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By: **James P. Sherman,** Pawan Gupta, Robert C. Levy, and Peter J. Sherman

Abstract

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ABSTRACT

The literature shows that aerosol optical depth (AOD) derived from the MODIS Collection 5 (C5) dark target algorithm has been extensively validated by spatiotemporal collocation with AERONET sites on both global and regional scales. Although generally comparing well over the eastern US region, poor performance over mountains in other regions indicate the need to evaluate the MODIS product over a mountain site. This study compares MODIS C5 AOD at 550nm to AOD measured at the Appalachian State University AERONET site in Boone, NC over 30 months between August 2010 and September 2013. For the combined Aqua and Terra datasets, although more than 70% of the 500 MODIS AOD measurements agree with collocated AERONET AOD to within error envelope of ± (0.05 + 15%), MODIS tends to have a low bias (0.02–0.03). The agreement between MODIS and AERONET AOD does not depend on MODIS quality assurance confidence (QAC) value. However, when stratified by satellite, MODIS-Terra data does not perform as well as Aqua, with especially poor correlation (r = 0.39) for low aerosol loading conditions (AERONET AOD less than 0.15). Linear regressions between Terra and AERONET possess statistically-different slopes for AOD < 0.15 and AOD ≥ 0.15. AERONET AOD measured only during MODIS overpass hours is highly correlated with daily-averaged AERONET AOD. MODIS monthly-averaged AOD also tracks that of AERONET over the study period. These results indicate that MODIS is sensitive to the day-to-day variability, as well as the annual cycle of AOD over the Appalachian State AERONET site. The complex topography and high seasonality in AOD and vegetation indices allow us to specifically evaluate MODIS dark target algorithm surface albedo and aerosol model assumptions at a regionally-representative SE US mountain site.

Keywords: Aerosol optical thickness; Air quality; Collection 5; Southern Appalachian mountains.

INTRODUCTION

Due to sparse sampling by ground monitors, satellite remote sensing of aerosol optical depth (AOD) is used for both air quality and climate applications. To be useful for these applications on a local scale, one needs to characterize how well a satellite product represents the daily average AOD, as well as the seasonal and annual AOD cycles. To quantify this information, one begins by comparing the satellite product to ground-truth observation at a site that is sufficiently representative of the region. For validation of such satellite-retrieved AOD, it is common to rely on collocated measurements by ground-based sunphotometers, such as those provided by NASA's Aerosol Robotic Network (AERONET).

A well-known satellite dataset is obtained by the "dark-target" (DT) algorithm that retrieves AOD from spectral reflectance observed by MODerate resolution Imaging Spectro-radiometers (MODIS) aboard the polar-orbiting Terra and Aqua satellites (Levy *et al.*, 2007a). The "Collection 5" (C5) DT product covers the entire lifetime of the two MODIS sensors (since 2000 for Terra, and 2002 for Aqua), and covers both global oceans and dark surfaces (primarily vegetated) over land. Levy *et al.* (2010) compared the MODIS C5 product with hundreds of AERONET sites around the globe, to derive error estimates (EE) for AOD (at 550 nm). Over land, this meant that 66% (or approximately one standard deviation) of all high-quality retrievals of AOD, matched with AERONET-observed AOD within EE of ±(0.05 + 15%).

Although Levy *et al.* (2010) and others (e.g., Hyer *et al.*, 2011) demonstrated the global "validation" of MODIS-retrieved AOD, these studies also picked out regions and conditions for which the AOD product did not meet the

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requirements of accuracy and correlation with AERONET data. In general, the MODIS C5 product compared well for AERONET sites over the eastern United States, western Europe, and other regions with vegetation and relatively flat surfaces (Levy *et al.*, 2010). On the other hand, there was poorer correlation for brighter surfaces, including semi-arid, urban, and mountain sites. There were no mountainous eastern US AERONET sites during the time period studied by Levy *et al.* (2010).

The DT algorithm assumes that surface albedo (and surface reflectance) is characteristic of vegetation (which appears dark for visible wavelengths) and that it can be easily constrained. However, for the less vegetated (semi-arid or urban), and/or complex terrain (e.g., mountains), the DT assumption may be violated. We hypothesize that the complex terrain of the Appalachian Mountains may introduce challenges for the MODIS spectral surface albedo model (Levy *et al.*, 2007b). Surface assumption errors represent the largest source of error for low AOD less than ~0.15 (Levy *et al.*, 2010), which occurs for most non-summer months over a majority of the southeastern US.

After the Levy *et al.* (2010) publication and other global validation studies, an AERONET site was deployed on the campus of Appalachian State University in Boone, NC. For the first time we can assess the performance of the MODIS DT algorithm over a site that represents the mountainous Southern Appalachian region of the southeastern US. At the same time, we determine whether the MODIS data are representative of daily mean AOD, and assess whether sampling of the MODIS retrievals (less than daily due to clouds and other obstructions) are able to capture the annual variation of AOD.

The current study compares the MODIS C5 AOD product to spatiotemporally collocated AOD measurements from the Appalachian_State AERONET site to evaluate the performance of the MODIS AOD product above the mountainous site. Although a new collection (Collection 6) of the MODIS product is now available with some upgrades to the DT algorithm (Levy *et al.*, 2013), there has not yet been comprehensive global evaluation analogous to Levy *et al.* (2010). Therefore, we report only C5 products in this paper and briefly discuss how the results may be different in C6, based on initial C6 studies (Levy *et al.*, 2013). MODIS temporal resolution is then evaluated by two means: (1) the correlation and level of agreement between AERONET AOD measured during MODIS overpass hours with daily-averaged AERONET AOD; and (2) the ability of monthly-averaged MODIS AOD to track AERONET over the 3+ year study period.

STUDY AREA AND DATA USED

AppalAIR Site

Established in 2009, the Appalachian Atmospheric Interdisciplinary Research facility (AppalAIR) at Appalachian State University in Boone, NC (36.21°N, 81.69°W, 1080 m asl) is home to the only AERONET site in the Appalachian Mountain region and the only collocated NASA AERONET and NOAA Earth System Research Laboratory (NOAA-ESRL) aerosol monitoring sites in the entire eastern US. The region is heavily forested and possesses a diversity of elevations (< 300 m to > 2000 m) and a variety of weather regimes (e.g., winter storms, convective cells, dying tropical cyclones, and stagnant summertime episodes). The region also includes a diversity of anthropogenic and biogenic aerosol sources. Lower tropospheric aerosol light scattering and absorption measured at AppalAIR is dominated by particles with diameter less than 1 µm (Sherman *et al.*, 2015) and sub-1 µm aerosol mass consists primarily of organics, with lower levels of sulfates (Link *et al.*, 2015). Summer aerosol optical depth in the southeastern US is influenced by isoprene-derived secondary organic aerosol (Goldstein *et al.*, 2009). A biomass-burning influence is also present in winter aerosol mass concentrations measured at AppalAIR (supplement to Link *et al.*, 2015), likely due to residential wood-burning in the region.

AERONET Aerosol optical Depth and Ångström Exponent

The CIMEL sunphotometer, deployed at the AppalAIR site (known as 'Appalachian_State' within the AERONET network), collected data over 30 months during the period August 2010–September 2013. There are no data available between Nov. 2011–May 2012 and for Oct. 2012, due to calibrations and instrument maintenance. The CIMEL measures direct solar radiance at nine wavelengths (λ = 340, 380, 440, 500, 670, 875, 940, 1020, and 1640 nm) and sky radiance at four of these wavelengths (λ = 440, 670, 870, and 1020 nm), using standard AERONET protocols (Holben *et al.*, 1998). The direct solar radiance measurements are used to calculate AOD at each of the nine wavelengths except 940 nm using the Beer-Lambert-Bouguer equation (Holben *et al.*, 1998). Direct solar radiance measurements are made at optical air mass intervals of 0.25, corresponding to every ~15 minutes near noon and more often near dawn and dusk. Only Level 2 AERONET AOD (cloud-screened, calibrated) is used in this study. The uncertainty for Level 2 AOD is small enough (0.01–0.02; Eck *et al.*, 1999) so that AERONET serves as ground-truth for comparisons with satellite-derived AOD (Levy *et al.*, 2010; Hyer *et al.*, 2011).

Sky radiance measurements are used to derive column-averaged aerosol properties including size distributions and single-scattering albedo (SSA). Single-scattering albedo can only be reliably retrieved to within ~0.03 for AOD (λ = 440 nm) ≥ 0.40 (Dubovik *et al.*, 2000). This high-loading condition is only satisfied on 2–4 days per year at the Appalachian_State site and therefore AERONET SSA is not available to use in this study. Ångström exponent in the visible spectral range is typically computed as the slope of a linear fit of log (AOD) versus log (λ) using available wavelengths between 440–870 nm and is used in Sect. 4.4 as a semi-quantitative indicator of aerosol size.

MODIS Aerosol Optical Depth

The "Level 2" (derived-geophysical) MODIS aerosol product is derived at 10 km spatial resolution (at nadir), and known as MOD04_L2 (for Terra) and MYD04_L2 (for Aqua). Collectively, referred to as MxD04, the data used here (Aug 2010–Sept 2013) are products from consistent application of the DT retrieval algorithm (Levy *et al.*, 2007a ,b), instrument calibration, and computer processing environment. Although the data are from Collection 5.1 (C51), the DT portion is identical to C5, so we refer to the set as Ç5. A short description of the algorithm, products, and validation follows here.

MODIS, aboard the Terra and Aqua polar-orbiting satellites, measures top-of-the-atmosphere (TOA) spectral reflectance or radiance in 36 channels ranging from visible to infrared wavelengths, with spatial resolution ranging from 250 m to 1 km. Terra (Aqua) crosses the equator going north to south (south to north) near 10:30am (1:30 pm) local solar time (LST). With wide swath (~2330 km), there is normally twice-daily overpass over Appalachian_State.

The DT algorithm attempts to interpret the contrast of aerosol (relatively bright) against the (dark) surface background. The retrieval algorithm (Levy *et al.*, 2007b) works by comparing the observed spectral reflectance to a lookup table (LUT) that simulates possible surface/molecular/aerosol scenarios. More specifically, the algorithm uses a subset of the spectral reflectance information to filter out cloudy pixels, and then aggregates remaining pixels into boxes that represent 10 km spatial resolution (at nadir). The (aggregated, 10 km) spectral reflectances in seven MODIS bands are used as the observations to drive the aerosol retrieval. These seven bands (Bands #1-#7 or B1-B7) are centered near 645, 855, 466, 553, 1243, 1628, and 2113 nm, respectively.

The LUT is represented by a prescribed aerosol model "type" (aerosol optical properties), along with a model of spectral surface reflectance appropriate for the regional vegetation indices and season. The prescribed aerosol "type" is one of three global aerosol models (Levy *et al.*, 2007b), which has been assigned to each 1° latitude × 1° longitude grid point, as a function of season. These three aerosol types differ primarily in SSA, with a weakly-absorbing aerosol type (SSA ~0.95 at 553 nm) used to represent the eastern US (Levy *et al.*, 2007b). As a "dark-target" retrieval, the algorithm attempts to retrieve when the observed reflectance at 2113 nm is between 0.01 and 0.25. For the surface properties, the algorithm makes a major assumption: specifically, that for primarily vegetated surfaces, the surface reflectance (that would be measured) in a shortwave-infrared (SWIR) MODIS channel (e.g., 2113 nm) is linearly correlated with surface reflectance in blue (466 nm) and red (645 nm) MODIS channels (e.g., Kaufman *et al.*, 1997). Levy *et al.* (2007b) noted also that this VIS/SWIR relationship also depends on scattering angle and on surface greenness, and that surface greenness could be parameterized by the Normalized Differential Vegetation Index (NDVI-Karnieli *et al.*, 2001) calculated using MODIS SWIR channels centered at 1243 nm and 2113 nm (Levy *et al.*, 2007a).

In theory, the assumed surface reflectance relationships, coupled with a prescribed model of aerosol properties (aerosol type), provides enough constraint to retrieve the total aerosol loading, in addition to some estimate of the aerosol size. Therefore, the products of the retrieval include AOD (at 550 nm) and some qualitative measures of the aerosol size distribution. Note that due to uncertainties in estimating surface reflectance, it is possible to retrieve a negative (non-physical) AOD value (allowed down to –0.05). As long as there are enough non-cloudy pixels within the 10 km box and the retrieval inversion finds an acceptable solution (see Levy *et al.*, 2007b for details), we have "confidence" in the retrieved AOD values. For conditions with fewer acceptable pixels, poor fitting to observed reflectance, or other retrieval issues, there is lower confidence in the retrieved product. Therefore, according to Levy *et al.* (2007b), each MODIS (10 km) AOD retrieval is assigned a quality assurance confidence (QAC) value ranging from 0 (lowest) to 3 (highest) (Levy *et al.*, 2007b).

Since QAC value does not indicate accuracy of the retrieved AOD product, the MODIS team turned to collocation with ground-based AERONET data to validate the MODIS product. Following Ichoku *et al.* (2002), MODIS AOD uncertainty over land is estimated based on global comparisons with AERONET observations. For the C5 version of the MODIS dataset, Levy *et al.* (2010) determined that the error envelope (EE) was

$$EE = \pm (0.05 + 0.15 \times AOD_{AERONET}) \quad (1)$$

Note that while AOD is determined at 10 km resolution, EEs are determined using averages of MODIS AOD retrievals over a 5 pixel by 5 pixel box, corresponding to 50 km × 50 km), centered at the AERONET site (Sect. 3). This reduces noise in the MODIS retrievals, as well as allowing for non-ideal representation of the area by the AERONET site. The primary sources of MODIS AOD retrieval errors over a region result from uncertainties in (1) surface reflectance; and (2) aerosol model (e.g., optical properties) used to construct the LUTs (Kaufman *et al.*, 1997). Although sensor calibration drift and inadequate cloud screening also contribute to errors in MODIS AOD, we will concentrate on the first two sources. Following Levy *et al.* (2010) and recommendations for the use of MODIS Level 2 AOD (http://modis-atmos.gsfc.nasa.gov/MOD04_L2/format.html), we retain negative MODIS AOD values down to –0.05 so as not to introduce an artificial positive bias under clean air conditions.

MODIS Surface Albedo

In addition to aerosol products, there are many algorithms to derive other geophysical parameters from the MODIS observations. One of these is the spectral surface reflectance product (Vermote and Kotchenova, 2008), known as MYD09A1 (derived from MODIS-Aqua data). MYD09 products are created by analyzing MODIS spectral observations over 8-day periods and identifying the invariant contributions (e.g., the surface). These products are gridded, reported at 500 m spatial resolution, and have their own quality assurance and error characteristics. Here, we concentrate on the same MODIS Bands 1–7 used for the aerosol retrieval. Each MYD09A1 pixel contains the best possible observation (with atmospheric correction applied) during an 8-day period as selected by high observation coverage, low view angle, absence of clouds and cloud shadow, and low aerosol loading.

To compare with the aerosol products (50 km × 50 km), we utilize a similar-sized box of MYD09A1 data centered at the Appalachian_State AERONET site. Only 8-day surface reflectance products with at least 50% of pixels in the 50.5 km × 50.5 km box passing MODIS quality assurance tests are used in this study and the mean surface reflectance of these pixels is calculated for each wavelength. In addition to surface reflectance in the seven bands that are compared with values used in the MxD04_L2 aerosol retrieval, we can estimate scene brightness (based on 2113 nm reflectance) and surface "greenness" (based on 1243 nm and 2113 nm reflectance), defined by the NDVI_swir

$$NDVI_{swir} = (R_{1243nm} - R_{2113nm})/(R_{1243nm} + R_{2113nm}) \quad (2)$$

Values of $NDVI_{swir}$ greater than ~0.6 correspond to active "green" vegetation and values less than ~0.2 correspond to dormant or sparse vegetation (Levy *et al.*, 2007a).

NOAA-ESRL Single-Scattering Albedo

Ground-based measurements of aerosol optical properties at the collocated NOAA-ESRL site can be used to evaluate the aerosol model assumptions in the DT retrieval. Specifically, monthly-averaged single scattering albedo (SSA) at 550 nm is derived from continuous sampling of aerosol light scattering and absorption coefficients from a 34 m tower at AppalAIR (Sherman *et al.*, 2015). In order to decouple the relative humidity (RH) dependence on light scattering (aerosol swelling), the aerosols are heated as needed to attain RH ≤ 40%. In-depth discussions of NOAA-ESRL aerosol sampling protocols, scattering and absorption coefficient measurements, and data analysis techniques are provided in Sheridan *et al.* (2001). A scanning humidograph (Sheridan *et al.*, 2001) is employed to measure the RH dependence of light scattering coefficient but SSA is not corrected to ambient RH in this study, as column-averaged RH measurements were not available for most of the study period. This likely leads to an SSA under-estimation, which may be up to of ~0.02–0.03 during humid summer months (based on RH values from radiosonde launches at AppalAIR during summer 2013). Vertical profiles of aerosol attenuated backscatter measured by collocated micro-pulsed lidar indicate that most of the aerosols above this site are contained in the boundary layer (not shown) and monthly-averaged SSA from the NOAA-ESRL site likely serves as a reasonable approximation of column-averaged SSA.

COLLOCATION STRATEGY

We apply a similar collocation strategy to that used by Levy *et al.* (2010) in their global validation of MODIS C5. We first interpolate AERONET AOD to match the MODIS-reported wavelength (550 nm) by applying a quadratic fit (on a log-log scale) to spectral AERONET AOD versus wavelength (Eck *et al.*, 1999). We then use the method (Fig. 1) of spatiotemporal collocation similar to that described by Ichoku, *et al.* (2002). For each Terra and Aqua overpass, we calculate the mean MODIS AOD over a 50 km × 50 km box (5 × 5 MODIS Level 2 pixels) centered at the Appalachian_State AERONET site, to compare with the average of AERONET AOD measured within ± 30 minutes of MODIS overpass (typically 2–4 measurements). We also keep track of the MODIS QAC (confidence) value. The difference between our collocation method and that of Ichoku *et al.* (2002) is that we removed the restrictions that at least five MODIS pixels are used to calculate MODIS box-averaged AOD and that at least two AERONET AOD measurements are used to calculate temporally-averaged AOD. The agreement between MODIS and AERONET AOD did not degrade, yet there were nearly double the number of collocations (from 285 to 500 for QAC = 3 cases). For all QAC cases there are 581 "valid" MODIS/AERONET collocations that span the 30 data months (e.g., Table 1).

Following the logic of previous studies (e.g., Levy *et al.*, 2010; Hyer *et al.*, 2011), we stratify the collocations by QAC, by satellite sensor (Terra versus Aqua), and by a threshold for "moderate" aerosol loading (AOD = 0.15; Levy *et al.*, 2010). Our 581 collocations are reduced to 566 if we require QAC ≥ 1 (moderate confidence), and to 500 if we require QAC = 3 (high confidence). The number of collocations is similar between Terra and Aqua (~290 for QAC ≥ 0). For the cases receiving QAC = 3, more than 80% are for AERONET reporting AOD < 0.15.

For each of the categories of stratification (rows in Table 1), we evaluate the performance of MODIS in capturing the AERONET AOD. We create a scatterplot and compute linear regression parameters (slope, intercept, and correlation coefficient), along with ninety-five percent confidence intervals for these parameters (Wonnacott and Wonnacott, 1981; Miller and Miller, 2012). Similar to other MODIS validation studies (Levy *et al.*, 2010; More *et al.*, 2013), we also calculate the percentage of MODIS AOD values lying within EE of AERONET AOD (Eq. (1)), along with the root-mean-squared error (RMSE), defined as the RMS difference in MODIS and AERONET AOD. MODIS AOD is 'validated' in this study if at least 2/3 of the spatially-averaged MODIS AOD retrievals lie within EE of the temporally-averaged AERONET retrievals, in addition to high correlation between the two (Levy *et al.*, 2010). In addition to the overall regressions, we use the collocated data (500 points with QAC = 3) to calculate monthly-averaged AOD for each dataset. Here, we can identify MODIS measurement biases (Fig. 2; Sect. 4.1) that are seasonally dependent.

Finally, we calculate monthly-averaged AOD using all MODIS and all AERONET measurements (independent of collocation) to assess MODIS ability to track monthly-averaged AERONET AOD over the 3+ year study period (Fig. 7(a); Sect. 4.6). Monthly-averaged AOD for the analysis in Sect. 4.6 is computed using daily-averaged AOD values. Daily-averaged MODIS AOD is the average of Terra and Aqua AOD if measurements from both satellites are available. If AOD on a given day is only retrieved by one satellite, that value is used as the daily-average MODIS AOD. Daily-averaged AERONET AOD is calculated as the average over all AERONET measurements for each day when three or more measurements are made (http://aeronet.gsfc.nasa.gov/new_web/data_description_AOD_V2.html).

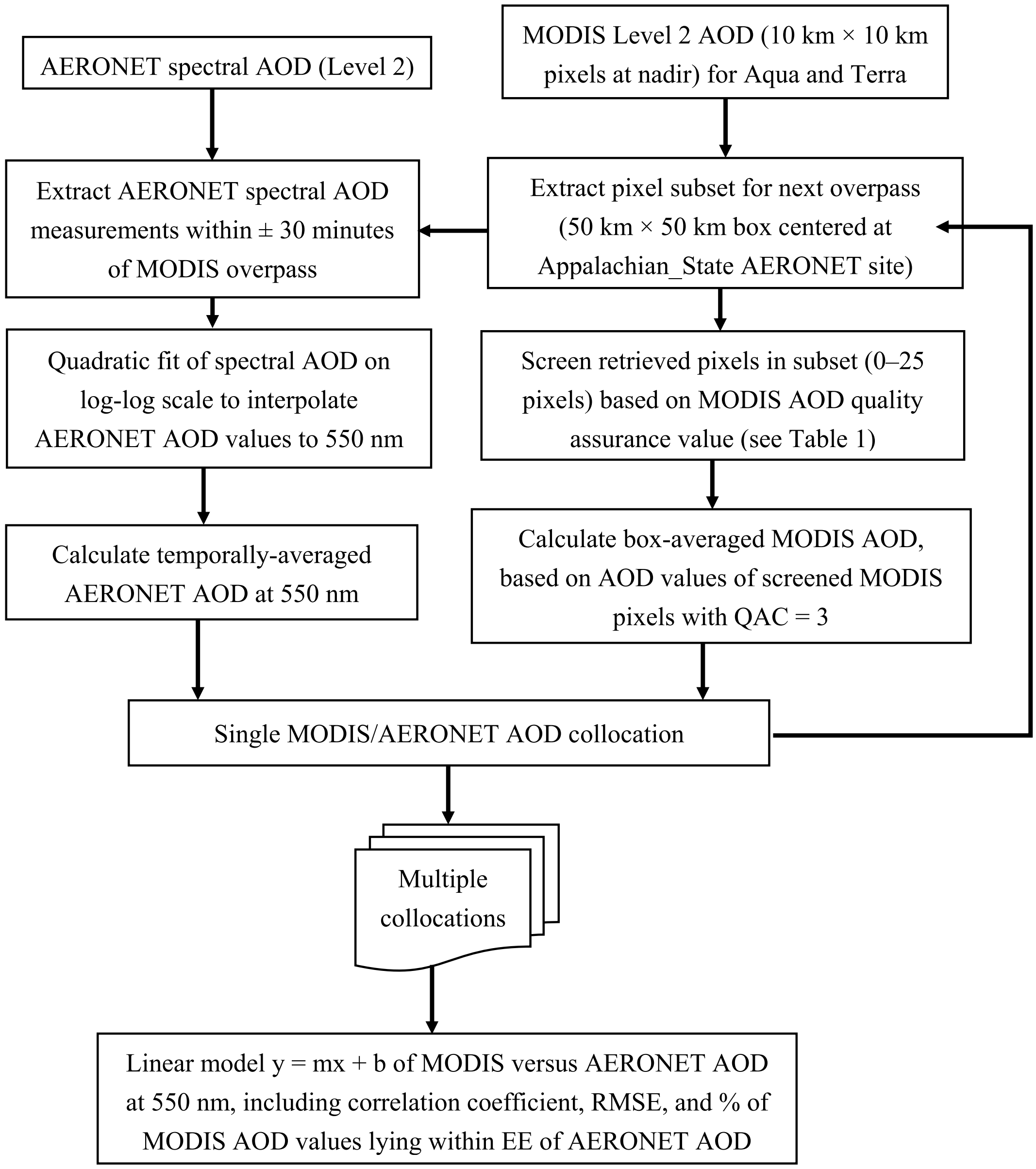

Fig. 1. Flowchart showing spatiotemporal collocation method used for comparing MODIS and AERONET aerosol optical depth (AOD) above the Appalachian_State AERONET site.

RESULTS AND DISCUSSION

Overall Agreement of MODIS and AERONET AOD and Dependence on QAC

Table 1 contains linear regressions for the MODIS/AERONET inter-comparisons, for Terra and Aqua separately, and their combination. When all Terra & Aqua collocations with QAC = 3 are considered, MODIS AOD shows excellent agreement with AERONET, with high correlation (r = 0.84) and 70.80% of the MODIS AOD retrievals fall within the EE envelope given by Eq. (1). The regression equation is near 1–1, with a slope of 1.06 and a small (~0.03) negative MODIS AOD bias. Monthly-averaged MODIS and AERONET AOD calculated using the collocations (Fig. 2) illustrates that the MODIS AOD bias is fairly uniform (–0.02 to –0.03) for most months over the 3+ year period. A more negative MODIS bias is observed for some warm-season months of 2012 and 2013.

Table 1 illustrates that MODIS/AERONET AOD agreement does not degrade when MODIS pixels with QAC < 3 are included in the calculation of box-averaged MODIS AOD. One exception is that the regression slope lies closer to one when only the highest quality pixels (QAC = 3) are used. Similar insensitivity to QAC is observed for Terra and Aqua individually as for their combination. Based on their global MODIS/AERONET inter-comparison, Levy *et al.* (2010) recommended restricting MODIS AOD usage to QAC = 3 for the highest-quality retrievals and strongly recommended against using QAC = 0 for any quantitative purpose. However, Levy *et al.* (2010) also acknowledged that "*the use of lower confidence data should depend on the trade-offs between an application's* *tolerance for uncertainty and the spatial coverage requirements*". For the rest of this paper, we focus on cases where MODIS QAC = 3 so as to maintain consistency with other published results (Levy *et al.*, 2010; Hyer *et al.*, 2011; More *et al.*, 2013). However, since the MODIS/AERONET agreement seems insensitive to assigned MODIS QAC value, we see the potential for improved MODIS AOD sampling in the Southern Appalachian Mountain region.

Dependence of MODIS/AERONET Agreement on Satellite and AOD

Levy *et al.* (2010) suggested that performance of MODIS

Table 1. Linear regression parameters of the relationship MODIS AOD = m × AERONET AOD + b, broken down by satellite, by MODIS QAC levels of the pixels used to calculate box-averaged AOD, and by AERONET AOD (for MODIS QAC = 3). N is the number of collocations. Lower and upper 95% confidence interval bounds of m, b, and correlation coefficient (r) are given in parentheses. RMSE is root-mean-square difference between MODIS and AERONET.

MODIS satellite	QAC	AERONET AOD (550 nm)	N	m	b	r	RMSE	MODIS retrievals within EE (%) (Eq. (1))
Aqua & Terra	≥ 0	all	581	1.24 (1.18,1.30)	–0.03 (–0.03, –0.02)	0.86 (0.84, 0.88)	0.07	71.60
	≥ 1		566	1.22 (1.15, 1.28)	–0.03 (–0.04, –0.02)	0.85 (0.83, 0.87)	0.07	71.55
	≥ 2		537	1.18 (1.12, 1.23)	–0.03 (–0.04, –0.02)	0.86 (0.84, 0.88)	0.06	71.69
	3		500	1.06 (1.00, 1.12)	–0.03 (–0.03, –0.02)	0.84 (0.82, 0.87)	0.06	70.80
	3	< 0.15	422	0.97 (0.83, 1.10)	–0.02 (–0.03, –0.01)	0.56 (0.49, 0.62)	0.06	69.91
	3	≥ 0.15	78	1.12 (0.94, 1.30)	–0.04 (–0.08, 0.01)	0.82 (0.73, 0.88)	0.07	75.64
Terra only	≥ 0	all	297	1.21 (1.12, 1.30)	–0.03 (–0.04, –0.01)	0.83 (0.80, 0.87)	0.07	64.31
	≥ 1		291	1.19 (1.10, 1.29)	–0.03 (–0.04, –0.01)	0.83 (0.79, 0.86)	0.07	64.95
	≥ 2		278	1.16 (1.07, 1.24)	–0.03 (–0.04, –0.02)	0.84 (0.80, 0.87)	0.07	64.03
	3		260	1.01 (0.92, 1.11)	–0.02 (–0.03, –0.01)	0.80 (0.75, 0.84)	0.07	62.31
	3	< 0.15	213	0.70 (0.48, 0.92)	0.00 (–0.02, 0.01)	0.39 (0.27, 0.50)	0.06	60.09
	3	≥ 0.15	47	1.31 (1.04, 1.59)	–0.09 (–0.16, –0.03)	0.82 (0.69, 0.89)	0.08	72.34
Aqua only	≥ 0		284	1.28 (1.20, 1.36)	–0.03 (–0.04, –0.02)	0.89 (0.86, 0.91)	0.06	79.23
	≥ 1		275	1.25 (1.17, 1.33)	–0.03 (–0.04, –0.02)	0.88 (0.85, 0.90)	0.06	78.55
	≥ 2		259	1.20 (1.13, 1.27)	–0.03 (–0.04, –0.02)	0.90 (0.87, 0.92)	0.05	79.92
	3		240	1.12 (1.05, 1.20)	–0.03 (–0.04, –0.02)	0.90 (0.87, 0.92)	0.05	80.00
	3	< 0.15	209	1.23 (1.08, 1.38)	–0.04 (–0.05, –0.03)	0.75 (0.68, 0.80)	0.05	79.90
	3	≥ 0.15	31	0.96 (0.74, 1.19)	0.01 (–0.05, 0.07)	0.85 (0.71, 0.93)	0.07	80.65

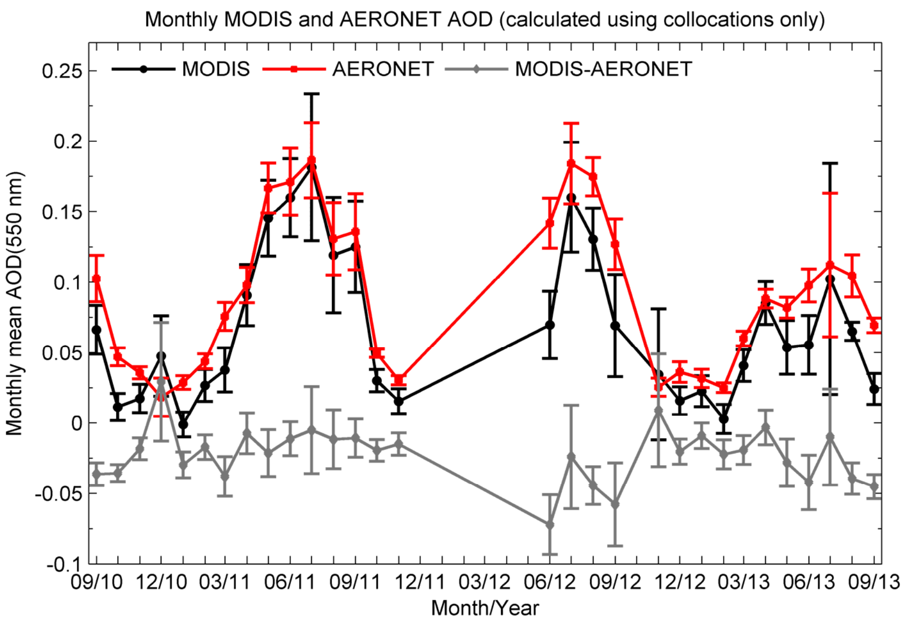

Fig. 2. Time series of monthly mean MODIS and AERONET AOD at 550 nm, along with monthly mean of their difference. Only AOD values for the collocations are used to calculate the monthly mean values and MODIS-AERONET AOD. Error bars represent standard error of mean values.

Terra and Aqua may differ, in that Terra appeared to have a negative bias since 2004. Hyer *et al.* (2011) quantified this more fully and found that retrievals of negative AOD were prevalent for low AOD conditions, and that there was a higher percentage of negative AOD retrievals for Terra than for Aqua.

Over Appalachian_State, we find that 80% of the 240 Aqua AOD values are contained within the EE envelope (Eq. (1)) with high correlation (r = 0.90). However, only 62.31% of the 260 Terra AOD values are within the EE envelope. Root-mean-squared error (RMSE) is also better for Aqua (0.05) than for Terra (0.07). This is in spite of the fact that the MODIS/AERONET regression slopes and intercepts are slightly better for Terra (m = 1.01; b = –0.02) than for Aqua (m = 1.12; b = –0.03). A large majority of the Terra and Aqua AOD retrievals lying outside the EE envelope occur for low AOD and are biased low (Fig. 3), especially for Terra.

The pattern of negative MODIS AOD bias under clean conditions is more transparent when stratifying by AERONET AOD (e.g., Levy *et al.*, 2010). We separate "low" and "high" AOD by AERONET AOD < 0.15 and ≥ 0.15, respectively. Combined MODIS Aqua & Terra AOD is poorly correlated with AERONET for low AOD (r = 0.56) and better correlated for high AOD (r = 0.82), as seen in Table 1. When separated, the high AOD cases are similarly correlated for both Terra and Aqua datasets (r = 0.82 and 0.85), but the correlation is much poorer for Terra than Aqua (r = 0.39 and r = 0.75) at low AOD. The linear regression slope difference between the low and high AOD cases is also much smaller for Aqua (m = 1.23 for low AOD versus m = 0.96 for high AOD) than for Terra (m = 0.70 for low AOD versus m = 1.31 for high AOD). In fact, based on applying 95% confidence tests, the slopes and correlation coefficients for the low and high Terra AOD cases are statistically different. The single linear model used in MODIS/AERONET inter-comparisons cannot be applied for Terra in this study. The poor correlation at low AOD, for the combined Aqua and Terra collocations, is almost entirely due to Terra.

Levy *et al.* (2010) found no significant difference between AERONET/Terra agreement and AERONET/Aqua agreement in their global C5 validation study. However, they did report that Terra measured higher (lower) AOD than AERONET over land up until (after) 2004. The Terra AOD drift was attributed to radiance calibration drift, especially in the blue channel. This drift has been reduced for MODIS C6, but the low bias for Terra AOD over land is expected to persist (Levy *et al.*, 2013). Evaluation of C6 data over Appalachian_State will require future study.

Dependence of MODIS/AERONET Agreement on DT Surface Assumptions

Monthly-averaged MODIS surface reflectance at 2113 nm (e.g., scene reflectance) and $NDVI_{swir}$ (from MYD09A1 data) are shown in Figs. 4(a) and 4(b) to examine possible roles of MODIS surface albedo assumptions on MODIS AOD accuracy. Scene reflectance of ~0.06–0.08 and $NDVI_{swir}$ ~0.60–0.70 during May-September are consistent with active, dark green vegetation in the heavily forested Southern Appalachian Mountain region. Scene reflectance of ~0.10–0.12 and $NDVI_{swir}$ values of ~0.30 during November–March are the result of somewhat brighter, less green vegetation during the dormant season. April and October represent transition months.

Levy *et al.* (2010) reported that MODIS C5 DT AOD agreed best with AERONET when scene reflectance was 0.10–0.12 and when $NDVI_{swir}$ ~0.4. AOD was overestimated for brighter surfaces (by ~0.02 for scene reflectance of0.17) and underestimated over darker surfaces (by ~0.02

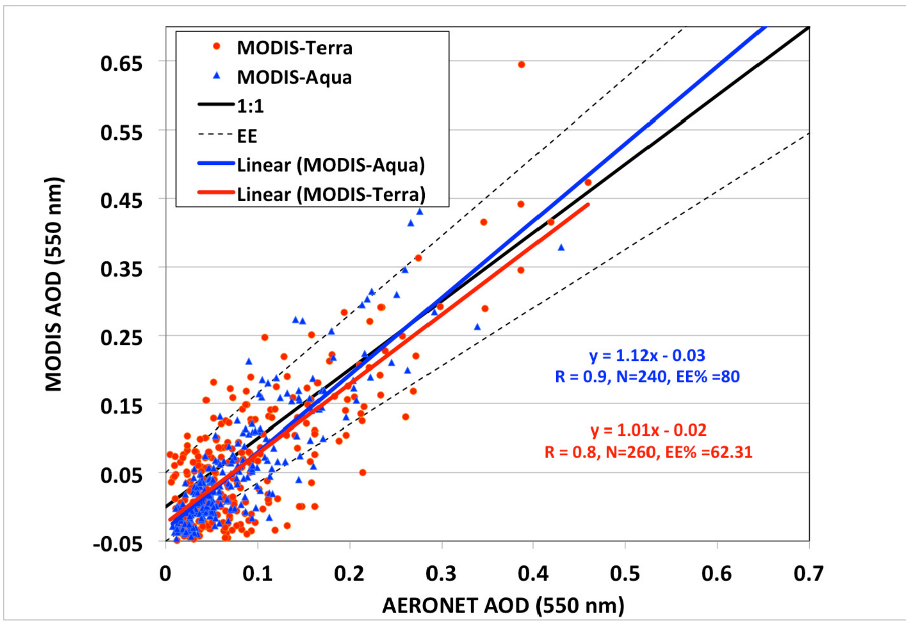

Fig. 3. Linear regressions of MODIS AOD versus AERONET AOD at 550 nm for Aqua (blue) and Terra (red) individually. The thick black trace represents the 1-to-1 line. The upper and lower dotted bounding lines encompass the MODIS expected error (EE) given by Eq. (1).

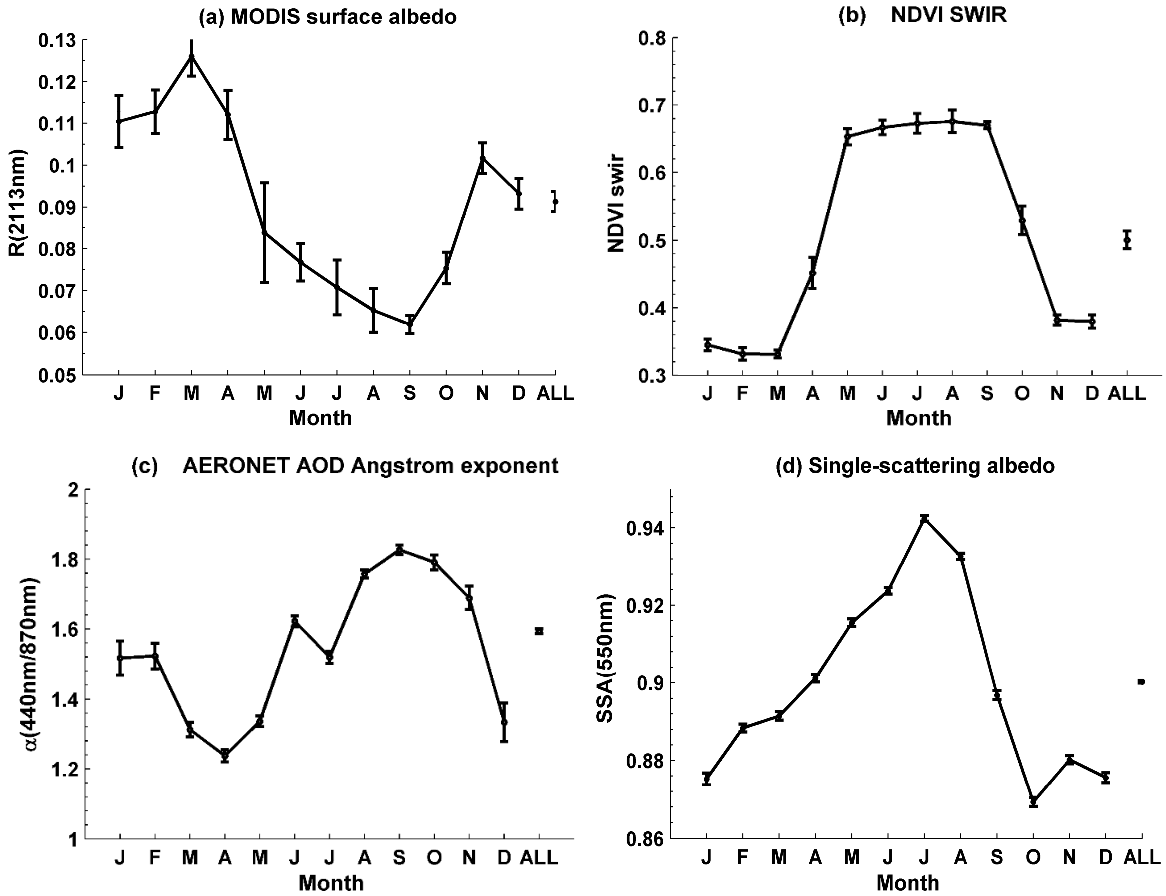

Fig. 4. Monthly mean (a) MODIS surface albedo at 2113 nm; (b) $NDVI_{swir}$, defined by Eq. (2); (c) AERONET Ångström exponent (440–870 nm); and (d) NOAA single-scattering albedo at 550 nm. Error bars represent standard error of mean values. The 'ALL' data point on each trace represents the mean value calculated using all measurements during the period of study (August 2010–September 2013).

for scene reflectance of less than ~0.07). Retrieved AOD was biased high for less green surfaces ($NDVI_{swir}$ < 0.25) and biased low (by ~0.03) for greener surfaces ($NDVI_{swir}$ about 0.60–0.70). From these global generalities, one can use Figs. 4(a) and 4(b) to estimate the expected bias to the MODIS –retrieved AOD over our site. We estimate a MODIS AOD bias of –0.05 during May–September (–0.03 due to $NDVI_{swir}$ and –0.02 due to scene reflectance), which lies close to the observed monthly-averaged MODIS bias of –0.03 to –0.04 for a majority of these months (Fig. 2). For November–April, the values of scene reflectance and $NDVI_{swir}$ are closer to optimal for dark-target retrieval, so that biases (of Fig. 2) are smaller. Surface assumption errors are thus consistent with the negative AOD bias during May–September but not during November-April. Changes made as part of MODIS C6 are expected to increase AOD over vegetated surfaces including much of the Eastern US by ~0.02, due to correcting a C5 processing software bug in the assumed relationship between VISvs2113nm surface reflectance and $NDVI_{swir}$ over land (Levy *et al.*, 2013).

Dependence of MODIS/AERONET Agreement on DT Aerosol Property Assumptions

Systematic biases in MODIS AOD also result from incorrect assumptions of aerosol type (optical properties) used in the LUT to retrieve AOD (Kaufman *et al.*, 1997). These may be errors of size distribution (and resulting effect on spectral dependence of AOD), and/or errors of absorption characteristics (characterized by SSA). Levy *et al.* (2010) showed that the AOD retrieval error (MODIS-AERONET) tended to be smaller when the aerosol was dominated by fine-mode particles, as indicated by larger values of Ångström Exponent (AE). Since the range of monthly mean AERONET AE observed in our study (Fig. 4(c)) is indicative of being dominated by fine-mode particles, there is no expected systematic bias due to aerosol size.

Based on studies such as Ichoku *et al.* (2002), the MODIS retrieval is expected to have a negative (positive) MODIS AOD bias where the algorithm overestimates (underestimates) aerosol SSA, The MODIS C5 LUT assigns a weakly-absorbing fine-mode dominated aerosol type (SSA ~0.95 at 553 nm) to the southeastern US during all seasons (Levy *et al.*, 2007b). This assumption can be compared with in-situ measurements (dried; RH < 40%) of SSA at AppalAIR's NOAA-ESRL site. SSA ranges from 0.88 during the winter to 0.94 during the summer (Fig. 4(d)), After accounting for scattering hygroscopic factors, also measured at the site (not shown), SSA during the summertime (under typical RH of 70–80% in boundary layer), is closer to 0.95 as assumed by MODIS. However, a moderately absorbing fine-mode aerosol type (SSA ~0.90) is a more suitable choice for the LUT during September–March (Fig. 4(d)). For C6, Levy *et al.* (2013) updated the retrieval to assume the moderately absorbing choice during the winter months, and we will evaluate the C6 results in a future study. Regardless, AOD in the winter tends to be low enough (Figs. 2 and 7(a)), such that errors in the aerosol model should not be the primary contributor to retrieval errors. It is possible, however, that assumption of SSA contributes to the observed ~–0.02 to –0.03 bias during September–March.

Diurnal Representativeness of MODIS AOD Measurements

Previous studies (e.g., Kaufman *et al.*, 2000; Zhang *et al.*, 2012) have considered whether AOD measured at the time of MODIS overpass is representative of daily-averaged AOD, and hence suitable for long-term climate or daily air-quality applications. On average (over 50–70 globally-spaced sites), MODIS overpass time is representative of the daily mean AOD (Kaufman *et al.* (2000)) However, diurnal variability is important for some sites (Zhang *et al.*, 2012). Fig. 5 shows AERONET AOD at Appalachian_State, averaged over the MODIS Terra and Aqua overpass hours (local solar hours 10 and 13, respectively), compared to daily-averaged AERONET AOD in different seasons. Correlation coefficients are between 0.90–0.97 for all seasons and slopes are between 0.92–1.12 (Fig. 5), indicating that that daily measurements made by Terra and Aqua should be representative of the daily average AOD over Appalachian_ State. Yet, during all seasons, there is a diurnal cycle of AOD (Fig. 6(a)), with dawn and/or dusk maxima and little AOD variability (~0.02 or less) during the intervening hours. Ångström exponent also demonstrates little diurnal variability (Fig. 6(b)). Sherman *et al.* (2015) reported minimal diurnal variability for lower tropospheric aerosol light scattering coefficient and scattering Ångström exponent at the collocated NOAA-ESRL site.

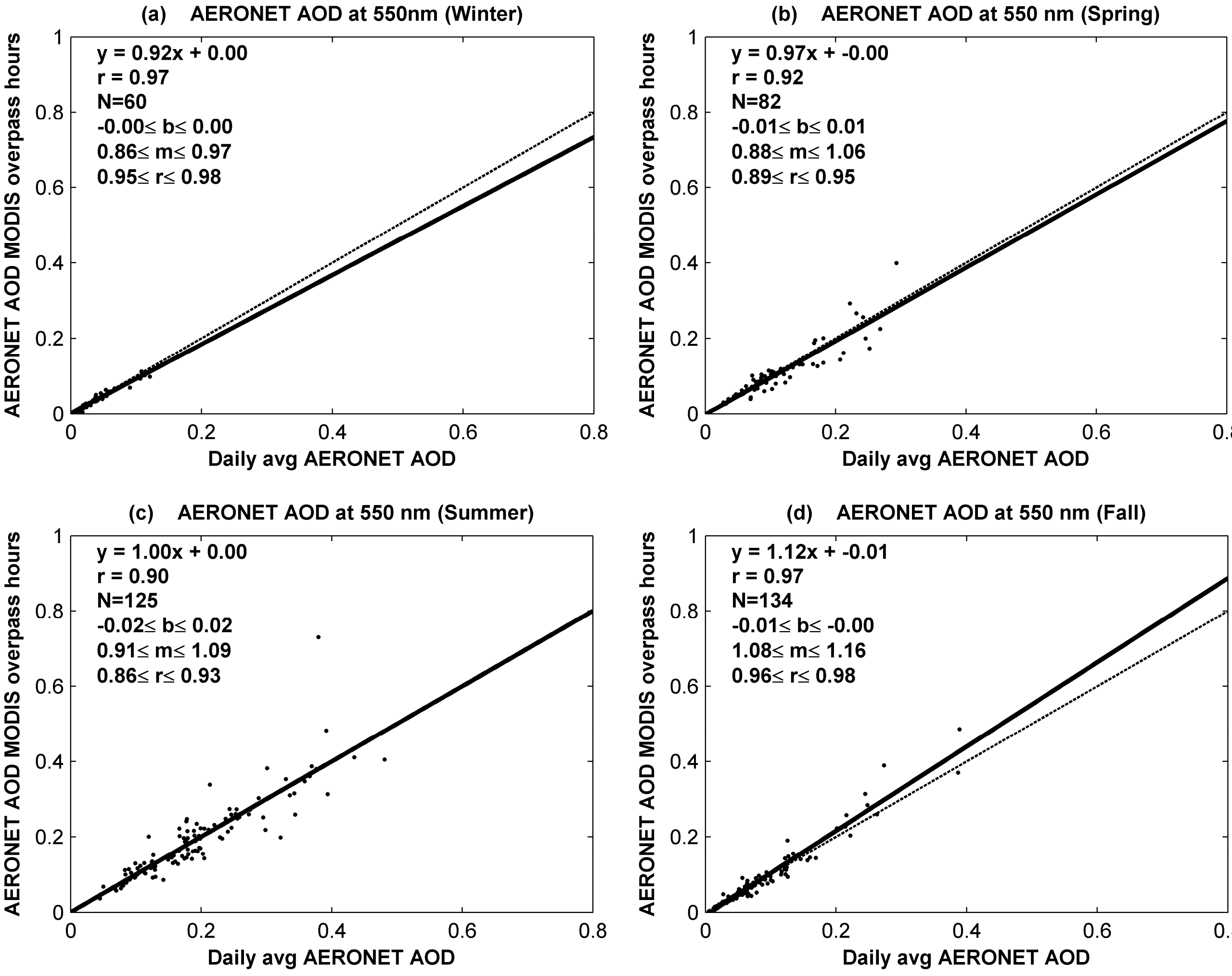

Fig. 5. Linear regressions of AERONET AOD (at 550 nm) averaged over the Terra and Aqua overpass hours (local standard hours 10 and 13, respectively) versus daily-averaged AERONET AOD. The thick solid black line is the best-fit line y = mx + b. The thin dotted black line represents the one-to-one line y = x. Lower and upper bounds listed for the linear regression parameters encompass 95% confidence intervals.

Representativeness of Monthly-Averaged MODIS AOD

Time series of monthly-averaged MODIS and AERONET AOD (Fig. 7(a)) demonstrate (along with Fig. 2) the large annual AOD cycle at the Appalachian_State site. Monthly-averaged differences, calculated using daily-averages on common measurement days, are also plotted in Fig. 7(a). The number of days used to compute each monthly average is shown in Fig. 7(b) and may help differentiate MODIS/AERONET differences due to MODIS measurement bias from those due to sampling differences.

Monthly-averaged MODIS AOD tracks that of AERONET over the 3+ year period to within ~0.01–0.02 for nearly all common measurement months (Fig. 7(a)), which is of the order of AERONET AOD measurement uncertainty (Eck *et al.*, 1999). The differences in monthly-mean MODIS and AERONET AOD also lie within the individual mean AOD uncertainties for nearly all months, as seen by the overlap of the error bars (calculated as standard error of monthly-mean values) in Fig. 7(a). Kaufman *et al.* (2005) reported a similar average agreement (~0.01) between monthly-averaged MODIS and AERONET AOD over oceans, from which they concluded that MODIS can represent AERONET's long term AOD statistics to within the measurement uncertainty of both instruments.

Significant differences in monthly-averaged AOD of ~0.03 or greater are observed for November–December 2010 and August–September 2012. In November 2010, the difference in monthly AERONET and MODIS calculated using only common measurement days was nearly zero (Fig. 7(a)) but common measurements occurred on only five of the 10–11 days (Fig. 7(b)). Sampling differences is likely not the source for the December 2010 monthly-mean AOD discrepancy, when mean MODIS AOD is very near zero. AERONET measured AOD on nearly all of the 10 days that MODIS measured AOD during this month (Fig. 7(b)) and the MODIS AOD under-estimation calculated using only collocations (Fig. 1) and common measurement days (Fig. 7(a)) is nearly the same as that using all measurements (Fig. 7(a)). Snow totals in December 2010 were much higher than normal (~72 cm for Boone, NC) and its effect on surface albedo could have possibly contributed to the MODIS AOD under-estimation. Similar to December 2010, the MODIS monthly-mean AOD under-estimation in August–September 2012 probably has less to do with sampling differences than measurement bias, although some sampling differences are seen in September 2012 (Fig. 7(b)). MODIS C5 aerosol and surface albedo model assumptions would be less likely than cloud contamination to explain the worse agreement in summer 2012, (relative to the 2011 and 2013 summers). The annual cycle of aerosol optical properties at Appalachian_

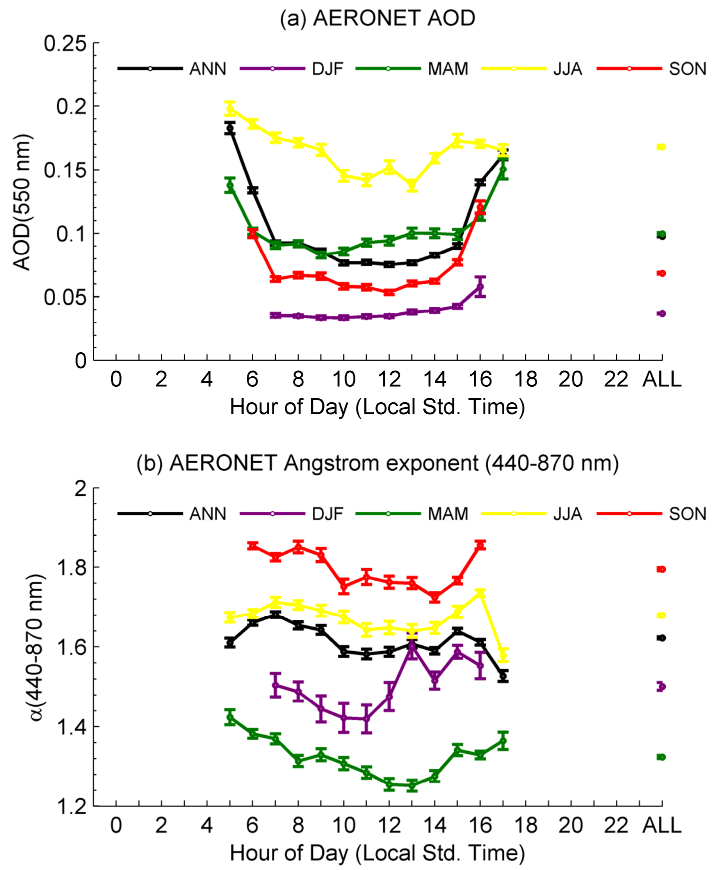

Fig. 6. Diurnal cycles of mean (a) AERONET AOD at 550 nm; and (b) AERONET Ångström exponent, calculated using the 440–870 nm wavelengths. The individual traces represent winter (DJF), spring (MAM), summer (JJA), and fall (SON). The 'ANN' trace reports mean values over all of that hour for the full annual cycle (all seasons). Error bars represent standard error of mean values.

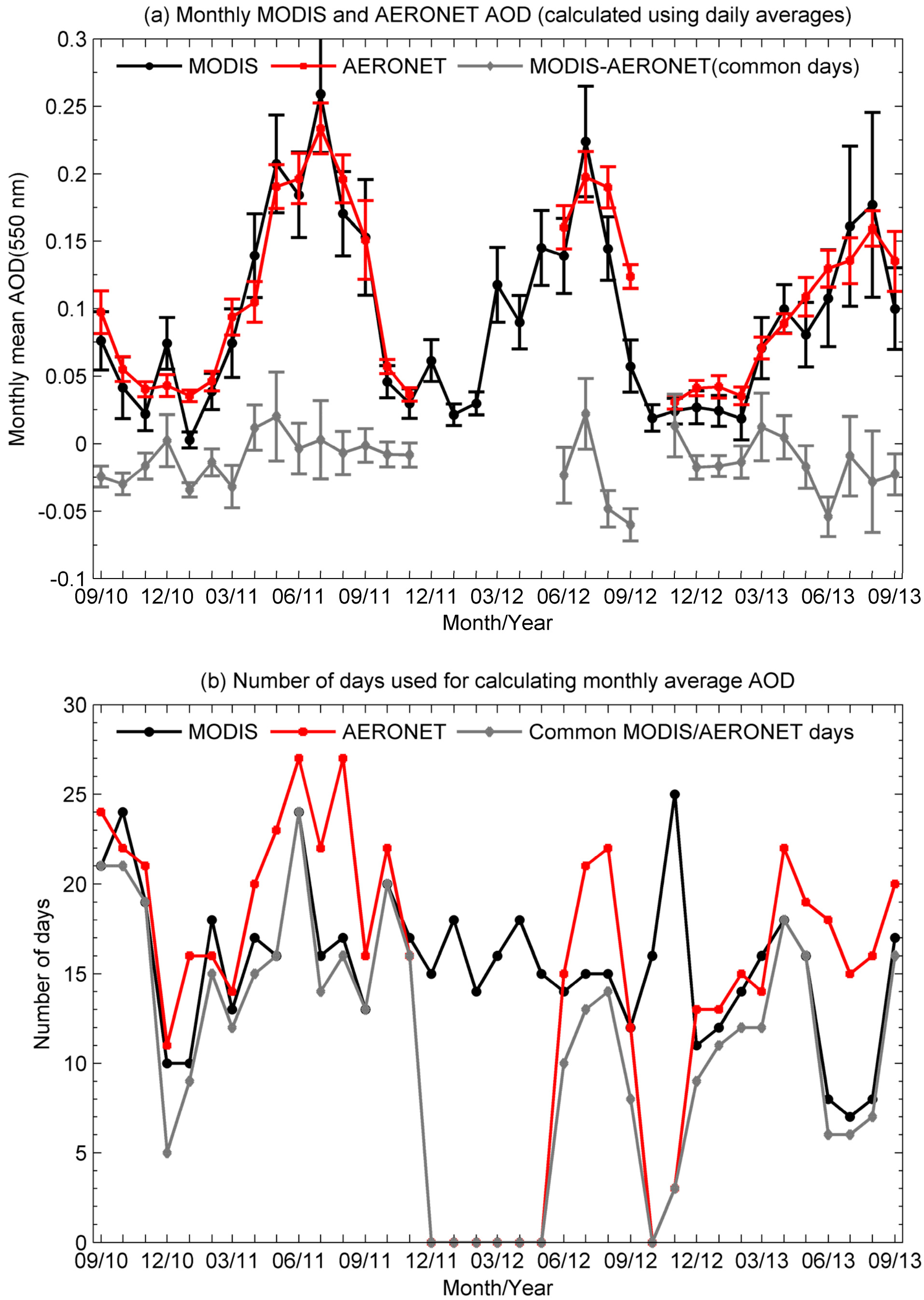

Fig. 7. Time series of (a) monthly-averaged MODIS AOD (combined Aqua and Terra) and AERONET AOD at 550 nm; and (b) number of days each month used to compute monthly-averaged AOD. Monthly averages of MODIS minus AERONET AOD are also plotted in (a), using only days with both MODIS and AERONET AOD measurements. Error bars represent standard error of mean values.

State is largely repeatable (Sherman *et al.*, 2015) and summer surface albedo (dictated primarily by vegetation) also changes little from year to year. .

SUMMARY AND CONCLUSIONS

MODIS (Terra & Aqua) C5 AOD retrievals at the mountainous Appalachian_State AERONET site in Boone, NC are evaluated (Table 1), based on criteria developed during a general global evaluation (Levy *et al.*, 2010). Aerosol chemistry at the Appalachian_State site is representative of background SE US (Link *et al.*, 2015) and the AOD is sufficiently low that effects of MODIS aerosol model and surface albedo assumptions can be tested. The main conclusions of the study are:

1. MODIS/AERONET AOD agreement demonstrates minimal dependence on MODIS QAC value but the agreement differs between Terra and Aqua, especially

for low AOD. When broken down by satellite, Aqua AOD satisfies the validation criteria but Terra AOD does not (Table 1). While both instruments tend to perform equally well under high loading conditions (AOD > 0.15), Terra in particular shows a negative bias in more pristine conditions (AOD < 0.15). A calibration drift or offset (e.g., Levy *et al.*, 2010, 2013) may be the reason for the low bias for Terra data, but more work, including analysis of Collection 6 data, is forthcoming.

2. MODIS/AERONET AOD agreement does not demonstrate a strong seasonal dependence. MODIS underestimates AOD (relative to AERONET) by ~0.02–0.03 for most months, with a slightly larger negative bias during some summer months in 2012 and 2013. Incorrect MODIS C5 assumptions dealing with surface greenness and scene reflectance lead to errors that are consistent with those observed during May–September but are not consistent with the errors during November–April. The SSA value of 0.95 for the weakly-absorbing aerosol type used in the MODIS C5 LUT for southeastern US pixels is higher than the surface-level SSA measured at our NOAA-ESRL site during non-summer months and may also contribute to MODIS AOD underestimation during these months.
3. MODIS possesses sufficient temporal resolution to characterize daily-averaged AOD above the Appalachian_ State AERONET site, as verified by high correlation and excellent agreement between AERONET AOD measured during MODIS overpass hours with daily-averaged AERONET AOD.
4. Monthly-averaged MODIS AOD is able to track that of AERONET to within ~0.02 for nearly all common measurement months of the 3+ year period (Fig. 7(a)). The small differences present in most months are of similar or smaller magnitudes than the MODIS AOD bias (Sect. 4.1). Disagreements can also be expected based on the number of days sampled by MODIS during a given month (as compared to AERONET), resulting from clouds present during the MODIS overpass.

The results of this study have potential implications for aerosol studies and air quality monitoring in the Southern Appalachian Mountain region of the southeastern US. The relative insensitivity of MODIS AOD to QAC indicates that MODIS AOD measurements with lower QAC values (QAC = 1 or 2) may be suitable for quantitative analysis, providing regional air quality agencies with better spatial and temporal coverage. The systematic underestimation of AOD means that MODIS C5 AOD retrievals in the region should be applied with caution, especially for low aerosol loading conditions (Figs. 2 and 7(a)). High correlation of AERONET AOD during MODIS overpass hours with daily-averaged AOD implies that MODIS AOD possesses sufficient temporal resolution to estimate daily-averaged surface air quality in the region. Such studies also implicitly assume that AOD measured during daylight hours by MODIS (or AERONET) is representative of 24-hour averaged values, which is impossible to assess without reliable nighttime measurements. We will expand upon this work in a future study, including evaluation of MODIS C6 and a longer time series.

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