Type of the Paper (Article)

Evaluation of MODIS-Retrieved Aerosol Optical Depth in Alaska: Implications for Surface Air Quality Applications

Alyson McPhetres, Srijan Aggarwal*

Civil & Environmental Engineering, University of Alaska Fairbanks, Fairbanks, AK 99701 USA
*Correspondence: saggarwal@alaska.edu; Tel.: +01-907-474-6120

Received: date; Accepted: date; Published: date

Abstract: The air quality monitoring network in Alaska is currently limited to ground-based observations in urban areas and national parks leaving a large proportion of the state unmonitored. The use of MODIS aerosol optical depth (AOD) to estimate ground-level particulate pollution concentrations has been successfully demonstrated around the world, and could potentially be used in Alaska. In this work, MODIS AOD measurements at 550 nm were validated against AOD derived from AERONET ground-based sunphotometers in Barrow and Bonanza Creek to determine if MODIS AOD from the Terra and Aqua satellites could be used to estimate ground-level particulate pollution concentrations. The MODIS AOD was obtained from MODIS collection 6 using the dark target Land and Ocean algorithms from 2000 to 2014. MODIS data could only be obtained between the months of April and October; therefore, it could only be validated for those months. Individual and combined Terra and Aqua MODIS data were considered. The results showed that MODIS collection 6 products at 10 km resolution for Terra and Aqua combined are not valid over land but are valid over the ocean. On the other hand, the individual Terra and Aqua MODIS collection 6 AOD products at 10 km resolution are valid over land individually but not when combined. Results also suggest the MODIS collection 6 AOD products at 3 km resolution are valid over land and ocean and perform better over land than the 10-km product. These findings indicate that MODIS collection 6 AOD products can be used quantitatively in air quality applications in Alaska during the summer months.

Keywords: AOD; MODIS; Alaska; AERONET; air quality

1. Introduction

Exposure to fine particulate matter (PM) air pollution adversely affects cardiopulmonary health and is associated with increased morbidity and premature mortality [1]. Fine particulate pollution consists of particulates smaller than 2.5 µm (PM2.5) in aerodynamic diameter. A risk analysis of the public health impacts of exposure to ambient PM2.5 estimated that 130000 PM2.5-related deaths in the continental United States would result from the PM2.5 concentration levels in 2005 [2]. Alaska is not immune to the effects of PM pollution. Between the years of 2003 and 2008 in Fairbanks, AK, each 10 µg/m^3 increase in the mean 24-hour PM2.5 was associated with a 6% to 7% increase in the risk for a cerebrovascular disease-coded and respiratory tract-coded hospital visits the following day. Air quality monitoring is essential for monitoring exposure, determining sources of pollutants, and providing air quality alerts to the public [3].

The air quality monitoring (AQM) network in Alaska is currently limited to urban areas (Fairbanks, Palmer, Anchorage, Juneau) and national parks. Moderate Resolution Imaging Spectroradiometer (MODIS) derived aerosol optical depth (AOD) has been used successfully around the world to estimate ground-level PM air pollution [4–6], and it could potentially be used to estimate ground-level particulate

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 May 2018 doi:10.20944/preprints201805.0123.v1

pollution in Alaska and thus enhance the spatial coverage to fill the gaps beyond what is covered by the state's AQM network.

MODIS currently acquires data across 36 spectral bands, and it has been onboard the Terra and Aqua satellites since 1999 and 2002, respectively. The MODIS Collection 6 (C6) aerosol algorithm consists of three separate algorithms that are used to retrieve AOD from MODIS-observed spectral reflectance: the dark target (DT) ocean algorithm, the DT land algorithm, and the Deep Blue (DB) algorithm (Levy et al. 2013, Hsu et al., 2012or13). The DT ocean algorithm retrieves AOD over the ocean seven wavelengths. The DT land algorithm retrieves AOD over vegetated and dark-soiled land in three visible wavelengths. The deep blue algorithm retrieves AOD over the desert and arid land and more recently has been expanded to all surface type around the globe (Hsu et al. 2013). AOD over land can be derived at wavelengths of 470, 550, and 660 nm. AOD over the ocean can be derived at wavelengths of 470, 550, 660, 870, 1200, and 2100 nm. Both of the DT algorithm products are available at 10 km and 3 km resolution.

MODIS collection 6 AOD has been validated at 550 nm globally for Aqua at 10 km resolution, but not specifically for Alaska or Terra at 3 km resolution [7], [8]. Therefore, to determine whether MODIS AOD can be used to estimate ground-level particulate pollution in Alaska, the 10 km and 3 km resolution products must first be validated against ground-based sunphotometers to determine if there is a strong relationship between ground and satellite measurements in Alaska. Thus, the overarching goal of this study is to determine if MODIS measurements of aerosol optical depth are reflecting actual conditions based on ground-based measurements of aerosol optical depth. If at least 67% of the collocated ground-based and satellite-based measurements are highly correlated and within the estimated uncertainty determined from global validation studies (Table 1) [7], then it is indicative that MODIS AOD can be used to model particulate pollution in Alaska. If the relationship is weak to non-existent, MODIS AOD cannot be used to model particulate pollution and other satellite-based measurements should be considered.

Table 1. Estimated error for MODIS collection 6 dark target algorithm [7].

Resolution	10 km		3km	
Satellite	AQUA	TERRA	AQUA	TERRA
Land	$\pm(0.05+0.15\tau_A)$	$\pm(0.05+0.15\ \tau_A)$	$\pm(0.05+0.2\tau_A)$	NA
Ocean	$-0.02-0.1\ \tau_A$ / $+0.04+0.1\ \tau_A$	NA	$\pm(0.04+0.05\tau\ \tau_A)$	NA

2. Validation Methods

AERONET AOD (τ_A)

The Aerosol Robotic Network (AERONET) (http://aeronet.gsfc.nasa.gov) is a ground-based global network of sunphotometers that measure aerosol properties using measurements of solar direct and diffuse radiances [9]. Measurements are obtained and recorded by AERONET sunphotometers approximately at the frequency of every 15 minutes. AOD is determined from direct measurements of solar radiance using the Beer-Lambert-Bouguer equation [10]. Due to the low level of uncertainty of AERONET AOD measurements (0.01 to 0.02), AERONET data is commonly used for the validation of satellite-derived MODIS AOD products [10–14].

The Alaska AERONET sites of Bonanza Creek and Barrow were used for the validation of the MODIS AOD product over Alaska. Table 2 lists the locations of the Bonanza Creek and Barrow sites. The sunphotometers in Barrow and Bonanza Creek measure direct solar radiance. The AERONET measurements are then used to determine AOD at the following wavelengths: 340, 380, 440, 500, 675, 870, 1020 nm. The AERONET level 2.0 version 2.0 (cloud-screened and quality-assured) dataset was used to

 doi:10.20944/preprints201805.0123.v1

interpolate the AOD at 550 nm in the Multi-sensor Aerosol Products Sampling System (MAPSS) using the quadratic fit on the log-log scale [9]. MAPSS is a framework that collects samples and generates the spatial statistics of various satellites (e.g. MODIS) over AERONET sites and other locations of interest and integrates them with ground-based measurements to facilitate validation [9]. The interpolated AOD at 550 nm, available in MAPSS between the years 2000 and 2014, were used in this study.

Table 2. Locations of AERONET stations.

Station	Location	Latitude (North)	Longitude (West)	Elevation (m)	Dates Operational
Barrow	Barrow, AK	71.31220°	156.66500°	0.0	30 July, 1994-present
Bonanza Creek	Bonanza Creek, AK	64.74281°	148.31627°	150.0	31 May, 1994-present

MODIS AOD (τ_A)

The MODIS C6 DT algorithms for land and ocean were used to derive AOD with 10 km and 3 km spatial resolutions at nadir from MODIS measurements at a wavelength of 550 nm at both the Bonanza Creek and Barrow AERONET sites [7], [9]. The MODIS dark target land algorithm was used to determine AOD over the Bonanza Creek site, and the MODIS dark target ocean algorithm was used to determine AOD over the Barrow site as little to no data existed over land for the Barrow site. Terra AOD with mode quality assurance (QA) values of 3 (highest quality) within the collocation area and Aqua AOD with QA values of 3 were used for the validation of the DT land algorithm-derived MODIS AOD. Terra AOD with mode QA values greater than 0 within the collocation area and for Aqua AOD with QA values greater than 0 were used for the validation of the DT ocean algorithm-derived MODIS AOD. Previous validation studies have also used MODIS AOD with QA of 3 over land and QA greater than 0 over the ocean [7], [11], [12]. AOD data was obtained from Terra between the years 2000 and 2014 and from Aqua between the years 2002 and 2014. Table 2 lists the error envelope (EE) for each satellite and the dark target land and ocean algorithms derived from global validation studies for collection 6 [7], [15]. The EE was added to or subtracted from the AERONET AOD (τ_A).

Collocation

Spatially and temporally collocated MODIS and AERONET AOD measurements were obtained from the MAPSS. In MAPSS, AERONET AOD measurements taken within 30 minutes before or after the satellite overpass time were considered temporally collocated with the MODIS measurements. This was consistent with previously described methods of temporal collocation [9–11]. MODIS pixels in MAPSS were sampled if the distance between the AERONET site and the MODIS pixels did not exceed 27.5 km [9]. Terra AOD was used only if the mode QA of the collocated product was 3, and Aqua AOD was used only for products with QA of 3. In MAPPS, the QA of 3 could only be specified for Aqua and not Terra at the time of the analysis, thus Terra AOD was selected based on a mode of QA 3. The minimum number of collocated AERONET and MODIS pixels were set as one to increase the number of samples as described in the validation study by Sherman et al. [10].

Analysis

The validation study was performed using spatially and temporally collocated AOD from AERONET and MODIS (Terra and Aqua) obtained from MAPSS. AERONET and MODIS AOD were plotted against each other with MODIS AOD on the y-axis and AERONET AOD on the x-axis. Linear regressions (MODIS_AOD=AERONET_AOD*m + b) were calculated using ordinary least squares (OLS) for all AOD, for AERONET AOD less than 0.15, and for AERONET AOD greater than 0.15. Previous studies found that

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 May 2018 doi:10.20944/preprints201805.0123.v1

ordinary least squares could be used to calculate statistically significant coefficients but could not be used to calculate standard errors when the residuals were heteroscedastic; therefore heteroscedasticity consistent errors were used to avoid incorrect interpretation of the data when heteroscedasticity (non-constant variance of errors) was present [16]. The residuals were tested for heteroscedasticity (non-constant variance) using White's test for heteroscedasticity. If the residuals were heteroscedastic, standard errors, significance tests, and confidence intervals were corrected using a heteroscedasticity consistent covariance matrix (HCCM) referred to as type 3 heteroscedasticity consistent (HC3) at a significance level of 0.05 [16]. If the residuals were not heteroscedastic, the standard errors calculated using OLS regression were used in the analysis.

The error envelopes (EE) for the Terra 10 km land, 3 km land, and 3 km ocean products were assumed to be equal to those found for Aqua [7], [15]. Root mean square error (RMSE) was calculated using equation 1, where τ_M is the MODIS AOD, τ_A is the AERONET AOD, and N was the number of collocations.

$$\mathrm{RMSE} = \sqrt{\frac{\sum(\tau_M-\tau_A)^2}{N}} \quad (1)$$

The median and mean bias were also calculated based on the difference between MODIS AOD and the AERONET AOD. The fraction of data within EE was also calculated as done in similar studies [10], [12]. The data was considered valid based on the following three criteria.

Criterion 1: the slopes of the linear regressions of MODIS AOD versus AERONET AOD less than 0.15 and AERONET AOD greater than 0.15 cannot be statistically different

Criterion 2: MODIS AOD and AERONET AOD (all and greater than 0.15) must be highly correlated (Pearson correlation coefficient greater than 0.7). MODIS AOD and AERONET AOD less than 0.15 must be moderately correlated (Pearson correlation coefficient between 0.5 and 0.7)

Criterion 3: At least 67% of the MODIS AOD versus AERONET AOD datasets must lie within the EE

3. Results and Discussion

3.1. Bonanza Creek

MODIS AOD cannot be obtained in the presence of snow or clouds due to the high reflectivity of snow and clouds. Due to the presence of snow in Alaska during winter months, MODIS AOD data could only be obtained between the months of April and October; therefore, the validation is only effective for the end of April through early October. Table 3 lists the slopes of the linear regressions of MODIS AOD versus AERONET AOD at the Bonanza Creek site at 10 km and 3 km resolutions. The errors were heteroscedastic based on White's test for heteroscedasticity, therefore HC3 was used to calculate the standard errors used in the t-tests. Chu et al. (2002) established that the departure of the slope from unity was representative of systematic bias and that the y-intercept represented the error in the estimate of the surface reflectance [12]. The systematic errors could be due to aerosol model assumptions, instrument calibration, or measurement selection [12]. While the slopes of the linear regressions for the 10 km datasets were lower than those of the 3 km datasets, the slopes of the regressions for the 10-km data were more variable than those of the 3-km data. For example, the slopes of the linear regressions of the 10 km Terra, Aqua, and combined Aqua and Terra datasets ranged from 1.40 to 1.49, while those of the 3 km resolution MODIS AOD data sets ranged from 1.41 to 1.42 (Figure 1). Also, in Figure 1, the 3 km (Figure 1d, 1e, 1f) data appeared to have more noise than the 10-km data (Figure 1a, 1b, 1c), which was presumably due to the higher resolution of the 3-km data.

3.1.1. Criterion 1: Linear Regression

As listed in Table 3, all of the 3 km resolution MODIS AOD data satisfied criterion 1. The slopes of the stratified combined Aqua and Terra MODIS AOD at 10 km resolution were significantly different ($p<0.05$;

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 May 2018 doi:10.20944/preprints201805.0123.v1

t-test), which indicated that combined Aqua and Terra AOD at 10 km resolution should not be used over Alaska. Similarly, the p-value for the stratified individual Terra MODIS AOD at 10 km resolution was relatively low at 0.06, indicating difference. For stratified individual Aqua MODIS AOD at 10 km resolution, slopes were not significantly different (p=0.35). Based on these, individual Aqua MODIS AOD at 10 km resolution could be used. For the all the 3-km data stratified by AERONET AOD (Terra and Aqua combined or individual), slopes were not significantly different (p>0.8; Table 3) indicating that the 3 km datasets could be used in Alaska. Overall, the 3-km dataset appeared to perform better than the 10-km dataset because the difference in slope when the data was stratified by AERONET AOD was not significant. The lower difference between slopes in the 3 km datasets could be due to the higher spatial resolution of the data and the resulting increase in number of retrievals. Combined Terra and Aqua MODIS AOD can be used to estimate ground-level air quality at a resolution of 3 km.

Table 3. Results of linear regression ($\tau_M = \tau_A * m + b$) and t-tests at a significance level of 0.05 for the Bonanza Creek AERONET sit

Satellite	AERONET AOD	Slope	Standard Error	P-value	Are the slopes significantly different?
10 km Resolution					
Terra & Aqua	<0.15	1.29	0.03	0.03	Yes
	≥0.15	1.48	0.08		
Terra	<0.15	1.32	0.04	0.06	No
	≥0.15	1.53	0.10		
Aqua	<0.15	1.31	0.05	0.35	No
	≥0.15	1.41	0.10		
3 km Resolution					
Terra & Aqua	<0.15	1.38	0.04	0.84	No
	≥0.15	1.40	0.08		
Terra	<0.15	1.38	0.05	0.87	No
	≥0.15	1.40	0.12		
Aqua	<0.15	1.43	0.06	0.83	No
	≥0.15	1.40	0.10		

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 May 2018 doi:10.20944/preprints201805.0123.v1

3.1.2. Criterion 2: Correlation

Overall, the full MODIS and AERONET AOD datasets were highly correlated with Pearson correlation coefficients (Figure 2) and thereby satisfied criterion 2. In Figure 1, the MODIS AOD and AERONET AOD do appear to be highly correlated, which is consistent with the calculated correlations shown in Figure 2. The Pearson correlation coefficients at 10 km resolution ranged from 0.95 to 0.97 for all AERONET AOD and AERONET AOD greater than or equal to 0.15, indicating high correlation. The Pearson correlation coefficient at 10 km resolution for AERONET AOD less than 0.15 ranged from 0.71 to 0.76 (highly correlated). The 10 km data satisfied criterion 2. The Pearson correlation coefficients of the 3 km data for all AERONET AOD and AERONET AOD greater than or equal to 0.15 ranged from 0.89 to 0.93 (highly correlated). The Pearson correlation coefficients of AERONET AOD less than 0.15 at 3 km resolution ranged from 0.64 to 0.66 (moderately correlated). The lower correlation coefficients for AERONET AOD less than 0.15 were most likely due to the higher density of data below an AOD of 0.15.

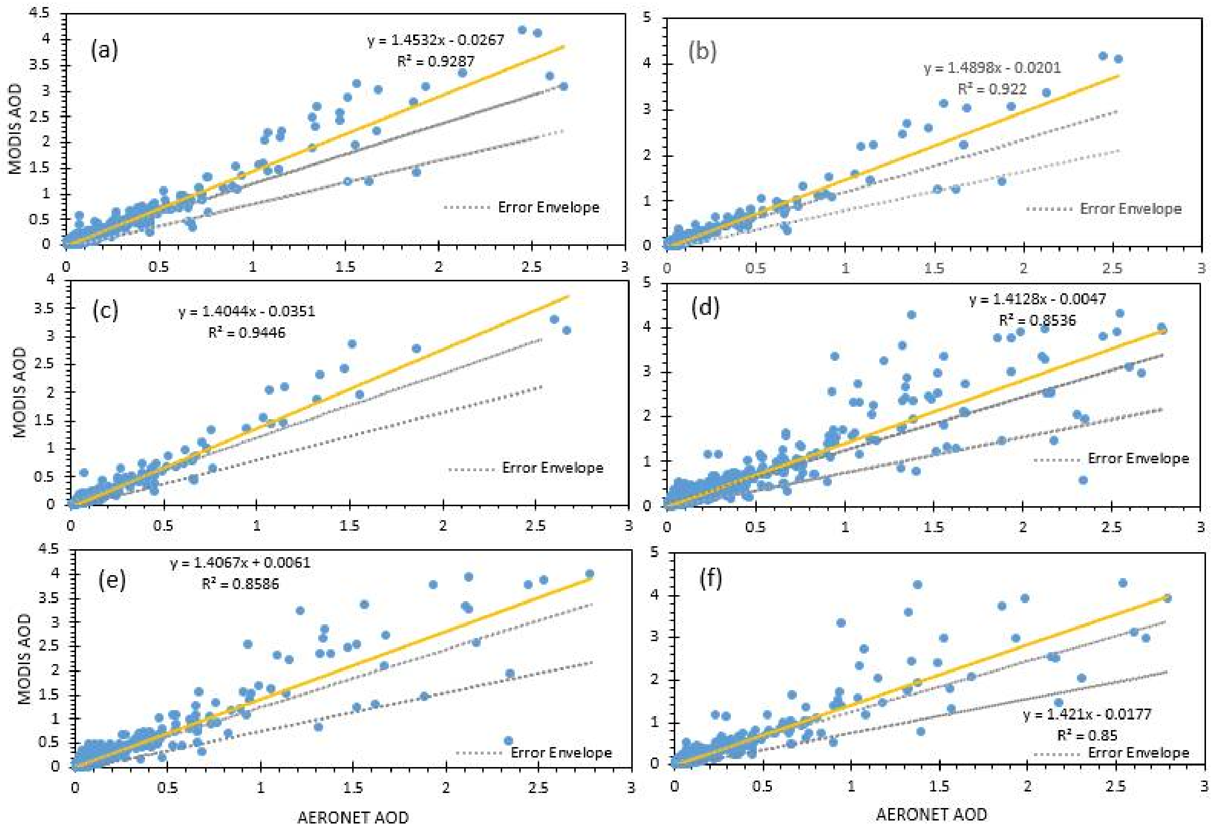

Figure 1. MODIS AOD versus AERONET AOD at the Bonanza Creek AERONET site with linear regression as solid yellow line and the dashed gray line as the error envelope where the following figures are for (a) Terra and Aqua 10 km combined, (b) Terra 10 km, (c) Aqua 10 km, (d) Terra and Aqua 3 km combined, (e) Terra 3 km, (f) Aqua 3 km.

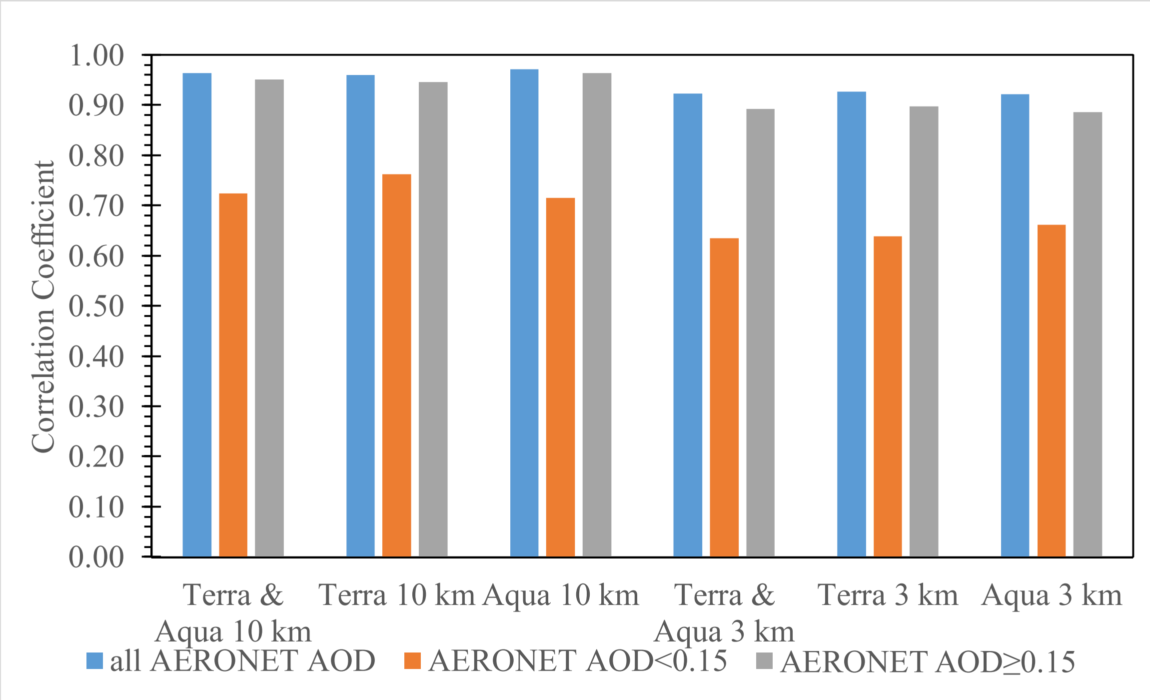

Figure 2. A comparison of the correlation coefficients for MODIS AOD versus AERONET AOD over the Bonanza Creek AERONET site. Criterion 2 was satisfied if the correlation coefficient was greater than 0.5 for AERONET AOD less than 0.15 and greater than 0.7 for all AERONET AOD and AERONET AOD greater than 0.15.

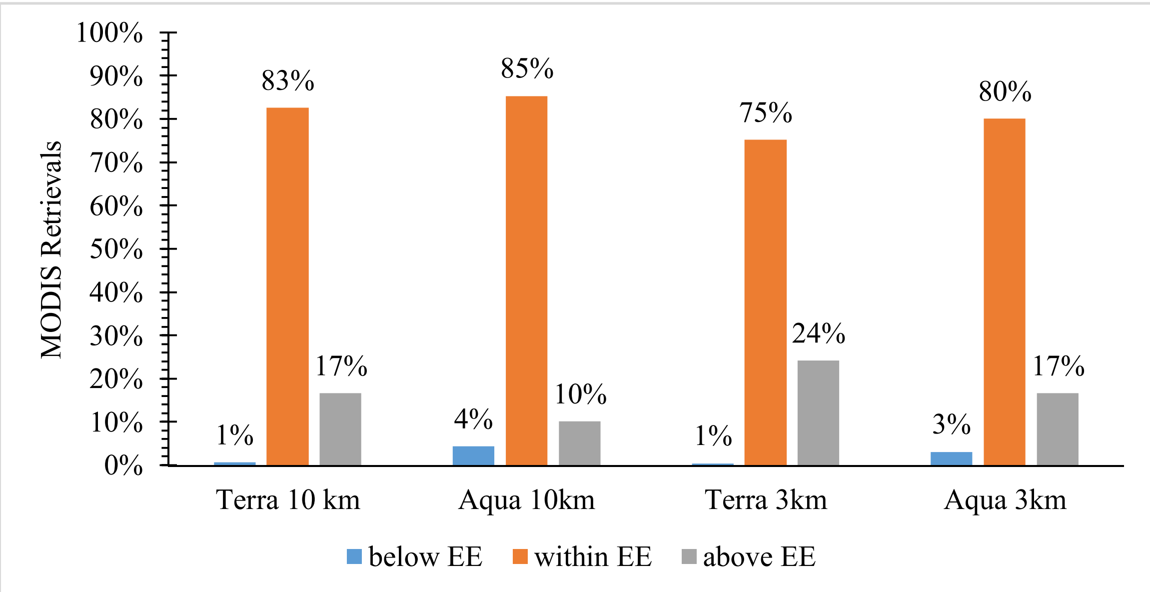

Figure 3. A comparison of the percentage of MODIS land retrievals over the Bonanza Creek AERONET site from Aqua and Terra with 3 km and 10 km resolutions below, within, and above the error envelope (EE). The MODIS Collection 6 error envelopes for land are listed in Table 1. Criterion 3 for validation is satisfied if 67% of MODIS retrievals are within the error envelope.

3.1.3 Criterion 3: Error Envelope (EE)

More than 67% of the data from both AQUA and TERRA were within the error envelope (Figure 3). The total percentage of the 10-km resolution and 3-km resolution combined Aqua and Terra data within the EE were 83.3 % and 78.7%, respectively. The amount of data within the EE satisfied the validation requirements for fraction of data within the EE used in various validation studies [10], [11].

3.1.4 Error and Bias

The Aqua and Terra MODIS AOD datasets appeared to have negative bias (y-intercept) at both the 10 km (-0.035 to -0.020) and 3 km resolutions (-0.018 to 0.006). The negative bias, indicated by the y-intercept, of MODIS AOD is consistent with the findings of Sherman et al. and Levy et al. ([7], [10]. Also, the RMSE of the Bonanza Creek 10 km data was slightly lower than that of the 3-km data. The difference in RMSE was most likely due to the higher number of retrievals over land at 3 km resolution. A validation study over Asia found that Aqua 3 km data was less reliable than the 10 km data as only 55% of retrievals were within the estimated error [15]; however, global studies show that MODIS AOD performance varies by region and terrain [7]. Due to the high correlation between MODIS AOD and AERONET AOD, the high proportion of data points within the EE, and the consistency of the results of the linear regression, the MODIS AOD 10 km and 3 km resolution data can be used in Alaska when using the dark target land and ocean algorithm in Alaska. Based on the overall performance of the 10 km and 3 km resolution data, it is recommended that only the Aqua 10 km data be used of all of the 10 km datasets. All of the 3 km MODIS AOD data are valid for use in Alaska between the months of April and October.

Overall, the following collection 6 Dark Target land products were determined to be valid: 10 km Aqua MODIS AOD, 3 km combined Aqua and Terra MODIS AOD, 3 km Aqua MODIS AOD, and 3 km Terra MODIS AOD. The 10 km Terra MODIS AOD could also be used at the discretion of the researcher as at a significance value of 0.05, the slopes were considered to not be significantly different with a p-value of 0.06. Potential sources of error include the incorrect identification of clouds in the masking process of the dark target land algorithm. Another source of error could be the incorrect assumption of the surface brightness by the dark target algorithm [7]. Another potential source of error could be the use of the mode quality assurance value, which should be to individual QA values when available; however, the error between MODIS Aqua AOD with QA 3 and mode QA 3 when collocated with the Bonanza Creek site was approximately 0.

3.2. Barrow

MODIS AOD was derived for Barrow over the ocean using the Dark Target Ocean Algorithm. As with the Bonanza Creek site, data was only available between the months of April and October; therefore, this validation study only applies between those months. Table 4 lists the results of the linear regression analysis of the relationship between MODIS AOD and AERONET AOD. White's test for heteroscedasticity revealed that the errors were heteroscedastic, therefore HC3 was used to calculate the heteroscedasticity robust standard errors.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 May 2018 doi:10.20944/preprints201805.0123.v1

Table 4. Results of linear regression ($\tau_M = \tau_A * m + b$) and t-tests at a significance level of 0.05 for the Barrow AERONET site.

Satellite	AERONET AOD	Slope	Standard Error	P-value	Are the slopes significantly different?
10 km Resolution					
Terra & Aqua	<0.15	0.97	0.06	0.08	No
	≥0.15	1.10	0.05		
Terra	<0.15	0.86	0.12	0.53	No
	≥0.15	0.97	0.05		
Aqua	<0.15	1.09	0.07	0.18	No
	≥0.15	0.93	0.24		
3 km Resolution					
Terra & Aqua	<0.15	1.01	0.03	0.16	No
	≥0.15	1.06	0.05		
Terra	<0.15	0.96	0.05	0.77	No
	≥0.15	1.02	0.03		
Aqua	<0.15	1.01	0.07	0.16	No
	≥0.15	0.98	0.04		

3.2.1. Criterion 1: Linear Regression

All of the AOD data for the Barrow AERONET site satisfied the criterion that the slopes of the linear regressions of MODIS AOD versus AERONET AOD greater than or equal to 0.15 and AERONET AOD less than 0.15 could not be significantly different. The slopes of the least squares regressions of the 10-km resolution MODIS AOD datasets versus AERONET AOD ranged from 0.96 to 0.97 (Table 4, Figure 2a, 2b, 2c), indicating low systematic bias (slopes of 1 would indicate no systematic bias). The slopes from the least squares regression of the 3-km MODIS AOD data versus AERONET AOD ranged from 1.00 to 1.02 for the full datasets (Table 4, Figure 2d, 2e, 2f). The greatest difference between slopes of the 10-km and 3-km data stratified by AERONET AOD were 0.24 (combined Aqua and Terra) and 0.28 (Aqua), respectively (Table 4). Based on t-tests with a significance level of 0.05, the slopes of the all of the 10-km and 3-km data stratified by AERONET AOD were not significantly different ($p>0.08$; Table 4). The proximity of the slopes to one indicated low systematic bias [17]. The MODIS AOD datasets at 10 km and 3 km were positively biased with values ranging from 0.030 to 0.032 and 0.031 to 0.035, respectively, for the full datasets based on the y-intercepts of the linear regressions [17].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 May 2018 doi:10.20944/preprints201805.0123.v1

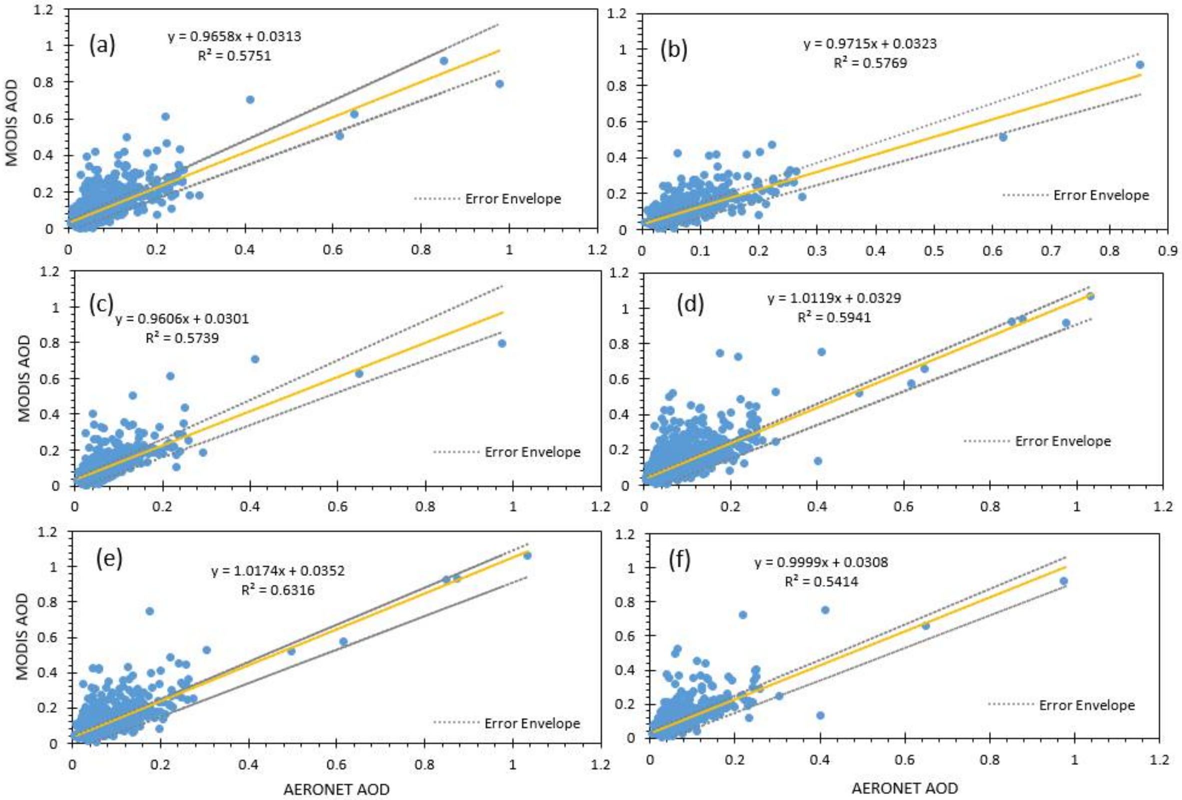

Figure 4. MODIS AOD versus AERONET AOD at the Barrow AERONET site with linear regression as solid yellow line and the dashed gray line as the error envelope where the following figures are for (a) Terra and Aqua 10 km combined, (b) Terra 10 km, (c) Aqua 10 km, (d) Terra and Aqua 3 km combined, (e) Terra 3 km, (f) Aqua 3km.

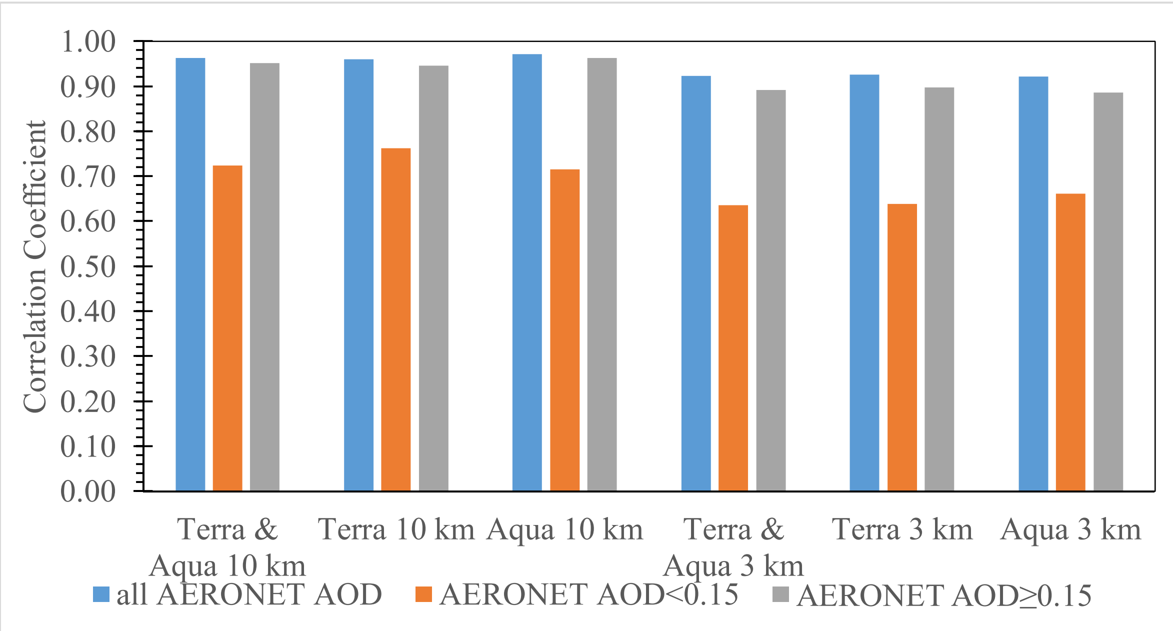

Figure 5. A comparison of the correlation coefficients for MODIS AOD versus AERONET AOD over the Barrow AERONET site. Criterion 2 was satisfied if the correlation coefficient was greater than 0.5 for AERONET AOD less than 0.15 and greater than 0.7 for all AERONET AOD and AERONET AOD greater than 0.15.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 May 2018 doi:10.20944/preprints201805.0123.v1

3.2.2. Criterion 2: Correlation

Another requirement for validation is that MODIS AOD and AERONET AOD are highly correlated [10]. For the Barrow site, MODIS AOD and AERONET AOD appeared to be moderately to highly correlated with most points having AERONET AOD less than 0.2 (Figure 2). The correlation coefficients for the full MODIS AOD datasets were greater than 0.7, indicating that MODIS AOD and AERONET AOD were strongly. For AERONET AOD less than 0.15, MODIS AOD and AERONET AOD were moderately correlated with correlation coefficients ranging from 0.51 to 0.58 (Figure 5). For AERONET AOD greater than or equal to 0.15, correlation coefficients greater than 0.75 indicated a strong correlation between MODIS AOD and AERONET AOD (Figure 5). The large difference in Pearson correlation coefficients indicates that the strength of correlation is impacted by the few larger values. Therefore, the correlation requirement for validation should be adjusted to the following: MODIS AOD and AERONET AOD must be moderately to strongly correlated for AERONET AOD less than 0.15, and they must be strongly correlated for all of AERONET AOD and AERONET AOD greater than or equal to 0.15. A moderate to strong relationship was evident in the correlation coefficients and Figure 4, therefore the recommended requirement and previous requirement of correlation to determine validity were satisfied.

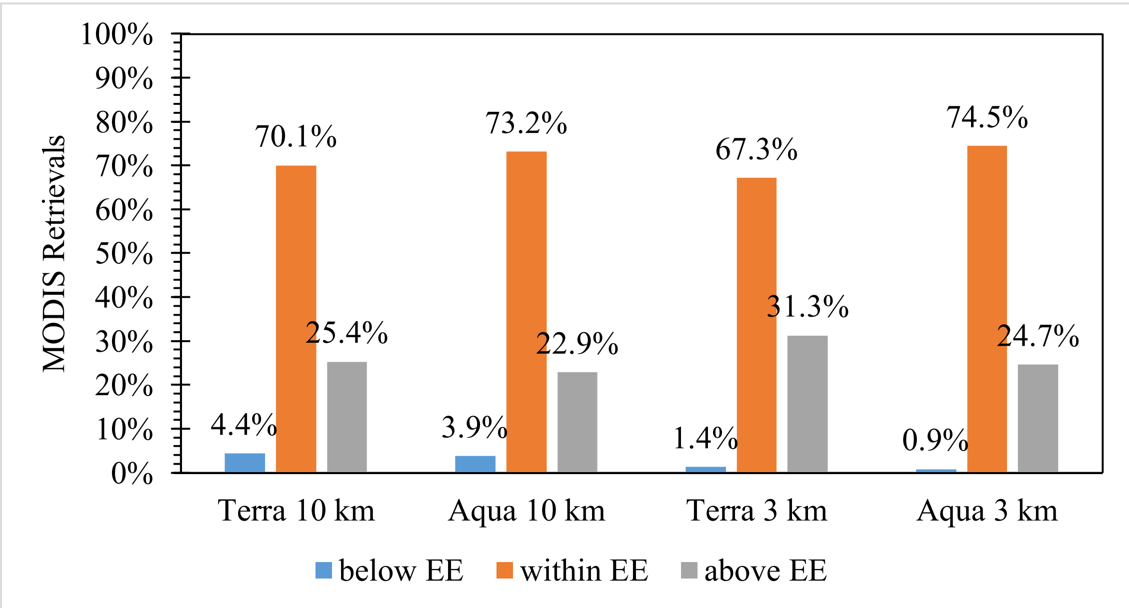

Figure 6. A comparison of the percentage of MODIS land retrievals over the Barrow AERONET site from Aqua and Terra with 3 km and 10 km resolutions below, within, and above the error envelope (EE). The MODIS Collection 6 error envelopes for land are listed in Table 1. Criterion 3 for validation was satisfied if 67% of MODIS retrievals were within the error envelope.

3.2.3 Criterion 3: Error Envelope (EE)

The final requirement for validity is that more than 67% of the collocated data be within the error envelope (Figure 6). The error envelope for Terra was assumed to be equal to that of Aqua, which was expected to be the same [7]. The lowest percentage within the error envelope was 67.3 % for Terra MODIS AOD at 3 km resolution, and the greatest percentage was 74.5% for Aqua MODIS AOD at 3 km resolution (Figure 6). When stratified by AERONET AOD, a larger percentage of the collocated data was within the error envelope for AEROENT AOD less than 0.15 (67.8-74.9%) than that for AERONET AOD greater than or equal to 0.15 (58.7-67.3%) (Figure 6). As the requirement of a minimum of 67% was for the full dataset, the requirement was satisfied.

3.2.4 Error and Bias

Overall, all of the MODIS AOD collection 6 Dark Target Ocean products satisfied the requirements for validity and are thus considered valid for use in Alaska between the months of April and October over the ocean. Based on the linear regression over the Barrow and Bonanza Creek sites, the Barrow data appeared to have less systematic bias than the Bonanza Creek site (Tables 3, 4). Also, RMSE for the Barrow site was lower than that of the AERONET site, which is consistent with the slope that was closer to unity. Potential sources of error could include incorrect assumptions in the Dark Target algorithm, such as incorrect identification of clouds or surface brightness [7]. Another potential source of error could be the use of the mode quality assurance value, which should be to individual QA values when available; however, the error between MODIS Aqua AOD with QA 1, 2, 3 and mode QA 1, 2, 3 when collocated with the Bonanza Creek site was approximately 0. Future analysis could use weighted least squares regression and compare the results to the findings in this study. The use of weighted least squares may result in a different estimation of bias and systematic error based on the regression, but that would not impact the determination of validity.

4. Conclusions

The Aqua MODIS AOD 10 km and all of the 3 km MODIS AOD products are valid between the months of April and October in Alaska. All of the collection 6 dark target ocean MODIS AOD products are valid over the ocean in Alaska. The successful validation of the MODIS AOD at Bonanza Creek and Barrow indicates that the collection 6 dark target MODIS AOD may be used to estimate ground-level air quality in Alaska [4], [10]. Further research in Alaska should be done to model the relationship between summertime particulate pollution and MODIS AOD. Care should be taken when modeling the relationship between particulate pollution and MODIS AOD in Alaska because the validity of MODIS AOD has been proven to vary by region [7], [10]. Therefore, a clear relationship between MODIS AOD and particulate pollution should be evident prior to use outside of the regions of the AERONET sites in Alaska and models should undergo significant testing and evaluation for robustness. Other validation studies could be done using other satellite platforms to determine which platform will work best in Alaska. Finally, if modeling of the relationship between particulate pollution and MODIS AOD is successful, MODIS AOD could be used to monitor air quality in the areas of Alaska that do not have ground-level air quality monitors, such as much of rural Alaska.

Author Contributions: The research was conceptualized, and written by AM and SA. The study design, and data analyses were undertaken by AM under the supervision of SA. Additionally, SA provided project oversight, supervision and funding resources. **Funding:** This material is based in part upon work supported by the Alaska NASA EPSCoR Program (NNX13AB28A).

Acknowledgments: Authors would like to acknowledge assistance from Pawan Gupta at NASA Goddard Centre and resources from department of Civil and Environmental Engineering at University of Alaska Fairbanks.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

[1] C. A. Pope and D. W. Dockery, Health Effects of Fine Particulate Air Pollution: Lines that Connect, Journal of the Air & Waste Management Association **56**(6) (2006): 709–742, doi:10.1080/10473289.2006.10464485.

[2] N. Fann, et al., Estimating the National Public Health Burden Associated with Exposure to Ambient PM2.5 and Ozone, Risk Analysis **32**(1) (2012): 81–95, doi:10.1111/j.1539-6924.2011.01630.x.

[3] D. Ware, et al., Sources and perceptions of indoor and ambient air pollution in rural Alaska, Journal of Community Health **38**(4) (2013): 773–780, doi:10.1007/s10900-013-9678-9.

[4] P. Gupta, et al., Multi year satellite remote sensing of particulate matter air quality over Sydney, Australia, International Journal of Remote Sensing **28**(November 2014) (2007): 4483–4498, doi:10.1080/01431160701241738.

[5] S. Dey and L. Di Girolamo, A decade of change in aerosol properties over the Indian subcontinent, Geophysical Research Letters **38**(14) (2011): 1–5, doi:10.1029/2011GL048153.

[6] Y. Xie, et al., Daily Estimation of Ground-Level PM2.5 Concentrations over Beijing Using 3 km Resolution MODIS AOD, Environmental Science and Technology **49**(20) (2015): 12280–12288, doi:10.1021/acs.est.5b01413.

[7] R. C. Levy, et al., The Collection 6 MODIS aerosol products over land and ocean, Atmospheric Measurement Techniques **6** (2013): 2989–3034, doi:10.5194/amt-6-2989-2013.

[8] A. M. Sayer, et al., Validation and uncertainty estimates for MODIS Collection 6 "deep Blue" aerosol data, Journal of Geophysical Research Atmospheres **118**(14) (2013): 7864–7872, doi:10.1002/jgrd.50600.

[9] M. Petrenko, C. Ichoku, and G. Leptoukh, Multi-sensor Aerosol Products Sampling System (MAPSS), Atmos. Meas. Tech **5** (2012): 913–926, doi:10.5194/amt-5-913-2012.

[10] J. P. Sherman, et al., An Evaluation of MODIS-Retrieved Aerosol Optical Depth over a Mountainous AERONET Site in the Southeastern US, Aerosol and Air Quality Research **16** (2016): 3243–3255, doi:10.4209/aaqr.2015.09.0568.

[11] C. Ichoku, et al., A spatio-temporal approach for global validation and analysis of MODIS aerosol products, Geophysical Research Letters **29**(12) (2002): 1–4, doi:10.1029/2001GL013206.

[12] L. A. Remer, Validation of MODIS aerosol retrieval over ocean, Geophysical Research Letters **29**(12) (2002): 2–5, doi:10.1029/2001GL013204.

[13] T. F. Eck, et al., Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols, Journal of Geophysical Research **104**(D24) (1999): 31333–31349, doi:10.1029/1999JD900923.

[14] B. N. Holben, et al., AERONET - A federated instrument network and data archive for aerosol characterization, Remote Sensing of Environment **66**(1) (1998): 1–16, doi:10.1016/S0034-4257(98)00031-5.

[15] J. E. Nichol and M. Bilal, Validation of MODIS 3 km resolution aerosol optical depth retrievals over Asia, Remote Sensing **8**(4) (2016), doi:10.3390/rs8040328.

[16] J. S. Long and L. H. Ervin, Using heteroscedasticity consistent standard errors in the linear

 doi:10.20944/preprints201805.0123.v1

regression model, The American Statistician **54**(May) (2000): 217–224, doi:10.2307/2685594.

[17] D. A. Chu, et al., Validation of MODIS aerosol optical depth retrieval over land, Geophysical Research Letters **29**(12) (2002): MOD2-1-MOD2-4, doi:10.1029/2001GL013205.