables for 500 nm.
daily_npoint_500 (ncomparisons)	Number of points available for comparison between two variables for 500 nm.
daily_mean_bias_500 (ncomparisons)	Mean bias between two variables for 500 nm.
daily_slope_500 (ncomparisons)	Slope of linear regression line between two variables for 500 nm.
good_data_flag	Daily value indicating which of 4 AOD datastreams declared good for a given day.

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