On the Misclassification of Dust as Cloud at an AERONET Site in the Sonoran Desert

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ABSTRACT: Here we present retrievals of aerosol optical depth τ from an Aerosol Robotic Network (AERONET) station in the southeastern corner of California, an area where dust storms are frequent. By combining AERONET data with collocated ceilometer measurements, camera imagery, and satellite data, we show that during significant dust outbreaks the AERONET cloud-screening algorithm oftentimes classifies dusty measurements as cloud contaminated, thus removing them from the aerosol record. During dust storms we estimate that approximately 85% of all dusty retrievals of τ and more than 95% of retrievals when $\tau > 0.1$ are rejected, resulting in a factor-of-2 reduction in dust-storm averaged τ . We document the specific components in the screening algorithm responsible for the misclassification. We find that a major reason for the loss of these dusty measurements is the high temporal variability in τ during the passage of dust storms over the site, which itself is related to the proximity of the site to the locations of emission. We describe a method to recover these dusty measurements that is based on collocated ceilometer measurements. These results suggest that AERONET sites that are located close to dust source regions may require ancillary measurements to aid in the identification of dust.

SIGNIFICANCE STATEMENT: In this study we demonstrate that, during dust storms, measurements made with a sun photometer at an AERONET site in the western Sonoran Desert are frequently classified as cloud contaminated by the network's processing algorithm. We identify the various algorithmic tests that result in the misclassification and discuss the physical reasons why dust typically fails those tests. We then present a method to restore these data that utilizes measurements from a collocated ceilometer. This work highlights the challenges, and one solution, to operating an AERONET site in a region that is close to the sources of airborne dust.

KEYWORDS: Remote sensing; Dust or dust storms; Aerosols/particulates

1. Introduction

By mass, aeolian dust is the most abundant aerosol in Earth's atmosphere (Kok et al. 2017) and affects the global energy budget directly via absorption and scattering of radiation (Mahowald et al. 2010; Miller and Tegen 1998; Myhre and Stordal 2001). Dust is also observed to be an ice nucleating particle (Ansmann et al. 2008), and thus may impact the global climate via the glaciation effect (DeMott et al. 2010). Furthermore, long-range dust transport and subsequent deposition is thought to be an important source of nutrients to remote ocean and terrestrial ecosystems (Das et al. 2013; Okin et al. 2011), which can in turn alter the global carbon cycle (Mahowald et al. 2010).

Although the processes by which dust directly and indirectly affects the global climate have been described, quantifying their respective magnitudes is challenging. For example, there is such wide disparity in estimates of the direct radiative effect that the sign of the globally averaged forcing is not known (Kok et al. 2017), and model estimates of the global

dust burden vary by an order of magnitude (Huneus et al. 2011). Certainly, one cause of the uncertainty in understanding the nature of dust in Earth's climate system is a relative paucity of observational data, which stems from the fact that most dust storms originate in sparsely populated regions (Prospero et al. 2002).

Probably the most ubiquitous and widely used record of dust is from the Aerosol Robotic Network (AERONET; Holben et al. 1998). AERONET is a global network of sun photometers making direct solar irradiance measurements that are used to retrieve aerosol optical depth τ at different wavelengths. Although τ is a measure of the vertically integrated extinction of light by an aerosol, it is also directly proportional to the column integrated aerosol mass. As such, retrievals of τ from AERONET stations impacted by dust are widely used by the research community, especially given the accuracy of the retrievals (Dubovik et al. 2000). For example, AERONET data have long been used to evaluate the representation of dust in climate models (Huneus et al. 2011; Albani et al. 2014), validate dust products from satellite data (Zhou et al. 2020; Habib et al. 2019; Peyridieu et al. 2013), estimate dust occurrence frequency (Toledano et al. 2007), and characterize dust optical properties (Kim et al. 2011).

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Here we present measurements from a new AERONET station located on the western edge of the Sonoran Desert, a region where dust storms frequently occur (Evan 2019). Specifically, we report how a processing algorithm for AERONET retrievals of τ , which is intended to screen the data for artifacts and cloud contamination, regularly rejects measurements made during dust storms as cloud contaminated. We find that several of the spectral and temporal variability-based tests are not effective at separating dust from clouds, at least at this one site. The purpose of this document is to serve as a reference for users of the data from this site and for other potential AERONET sites situated closely to dust source regions.

The paper is organized as follows. In section 2 we describe the field site, instrumentation, and measurements utilized in this study. In section 3 we examine measurements made during a dust outbreak on 29 January 2020 and identify the specific components of the AERONET processing algorithm that result in the rejection of dusty measurements as cloud contaminated. In section 4 we broaden our findings and examine measurements made during dust storms on 12 separate days. In section 5 we summarize our findings and conclude on potential implications of screening out dusty measurements on the AERONET aerosol record.

2. Field site and data

The Salton Sea AERONET field site is located at 33.17°N and –115.86°E (blue square in Fig. 1). This sub-sea level site is at an elevation of –32 m above mean sea level, lies directly to the east of the Anza Desert, and is approximately 2.5 km from the shoreline of the Salton Sea. As such, the site is well positioned to measure dust emitted both from desert and dry playa sources. The landscape immediately surrounding this site includes dirt roads, citrus and date palm orchards, and barren shrublands.

The AERONET instrument at this site is a CIMEL Electronique sun-sky photometer, which is used to measure sun collimated direct beam irradiance and directional sky radiance at eight spectral bands centered on 1020, 870, 675, 440, 936, 500, 380, and 340 nm (Holben et al. 1998). The instrument base is mounted approximately 2 m above the ground level. Direct solar irradiance measurements are made at 5-min intervals and directional radiances in the almucantar and principal planes are made at 30-min intervals. The data are inverted to determine aerosol properties in the total atmospheric column with algorithms described in Dubovik and King (2000) and Dubovik et al. (2000).

Here we utilize data from the AERONET level-1.0 (hereinafter L1) and level-1.5 (hereinafter L1.5) products. The L1.5 AERONET products are processed by the version-3 AERONET algorithm (hereinafter referred to as the V3 algorithm), which provides fully automatic cloud screening and instrument anomaly quality controls in near-real time (Giles et al. 2019). Thus, optical depth τ from the L1 products may be contaminated by clouds, whereas τ from the L1.5 products is only reported for clear-sky conditions. The V3 algorithm tests that are most relevant to this study are summarized in Table 1.

Also located at this site is a Vaisala, Inc., CL51 ceilometer, which is a single-lens lidar system that makes continuous profiles of attenuated backscatter (BS) at a nominal wavelength of 910 nm and up to heights of 15 km. The CL51 range-corrected BS profiles used here are generated at 36-s temporal resolution and 10-m vertical resolution. In addition to cloud detection, ceilometers, including the CL51, have been shown to be useful in the detection of aerosol layers in the lower troposphere (Münkel et al. 2007; Wiegner et al. 2014; Jin et al. 2015; Marcos et al. 2018; Yang et al. 2020). The Vaisala processing software for the CL51 measurements (BLView) produces retrievals of vertical profiles of extinction σ and optical depth τ from the BS profiles for the clear-sky atmosphere below 5 km. Although details about the retrieval process used in BLView are not publicly available, we were able to produce extinction profiles that were qualitatively similar to those from the BLView software using the methods described in Fernald (1984), suggesting that BLView uses a similar method to retrieve extinction profiles and calculate aerosol optical depth (we note that the differences between our retrievals of extinction and those from BLView appeared to be associated with a smoothing procedure applied to the range-corrected signal prior to application of the retrieval algorithm, and a scaling factor difference between the two).

We utilize hourly averaged measurements of 10-m wind speed and direction and 10- μm particulate matter concentrations (PM_{10}) made at a number of sites around the Salton Sea. We also present images from a 360° Roundshot web camera that is located approximately 28 km west of the field site at an elevation of just over 300 m (red square in Fig. 1). Roundshot images are available at approximately 10-min intervals during daytime hours.

Last, we incorporate into our analysis satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) flying on board the *Terra* satellite and from the Advanced Baseline Imager (ABI) flying on board *GOES-17*.

3. Results

We begin with a case study of a dust outbreak that occurred on 29 January 2020. Based on surface and upper-level charts from the National Oceanographic and Atmospheric Administration Weather Prediction Center and the Area Forecast Discussion from the San Diego National Weather Service field office, during the daytime hours of 29 January 2020 strong northerly low-level flow was prevalent across Southern California as a result of an intensifying upper-level low located to the east and a building high pressure to the north (not shown). Hourly averaged wind speeds at the AERONET site peaked on this day at 11.4 m s^{–1} and at 330° at 2000 UTC (not shown).

The northerly high winds on 29 January resulted in dust emission throughout the area. A true color image acquired at approximately 1910 UTC from the MODIS instrument flying on board the *Terra* satellite shows a northwest to southeast oriented plume of dust clearly visible over the western half of the Salton Sea (Fig. 1). A *GOES-17* animation from 1800 to 2030 UTC shows dust being advected southeastward from the

FIG. 1. MODIS *Terra* red–green–blue (RGB) satellite image at 2010 UTC 29 Jan 2020 of a dust storm outbreak within the region of interest. The location of the Salton Sea AERONET site is indicated by the blue square, and the location of the 360° Roundshot camera is indicated by the red square. The body of water is the Salton Sea. Although dust is present over much of the region, these mineral aerosols are most visible over the Salton Sea due to the contrast they make with the dark water surface.

northern tip of the Salton Sea and over the field site (see the online supplemental material). The presence of dust is also confirmed in imagery from the Roundshot camera (red square in Fig. 1) at 1910 UTC, which shows dust in the westward direction and thus over the AERONET site (Fig. 2a). Also confirming the presence of dust are hourly averaged PM_{10} measurements from a location approximately 15 km north-northwest of our site (Salton City) that peaked at 2000 $\mu\text{g cm}^{-3}$ at 2000 UTC on this day (not shown).

Backscatter profiles from the CL51 show a strong signal from the surface to heights of approximately 1.5 km AGL, starting at 1830 UTC and terminating less than two hours later at 2020 UTC (Fig. 2b). At approximately 1900 UTC the *GOES-17* animation shows the dust plume orientation turning clockwise, which results in dust being advected directly over the AERONET site (see the online supplemental material), and at this same time the magnitude of the BS signal also increases (Fig. 2b). At 1900 UTC there is also an apparent increase in the opacity of the dust in the *GOES-17* animation, which implies that after this time a particularly dense component of the dust plume is over the site.

Having demonstrated that there was a dust storm in this region on 29 January 2020, and that dust was advected over the AERONET site from 1800 to 2030 UTC, we next turn our attention to the retrievals of τ from the CIMEL. First,

according to the CL51 profiles the atmosphere directly over the site was cloud-free until 2040 UTC, when clouds at elevations of 3.2–4.9 km were detected (Fig. 2b). Consistent with the CL51 data, the 5-min *GOES-R* imagery from 1803 to 2023 UTC shows that there were no clouds near the site during these times that could have been casting a shadow on CIMEL (see the online supplemental material). As such, τ retrievals from the CIMEL measurements during this time span reflect the presence of aerosols in the atmospheric column and are not impacted by cloud contamination (hereinafter τ is assumed to be at 500 nm unless otherwise specified).

On this day, the L1 AERONET retrievals of 500 nm τ are near 0.05 at 1800 UTC, which is just before dust is advected over the site, and then from 1830 to 2000 UTC the L1 τ increases to the maximum retrieved value of 0.57 (Fig. 3a, blue). Although τ is increasing during this time period, these measurements show increasing variance in dust concentrations over the site; between 1930 and 2000 UTC τ values increase from 0.25 to 0.47, drop down to 0.14, and then rise to 0.57. After the 2000 UTC peak τ drops back to preoutbreak values by 2030 UTC. These τ data are consistent with the CL51 BS profiles, which show the largest BS values from 1830 to 2030 UTC, and a brief incidence of very low BS values just before the 2000 UTC peak in τ (Fig. 2c).

The AERONET L1.5 τ retrievals (Fig. 3a, red) are in general only available when $\tau < 0.1$, meaning that the V3 algorithm has incorrectly identified the dusty measurements as cloud contaminated, effectively removing all of the optical depth retrievals during the dust outbreak from the L1.5 data record. We next identify the specific tests in the AERONET V3 algorithm (Table 1) that resulted in the rejection of τ retrievals during this dust outbreak.

a. Triplet criterion

Each reported value of τ is based on three individual direct solar irradiance measurements made within a 1-min interval (a so-called triplet measurement). If the variability of a triplet measurement made at the 675, 870, or 1020 nm wavelengths is greater than $0.015 \times \tau$ (retrieved at that wavelength) or 0.01, whichever is larger, than the measurement is rejected as possibly cloud contaminated. We applied this triplet variability threshold test to the L1 τ retrievals. Of the 28 retrievals of τ from the 1830–2030 UTC time period, 26 were rejected as cloud contaminated because of the triplet measurements exceeding these threshold values (Fig. 3b).

The highly variable nature of the BS profile during the dust outbreak (Fig. 2c) is qualitatively consistent with these high triplet variability values. For each AERONET observation we generated a set of CL51 “triplet” measurements by linearly interpolating the CL51 optical depth retrievals to the AERONET observation times, which we interpret as the reported triplet observation time, and then 30 and 60 s past this time. The average of these three retrievals is an equivalent CL51 triplet optical depth at 910 nm $\tau_{\text{cl},910}$ (Fig. 4a, horizontal axis values).

We next compare $\tau_{\text{cl},910}$ with the AERONET 870-nm optical depth τ_{870} , since this is the closest AERONET wavelength

TABLE 1. The AERONET version-3 cloud screening tests that are most relevant to dusty conditions.

Test	Criteria for rejecting measurements
Triplet criterion	Range of triplet retrievals of τ at 675-, 870-, and 1020-nm wavelengths $>$ maximum of 0.015τ or 0.01
Smoothness check	If $\Delta\tau/\Delta t > 0.1 \text{ min}^{-1}$, for τ at 500 nm, reject the larger τ in the pair, and then repeat
Solar aureole curvature check	1020-nm radiance measurements for scattering angles between 3.2° and 6° are used to determine forward-scattering-peak curvature k_o and slope M ; if $k_o > 2 \times 10^{-5}$ and $M > 4.3$, τ retrievals within ± 30 min of the radiance measurement are removed
Reverse spectral dependence test	Decision-tree algorithm consisting of various spectral threshold tests for AE and τ at 440-, 675-, 870-, and 1020-nm wavelengths (Giles et al. 2019, their Fig. 12).

to the ceilometer nominal wavelength of 910 nm, and since τ_{870} is one of the three wavelengths used in the triplet variability test (Table 1). An analysis of $\tau_{\text{cl},910}$ and τ_{870} for the 1800–2100 UTC time period, which includes 40 data points, suggests that $\tau_{\text{cl},910}$ is approximately proportional to τ_{870} (Fig. 4a), where the data are correlated at an r value of 0.89 (p value < 0.01). For the three retrievals where $\tau_{870} > 0.3$ (Fig. 2a, vertical axis) the CL51 proprietary algorithm did not retrieve extinction coefficients high enough into the atmospheric column (e.g., the top of the aerosol layer was incorrectly identified) and thus the CL51 optical depth retrievals underestimate the true optical depth at these times.

We estimate an 870-nm optical depth $\tau_{\text{cl},870}$ from the CL51 data as

$$\tau_{\text{cl},870} = c_1 \tau_{\text{cl},910} + c_2, \quad (1)$$

where the constants c_1 and c_2 are determined by linear least squares regression of τ_{870} onto $\tau_{\text{cl},910}$ using data collected during the time period 1800–2100 UTC and have values of 3.6×10^{-3} and 0.21, respectively (Fig. 4a, black dashed line). A comparison of the AERONET τ_{870} and the CL51 $\tau_{\text{cl},870}$ suggests good agreement, with a RMSE of 0.043 (Fig. 4b). We also estimated $\tau_{\text{cl},870}$ by first using 1020–870-nm Ångström exponent (AE) values from AERONET to generate an initial estimate of $\tau_{\text{cl},870}$ and then using linear regression to “calibrate” the ceilometer optical depth to that from AERONET, obtaining qualitatively identical results.

We apply Eq. (1) to the individual CL51 “triplet” measurements to calculate an equivalent CL51 triplet variability at 870 nm, which is the difference between the maximum and minimum values for each triplet (Fig. 5). The correlation between the AERONET and the CL51 triplet variability estimates is statistically significant (correlation r value 0.60; significance p value < 0.01), and the RMSE is 0.026. The agreement in the triplet variability from AERONET and the CL51 is not as good as that for τ (Fig. 4b), although this is not surprising since the CL51 retrievals of τ have a temporal resolution of 36

s but we are interpolating the measurements to 30-s intervals and because we do not know the exact times of the AERONET triplet observations. We experimented with adjusting the timing of the CL51 “triplets” to generate a better fit to the AERONET data but were not able to produce a better fit than that shown in Fig. 5. Nonetheless, the CL51 and AERONET 870-nm triplet variability estimates are consistent in that they both show that the triplet variability is greater than the threshold of 0.01 for most of the 37 data points between 1800 and 2100 UTC; from the AERONET data, 30 of the 37 triplet variability estimates exceed the threshold of 0.01, and, from the CL51 data, 33 of these estimates exceed this threshold (Fig. 5). Thus, the CL51 measurements corroborate the high triplet variability seen during the 1800–2100 UTC time period, suggesting that these AERONET measurements are reflecting a physical signal in the dust and are not due to artifacts in the data collection process or cloud contamination.

b. Smoothness check

Another step in the cloud-screening procedure is to check the “smoothness” of the time series of τ . Specifically, if the rate of change of 500-nm τ between subsequent measurements is greater than 0.1 min^{-1} , then the larger of the two τ values is classified as cloud contaminated and is removed. This procedure is then repeated until the rate of change of any two adjacent values of τ is below this threshold value for a given day. We applied this smoothness test to the L1 AERONET data, finding that it removed 11 of the 28 τ retrievals (Fig. 3c).

c. 3σ test

Within the V3 algorithm the 3σ test removes data points if τ at 500 nm is 3 standard deviations greater than the distribution mean for a given day. For the 29 January case, the 3σ test only removed data points that were also removed by the smoothness check. Therefore, we do not provide a separate analysis for this component of the V3 algorithm beyond that which is done for the smoothness check.

d. Solar aureole curvature check

At hourly increments the CIMEL instrument measures radiances L_A along the almucantar and principal planes, and the radiances measured at small scattering angles ψ with the sun are used to characterize the curvature of the forward-scattering peak. Specifically, two metrics describing the curvature k_o and slope M of the forward-scattering peak are calculated for each almucantar and principal plane scan. First,

$$\ln L_A = a + b \ln \psi$$

is solved with linear least squares regression for each set of positive and negative scattering angles between 3.2° and 6° , for cases in which the correlation coefficient between L_A and ψ for this subset of angles is greater than 0.99 (and for ψ in units of radians). Then these coefficients are used to describe the forward-scattering-peak slope

FIG. 2. Ceilometer and Roundshot imagery of the 29 Jan 2020 dust outbreak: (a) A Roundshot image acquired at 1910 UTC, which corresponds to the time of the *Terra* overpass in Fig. 1 and which shows dust west of the camera location (Fig. 1). (b) A plot of the CL51 backscatter BS profile from 1700 to 2200 UTC. The main dust outbreak is highlighted by the red-outlined box, and cloud are indicated by high BS values just below 5 km above ground level starting just before 2100 UTC. (c) A close-up of the BS profiles during the dust outbreak [red-outlined box in (b)].

$$M = 1 - 2b$$

and curvature

$$k_o = \exp[-a(1 - 2b)\ln\psi_o],$$

where ψ_o is the smallest scattering angle in the 3.2° and 6° range (also in radians). Since ice particles are associated with a strong forward-scattering peak, ice clouds are assumed to be present if $k_o < 2 \times 10^{-5}$. However, dust also typically exhibits a strong forward scatter peak (Ding et al. 2009), so an additional criterion of $M > 4.3$ is added to distinguish dust from thin cirrus. If these two thresholds are exceeded, then all measurements within 30 min of the almucantar or principal plane scan are classified as cloud contaminated.

We apply this solar aureole curvature check to the 29 January L1 data during the 1800–2100 UTC period. We found that k_o and M from the almucantar scan at 1859 UTC exceeded these thresholds, which would have resulted in all of the L1 τ estimates from 1830 to 1930 UTC being rejected as cloud contaminated, corresponding to half of the 28 retrievals of τ made during the dust outbreak and when $\tau > 0.1$ (Fig. 3d).

e. Reverse spectral dependence test

Last, the L1 data undergo a decision-tree algorithm that uses τ and AEs at various wavelengths to identify cloud contamination (Giles et al. 2019, their Fig. 12). When the reverse spectral dependence test is applied to the L1 data on 29 January this test causes rejection of 17 of the 28 τ measurements during the peak of the dust outbreak from 1830 to 2030 UTC (Fig. 3e).

FIG. 3. Aerosol optical depth retrievals on 29 Jan 2020: (a) A time series of τ at 500 nm from the AERONET L1 (blue circles) and cloud-screened L1.5 (red filled circles) retrievals. Clear-sky conditions persisted until just after 2100 UTC, and so the lack of L1.5 retrievals from approximately 1830 to 2030 UTC indicate that the V3 algorithm misidentified the dust signal as cloud contamination. (b)–(e) The same L1 and L1.5 retrievals of τ , but where a black “x” indicates when a specific algorithm test triggered a rejection of the data.

We identified the key components of the reverse spectral dependence test that resulted in the majority of these rejected retrievals of τ during the dust outbreak. First, 12 measurements were rejected on the basis of the following criteria: 1) $AE_{440,870} < 0.2$, 2) $\tau_{1020} > \tau_{675}$, 3) $\tau_{1020} > \tau_{870}$, and $AE_{870,1020} < 0$, where the subscripts on AE indicate the wavelength pairs for which the exponent is calculated, and the subscripts on τ indicate the wavelength of the optical depth, both in nanometer units. In general,

we find that as dust concentrations increase AE tends toward lower values, which is consistent with measurements made in North Africa (Toledano et al. 2009).

Next, we found that 11 of the measurements were rejected on the basis of the criteria 1) $AE_{440,870} < 0.2$, 2) $\tau_{1640} > \tau_{870}$, 3) $\tau_{1640} > \tau_{1020}$, and $AE_{870,1640} < 0$. Similar to the previous case, as dust concentrations over the site grew, AE tended toward lower values.

f. High AOD restoration test

We note that within the version-3 algorithm there is a test intended to restore high values of τ that were rejected as cloud contaminated. The criterion for this check is that if $\tau_{500} > 0.5$ the measurement will be restored as not contaminated if $AE_{675,1020} > 1.2$ and $AE_{870,1020} > 1.3$. There was one measurement on 29 January for which $\tau_{500} > 0.5$, where $\tau_{500} = 0.57$ at 1958 UTC (Fig. 3). At this time $AE_{675,1020} = -0.05$ and $AE_{870,1020} = -0.04$, both well below the threshold for restoring the high optical depth retrieval. Furthermore, during the 1830–2030 UTC time period the AE values for this restoring test are all near zero; the average $AE_{675,1020}$ during the dust outbreak is 0.01, and the average $AE_{870,1020}$ is 0.02. Such low values of the AE in the visible part of the spectrum are consistent with AERONET-based studies of the optical properties of dust (Tanré et al. 2001; Kim et al. 2011). Therefore, the restoring test is likely ineffective for periods of high dust concentrations at this AERONET site.

4. Discussion

In the previous section, we documented that retrievals of τ during a dust outbreak on 29 January at an AERONET station near the Salton Sea were rejected as cloud contaminated, and we identified the specific components of the V3 algorithm that led to the removal of those measurements; however, how common is this for dust events at this site? While our own anecdotal evidence suggests that rejection of L1 retrievals of τ during dust outbreaks is pervasive, we attempted to quantify such effect by repeating our analysis of 29 January 2020 for 12 additional days during which there were dust outbreaks. We selected these days (Table 2) since, for each, dust was clearly visible in satellite imagery, Roundshot camera images, and the ceilometer BS profiles and there was not an obvious influence from other aerosol types (e.g., advection of smoke over the site). We identified continuous cloud-free time spans as those for which the ceilometer measurements indicated cloud-free conditions within 30 min of the CIMEL measurement time, and from visual inspection of satellite imagery. This is not an exhaustive list of dusty and clear-sky conditions at this location.

The distribution of AERONET L1 τ is skewed with a long tail toward high τ ; the median value of τ is 0.17, and the range is from 0.02 to 0.46 (Fig. 6a, blue). For these dust retrievals, the cloud-screening algorithm rejected 84% of the L1 retrievals as contaminated and rejected 95% of the retrievals for $\tau > 0.1$ as being contaminated. Consequently, the distribution of L1.5 τ is very different than that for the L1 data, with a

FIG. 4. Comparison of τ from AERONET and the CL51: (a) AERONET τ_{870} retrievals from 1800 to 2100 UTC 29 Jan 2020 (vertical axis) and an estimate for these same times generated from extinction profiles retrieved from the CL51 BS data ($\tau_{cl,910}$; horizontal axis). (b) The same AERONET τ_{870} retrievals but plotted as a function of the estimated CL51 870-nm τ via Eq. (1) ($\tau_{cl,870}$; horizontal axis).

median τ of 0.05 and a range of 0.02–0.18 (Fig. 6a, orange). Furthermore, the mean τ for the L1 retrievals (0.17) is greater than that for the L1.5 retrievals (0.08) by more than a factor of 2.

We examined the roles of the triplet variability, solar aureole curvature, and reverse spectral dependence tests (Table 1) in rejecting these dusty measurements since these three tests resulted in the largest rejection of data for the 29 January 2020 case, and since data removed by the smoothness check were mostly also removed by the triplet criterion. For these three tests we found that 60% of the rejected L1 retrievals failed the triplet criterion, meaning that the dust concentrations were highly variable in time. Indeed, most of the BS profiles for these days were qualitatively similar to that for 29 January (Fig. 2c), with rapidly changing periods of high and low dust concentrations (not shown).

FIG. 5. AERONET and CL51 triplet variability comparison, showing the 870-nm triplet variability TV estimates from AERONET (vertical axis) and CL51 (horizontal axis) at 870 nm. The dashed black line represents equivalence between the datasets and is used only for reference.

Approximately 16% of these measurements failed the solar aureole curvature check, reflective of the strong forward-scattering peak of dust. Last, 27% of the measurements failed the reverse spectral dependency test, which mainly reflects the low values of the AE for dust in the near-infrared range.

While the high temporal variance of dust advected over the site appears to be the main reason for rejection of dusty retrievals of τ , on days for which the dust signal varies more smoothly in time, the spectral signature of the dust aerosols still resulted in the rejection of data by the V3 algorithm. For example, on 8 June 2020 there was a gradual buildup of dust over the site, which was corroborated by concurrent PM_{10} measurements (not shown), and during this time 20 of the 26 L1 τ retrievals failed the reverse spectral dependency test.

To recover these dusty AERONET measurements we developed a simple algorithm based on the CL51 measurements that will restore the rejected L1 retrievals of τ . This dust-restoration algorithm is only applied if the L1 $\tau > 0.1$, since the loss of dusty measurements is most pronounced when τ is greater than this value (Figs. 3a, 6a), and if the L1.5 τ is not retrieved (i.e., the measurement has been flagged as contaminated). Available from AERONET are retrievals of the fine-mode fraction f , which is an estimate of the fraction of particles with a diameter less than $10 \mu m$ (Dubovik et al. 2002). We identified 647 dusty measurements on the days in Table 2 for which $\tau > 0.1$ and the data were classified by the V3 algorithm as potentially cloud contaminated. Of these measurements 97% have values of $f < 0.5$ (Fig. 7), and thus we only apply this dust-restoring algorithm for f below this value.

Our own analysis suggests that the criteria of L1 $\tau > 0.1$ and $f < 0.5$ will be met primarily for measurements of thin cirrus and dust. Thus, we assume the scene is cloud free if the CL51 has not reported a cloud within 30 min of the measurement time, which is a time span used to estimate fractional horizontal cloud cover from upward looking ceilometers (Wagner and Kleiss 2016). We noted cases in which very thin

TABLE 2. AERONET measurement dates and start and stop times (UTC) identified as dusty and clear sky conditions.

Date	Start time	End time
9 Jan 2020	2030	2130
4 Feb 2020	1650	1815
1 Mar 2020	1812	1945
23 Mar 2020	1725	1835
6 Apr 2020	0050	0123
8 Jun 2020	1434	1628
25 Oct 2020	2037	2200
26 Oct 2020	2037	2137
12 Dec 2020	2120	1225
9 Mar 2021	2010	2155
15 Mar 2021	2302	2350
21 Apr 2021	2110	2243

and high clouds were not identified by the CL51 processing software. Thus, we applied the additional constraints that for a given day there should be more than 5 L1 retrievals of τ that meet the above criteria, since days with dust outbreaks typically loft dust over the site for more than 30 min. Furthermore, the L1 and CL51 retrievals of τ for each day must be positively and significantly correlated (p value < 0.05). Since τ for the CL51 is only retrieved in the lower 4 km of the atmosphere, during dust outbreaks the retrievals of τ for both the AERONET and CL51 are typically positively and significantly correlated (e.g., Fig. 5a), whereas in the case of cirrus contamination, τ from the CL51 is not affected by these high clouds while τ from the AERONET instrument is. This dust-restoring algorithm is summarized in Table 3.

When applied to the L1 data for the 12 days in Table 2, the algorithm described above restored 98% of the dusty τ retrievals for which the L1 $\tau > 0.1$ and $f < 0.5$ (Fig. 6b). The L1.5 dust-restored τ nearly perfectly matches that for the L1 data (Fig. 6a) for $\tau > 0.1$; the median and range of the L1.5 dust-restored τ is 0.17 and 0.02–0.46, respectively. When applied to the 29 January 2020 case (Fig. 3a), the algorithm restored all of the measurements for which $\tau > 0.1$ and $f < 0.5$.

Examination of the CL51 cloud products suggests that the instrument's processing software occasionally fails to identify thin and high cirrus clouds. To test our algorithm for such cases we identified 32 days during which thin high cirrus were present over the region. For these days, we further identified four time intervals during which thin high cirrus was present but the CL51 processing software failed to correctly detect the clouds (Table 4). There were 32 AERONET measurements falling within these time intervals, which include 26 L1 retrievals where $\tau > 0.1$ and $f < 0.5$. For these data (and more broadly for those days) our algorithm did not restore any of the L1 measurements as being dusty, suggesting a false-positive rate of zero.

5. Conclusions

Here we presented measurements of dust made at a site in the far western Sonoran Desert and adjacent to the rapidly drying Salton Sea (Fig. 1). An analysis of AERONET retrievals of τ made at this site and during a dust storm on 29 January 2020 suggested that the AERONET V3 algorithm (Giles et al. 2019) misidentified dusty measurements as cloud contaminated, and thus rejected these data from inclusion in the AERONET L1.5 dataset (Fig. 3a). Via an examination of satellite data, camera imagery, and backscatter profiles (Fig. 2) we were able to confirm that these observations were made during dusty and cloud free conditions.

One reason for the rejection of AERONET measurements on this day was the high temporal variability of τ (Fig. 3b). An analysis of τ retrieved from the ceilometer (Fig. 5) strongly suggested that this high temporal variability reflected the physical nature of the dust plumes over the area and was not due to any artifacts in the data collection or processing methods. We found that the strong forward-scattering peak of dust resulted in the rejection of measurements via a check intended to identify thin cirrus (Fig. 3d). We also found that the relatively small variations in τ as a function of wavelength gave AE values that were near-zero during the dust outbreak, thus also resulting in the rejection of measurements (Fig. 3e).

FIG. 6. Histograms of τ retrievals during dust storms on 12 days (Table 2): (a) Histograms of the L1 and L1.5 τ for the time intervals indicated in Table 2. (b) The histogram of the L1.5 τ after the application of a dust-restoring algorithm. For reference, the histogram of the L1.5 τ is repeated in (b).

FIG. 7. AERONET fine-mode fraction f retrievals during dust storms, showing a histogram of f retrievals made during times with overhead dust and $\tau > 0.1$ during the 12 days in Table 2.

As such, these dusty measurements failed several of the V3 cloud-screening tests.

We repeated our analysis of the 29 January case for 12 other days during time periods for which we were confident that there were otherwise clear-sky conditions (Table 2). Our results were consistent with the case study in that most of the measurements for $\tau > 0.1$ were rejected by the V3 algorithm (Fig. 6), and that this loss of data resulted in a reduction in τ by more than a factor of 2 averaged over these dusty time periods. Similar to the 29 January case, dust was rejected because of 1) high temporal variability, 2) low AE values, and 3) strong forward-scattering characteristics. We then described a simple algorithm to identify and restore dusty measurements that were incorrectly rejected as cloud contaminated by the V3 algorithm using collocated measurements from the CL51. When we applied this algorithm to the cases examined here, we found that the algorithm restored nearly 100% of the dusty measurements for which $\tau > 0.1$ and $f < 0.5$.

This work illustrates the challenges of using sun photometry in a location close to several dust source regions and suggests that supplemental collocated instrumentation may be needed to aid in the discrimination of dust and cirrus in places like the Salton basin. The restoring algorithm described here cannot be scaled up to other AERONET sites in dusty locations since it relies on collocated measurements from a ceilometer. Preliminary work exploring restoring algorithms that only utilize AERONET data showed promising results, although more work would be required to draw from a larger sample than just one AERONET site.

We note that during the first 4 months of 2021 the site frequently experienced issues related to dust contamination inside the collimator tubes, which resulted in an unphysical diurnal signal in the retrievals of τ that was apparent during days with more pristine sky, as discussed in Giles et al. (2019). This problem was ameliorated by more frequent cleaning of

TABLE 3. Tests for the dust-restoring algorithm for the Salton Sea AERONET site.

Dust-restoring algorithm
$\tau > 0.1$ and $f < 0.5$ and no cloud detected ± 30 min
If above conditions are met for five or more measurements during a given day: r value > 0 and p value < 0.05 for those τ_{870} and $\tau_{cl,870}$ retrievals

the filter windows and by blowing more compressed air through the detached tubes.

We are unaware of similar pervasive rejection of dusty scenes at other existing AERONET sites in desert regions, although preliminary work has suggested that similar effects may occur elsewhere (e.g., the Tamanrasset, Algeria, Meteorological State Agency of Spain [AEMET, formerly INM (National Institute of Meteorology)] site on March 13 during the *Terra* and *Aqua* overpasses at 1050 and 1220 UTC). Closed topographic depressions like the Salton basin are globally widespread, often contain highly erodible soil (Prospero et al. 2002; Mahowald et al. 2003; Engelstaedter et al. 2003), and may account for 30% of the global dust burden (Ginoux et al. 2012). Thus, it is at least plausible that regular misclassification of dusty measurements may have occurred—or will in the future occur—at other similarly located AERONET sites, particularly since the strong forward-scattering peak and low AE values are common features of mineral aerosols (Tolédano et al. 2009; Ding et al. 2009). As such, this work can serve as a starting point for identifying and solving such challenges at other locations.

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Data availability statement. AERONET data are available online (<https://aeronet.gsfc.nasa.gov>). MODIS imagery is from the NASA Worldview application (<https://worldview.earthdata.nasa.gov>), which is part of the NASA Earth Observing System Data and Information System (EOSDIS). GOES-17 data were accessed via <https://www.class.noaa.gov>.

TABLE 4. Dates and start and stop times (UTC) during which cirrus clouds are present but not identified by the CL51 processing software.

Date	Start time	End time
14 Jan 2020	2240	2333
28 Mar 2020	2210	2321
24 Oct 2020	1751	1807
7 Jan 2021	2120	2126

Roundshot camera imagery is from <https://iid.roundshot.com>. Surface and upper-air analyses were accessed from <https://www.wpc.ncep.noaa.gov>, and archived Area Forecast Discussions from the San Diego National Weather Service field office were obtained at <https://mesonet.agron.iastate.edu>. Regional wind speed and direction and PM₁₀ measurements are available from the California Air Resources Board (<https://www.arb.ca.gov/aqmis2/aqdselect.php>). Site CL51 backscatter and extinction profiles are available upon request.

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