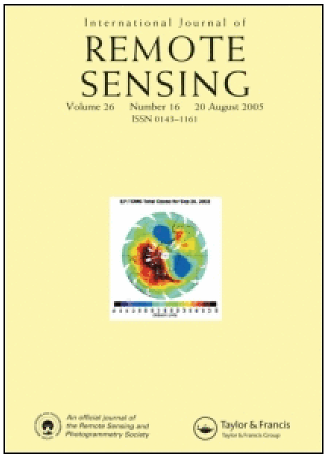

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Validating a new algorithm for estimating aerosol optical depths over land from MODIS imagery

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Aerosols greatly affect the signals of satellite sensor imagery for remote sensing of land surfaces and play a dual role in global climate change and the hydrological cycle. However, there has not been a reliable method for estimating aerosol properties over land directly from multispectral remotely sensed imagery. In a recent study, a new algorithm to estimate aerosol optical depths (AODs) from Moderate-Resolution Imaging Spectroradiometer (MODIS) imagery suitable for all land surfaces was proposed. It is based on a sequence of imagery over a period of time with the assumption that the surface property is relatively stable and atmospheric conditions vary much more dramatically. Although this algorithm was validated over several sites, more validation was necessary. In this study, this algorithm was validated using 3-month measurements at 25 AErosol RObotic NETwork (AERONET) sites in North America. The validation results show that this algorithm can estimate AODs with close agreement with the AERONET measurements [R^2=0.69, root mean square error (RMSE) 0.06].

1. Introduction

Aerosols have an important effect on the Earth's radiation budget, both directly by absorbing and scattering radiation and indirectly by altering the formation and precipitation efficiency of clouds. Radiative forcing of climate by aerosols is thought to be similar in magnitude, but of opposite sign, to that of greenhouse gases. However, the interactions between aerosols and climate represent a large source of uncertainty in climate forcing (IPCC 2001) because of variability in the physical and chemical properties of aerosols and the complexity of aerosol–climate interactions. Characterizing global aerosol distribution presents a major challenge today (King *et al.* 1999, Kaufman *et al.* 2002).

Aerosol properties, particularly the aerosol optical depth (AOD), are of great importance in atmospherically correcting satellite sensor imagery for generating high-level land products. The signal received by a multispectral sensor at the top of the atmosphere (TOA) contains information about both the surface and the atmosphere. For the land community, the atmospheric information must be removed to facilitate accurate estimations of a series of land products that require surface reflectance as input.

Estimation of AOD over land is challenging because the relative information content of atmospheric properties is smaller over land than over ocean, particularly when the surface (e.g. desert, snow, ice) is 'bright'. The Moderate-Resolution Imaging

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Spectroradiometer (MODIS) algorithm for estimating the spatial distribution of AOD over land is based on a 'dark-object' method that works only over densely vegetated surfaces (Kaufman *et al.* 1997, 2000, Remer *et al.* 2005). There are few alternative algorithms (e.g. Hsu *et al.* 2004, Tang *et al.* 2005). For example, Hsu *et al.* (2004) proposed a new approach to estimate aerosol properties over bright surfaces using the minimum reflectance determined from a $0.1^{\circ} \times 0.1^{\circ}$ grid. Tang *et al.* (2005) established an empirical relationship between the TOA reflectance and surface reflectance, and MODIS data from two successive orbits were used to solve a nonlinear equation. Liang *et al.* (2006) developed a practical algorithm for estimating AOD using multi-temporal MODIS data over land surfaces. The new aerosol estimation algorithm over land takes full advantage of MODIS multi-temporal observation capability, particularly when observations from both Terra and Aqua platforms are combined. Initial validation results indicate that this algorithm is very reliable, but more validation is needed, which is the primary objective of this study.

2. Summary of the new algorithm

The basic idea of the new algorithm (Liang *et al*. 2006) is to detect the 'clearest' observation of the blue band during a temporal series for each pixel. If the AODs for these 'clearest' observations are assumed to be known, the corresponding surface reflectance can be estimated. As the surface reflectance is relatively stable in a short temporal window, it can be interpolated either directly (Lambertian case) or through a bidirectional reflectance distribution function (BRDF) model (e.g. the Walthall model; Walthall *et al.* 1985). Thus, the AODs of other 'hazy' observations can be directly estimated by searching the pre-calculated look-up tables that are established through MODTRAN4 or 6S. The steps of the new algorithm can be described briefly as follows:

(1) Identify the 'clearest' blue-band observations of each pixel and convert their TOA reflectance to surface reflectance using the parameters of a clear atmosphere.
(2) Fit the converted surface reflectance of the 'clearest observations' to a statistical BRDF model.
(3) Interpolate the reflectance of other 'hazy' observations from the fitted surface BRDF in step 2 above within this temporal window.
(4) Retrieve the AOD of the 'hazy' observations in each visible band by searching the look-up tables based on the TOA radiance and surface reflectance.
(5) Spatially smooth the estimated AOD, which is estimated on a per-pixel basis in the previous steps.

3. Validation procedures and data analysis

In brief, the validation procedure is as follows:

(1) Extract 3-month MODIS TOA radiances and the relevant parameters in 2003 (January–March) at 25 AErosol RObotic NETwork (AERONET) sites over North America. A window of 3 by 3 pixels of each site was extracted, but only the central pixel was used in this study.
(2) Calculate the AODs using the new algorithm. The sensitivities of two key parameters (aerosol models and percentage of observations within the temporal window as the 'clearest' one) were also investigated.

Figure 1. The geographic distribution of the validation sites from AERONET.

(3) Organize the time series of AODs. For each MODIS estimate, the closest AERONET measurement within a temporal window of 20 minutes was identified because it is almost impossible to match them at the exact time.
(4) Compare the matched data points from the MODIS estimates and AERONET measurements.

Figure 1 shows the distribution of the validation sites. Table 1 lists their names and geographic locations, in which the first column is the ID number for data analysis later. The validation results are summarized in table 2 and shown in figure 2. Note that only one aerosol model (rural aerosol) is used. The fitting is characterized by

Table 1. The geolocations of the selected 25 AERONET sites.

Site ID number	Name	Longitude	Latitude	Site ID number	Name	Longitude	Latitude
1	Billerica	−71.20	42.517	19	KONZA_EDC	−96.6	39.10
3	BONDVILLE	−88.3	40.053	21	La_Jolla	−117.2	32.8
4	Bratts_Lake	−104.7	50.28	24	Maricopa	−111.9	33.0
5	Brookhaven	−72.8	40.87	25	MD_ Science_Center	−76.6	39.20
6	BSRN_ BAO_Boulder	−105.0	40.045	27	Monterey	−121.8	36.5
10	CCNY	−73.9	40.821	31	San_Nicolas	−119.4	33.20
11	Columbia,_SC	−81.0	34.023	33	SERC	−76.5	38.8
12	COVE	−75.7	36.9	37	Stennis	−89.6	30.3
13	Fresno	−119.7	36.782	41	UCLA	−118.4	34.0
14	GSFC	−76.8	38.992	42	UCSB	−119.8	34.4
15	Halifax	−63.5	44.638	43	Walker_Branch	−84.20	35.9
17	Howland	−68.7	45.2	44	Wallops	−75.4	37.9
18	Kellogg_LTER	−85.3	42.408				

Table 2. Summary of the new algorithm validation results.

Site ID number	Using estimated aerosol models from AERONET				Using the default rural aerosol model			
	Slope	Intercept	R^2	RMSE	Slope	Intercept	R^2	RMSE
1	1.05	−0.05	0.67	0.04	0.69	−0.00	0.710	0.020
3	0.73	−0.03	0.85	0.04	1.07	−0.05	0.710	0.06
4	0.73	−0.00	0.88	0.010	0.920	−0.07	0.77	0.020
5	0.98	−0.04	0.65	0.03	0.77	−0.020	0.710	0.020
6	0.910	−0.03	0.710	0.03	0.90	−0.03	0.59	0.04
10	0.67	−0.020	0.83	0.03	0.83	−0.03	0.69	0.05
11	0.98	−0.03	0.68	0.03	0.78	−0.03	0.610	0.05
12	0.810	−0.020	0.76	0.03	0.83	−0.03	0.810	0.020
13	0.76	−0.00	0.78	0.05	1.03	−0.05	0.77	0.05
14	0.820	−0.03	0.720	0.06	0.99	−0.06	0.74	0.07
15	0.78	−0.03	0.80	0.03	0.83	−0.020	0.65	0.04
17	1.00	−0.03	0.87	0.07	0.93	−0.05	0.720	0.10
18	0.75	−0.010	0.910	0.03	1.04	−0.010	0.88	0.08
19	0.77	−0.020	0.70	0.03	1.00	−0.04	0.80	0.020
21	0.70	−0.020	0.90	0.020	0.88	−0.04	0.63	0.05
24	0.620	0.00	0.76	0.010	0.70	0.00	0.63	0.020
25	0.78	−0.03	0.79	0.04	0.810	−0.04	0.710	0.06
27	0.63	−0.00	0.58	0.020	0.70	−0.00	0.510	0.020
31	0.88	−0.06	0.87	0.04	0.97	−0.020	0.49	0.06
33	0.90	−0.020	0.67	0.05	1.05	−0.03	0.40	0.07
37	0.79	−0.010	0.710	0.03	0.73	−0.03	0.63	0.06
41	0.45	0.06	0.17	0.07	0.70	0.04	0.55	0.06
42	0.40	−0.00	0.84	0.020	1.03	−0.09	0.76	0.10
43	0.910	−0.010	0.77	0.05	1.03	−0.010	0.59	0.06
44	0.96	−0.04	0.77	0.03	0.90	−0.03	0.65	0.06
Average			0.74	0.03			0.67	0.05
Variance			0.020	0.00			0.010	0.00

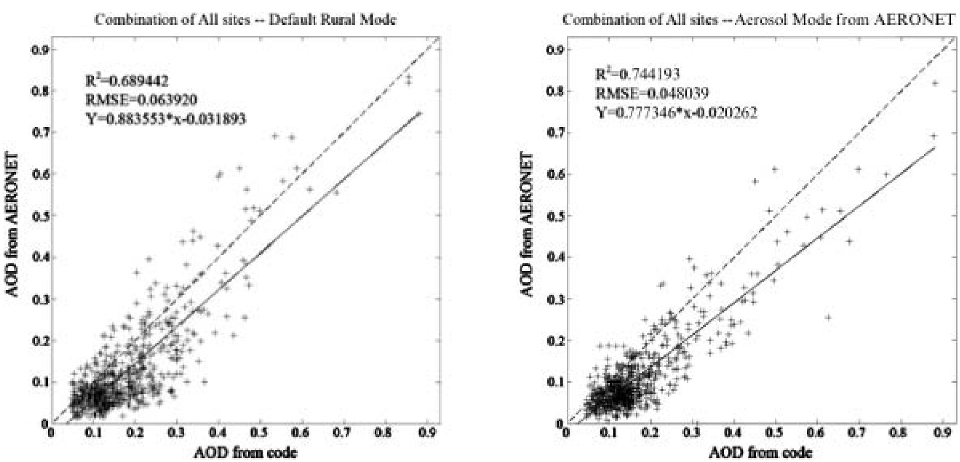

Figure 2. The validation results using the AERONET measurements at all 25 sites: using (*a*) the default rural aerosol model in MODTRAN4 and (*b*) the actual aerosol models estimated from AERONET.

both the root mean squared error (RMSE) and the multiple R-squared (R^2) value. The results show that the AOD estimations from the new algorithm are in close agreement with those measured by AERONET.

First, the impacts of the aerosol models on the AOD estimation were evaluated. The comparison was made between the results using the default rural aerosol model in MODTRAN4 and those using the estimated AERONET aerosol model parameters (e.g. size distribution, refractive index) that were input to the 6S atmospheric radiative transfer model. The results are also shown in table 2 and figure 2. The results from the estimated aerosol models from AERONET are slightly more accurate than those from the default rural model with a larger R^2 and smaller RMSE. However, as it would not be possible to determine the actual aerosol parameters for each MODIS pixel for the operational estimation, it seems that the default rural aerosol model is an acceptable solution for the winter season of North America.

One of the parameters in the new algorithm is the percentage of observations of each pixel within the temporal window that are treated as the 'clearest' ones. In this study, we tested the relationship between the percentage of clear pixels and the accuracy of AOD estimation. Four percentage values (10%, 15%, 20% and 30%)

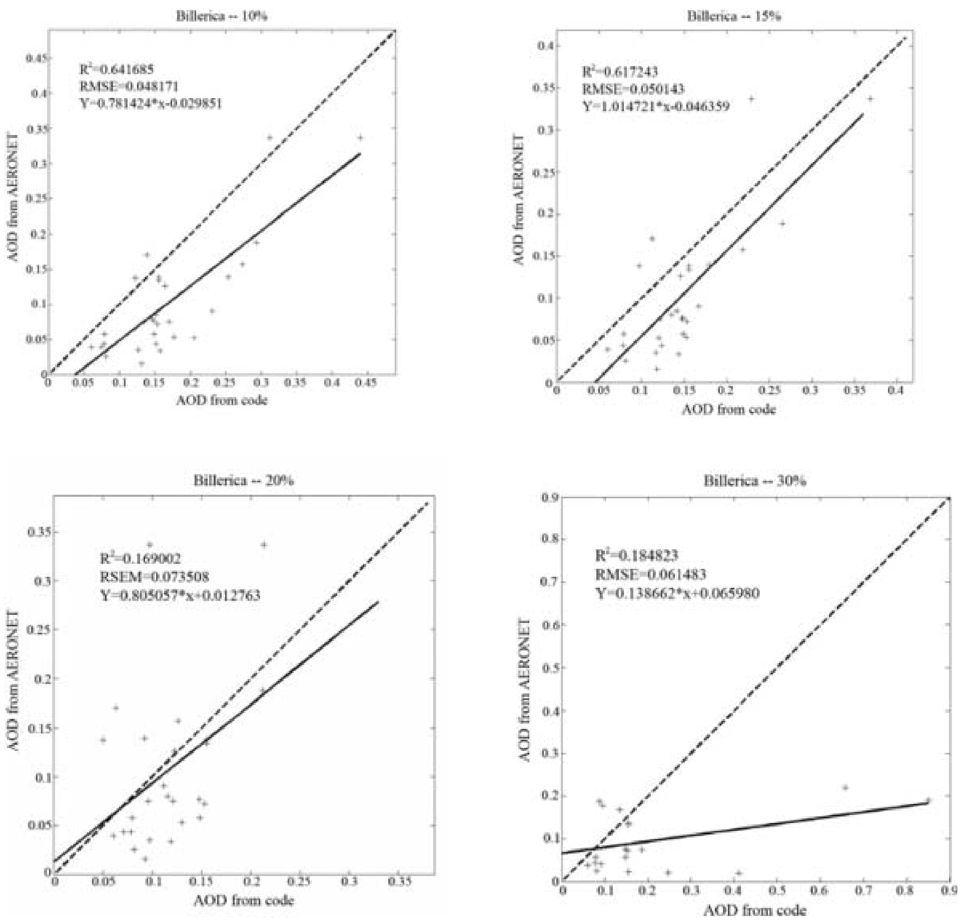

Figure 3. Comparison of the algorithm performances using four different percentages of observations of the same pixel within a temporal window to estimate surface reflectance.

were used. Figure 3 shows that 15% is the most appropriate value for the AOD estimation, and the results with 10% and 20% are reasonable. When the percentage is increased to 30%, the results become less accurate. Note that because the atmosphere is very clear over North America, the AODs are small. The most appropriate percentage value over other regions where the atmosphere is more turbid may be different and more validation will be needed to clarify this.

The MODIS aerosol product (MOD04) was also compared with AERONET measurements. For all 25 sites, the agreement varies dramatically, as shown in table 3. Some sites have close agreement, but most of them do not. Figure 4 shows their comparison with all those pixels together. Although only the MOD04 values with high quality assurance were used, the agreement between these two datasets is not very high (R^2=0.41 and RMSE is 0.09). Note that MOD04 has a spatial resolution of 10 km such that the scale mismatch may contribute to some of the differences.

4. Summary

A new AOD estimation algorithm over land from MODIS imagery has been validated using 3-month (January–March 2003) AERONET measurements of 25 sites over North America. The results indicate that this new algorithm performs very well and the resulting AOD estimate is much more accurate than the corresponding MODIS aerosol products.

Table 3. Summary of the MOD04 collection-4 validation results.

Site ID number	Slope	Intercept	R^2	RMSE
1	0.53	−0.00	0.68	0.04
3	0.46	0.020	0.48	0.07
4	0.410	0.07	0.59	0.20
5	0.06	0.09	0.09	0.08
6	0.49	0.05	0.38	0.05
10	0.48	0.00	0.620	0.09
11	0.510	0.03	0.78	0.03
12	−0.09	0.10	0.04	0.03
13	0.17	0.13	0.10	0.10
14	0.67	−0.010	0.80	0.05
15	0.510	−0.00	0.610	0.05
17	0.86	−0.03	0.85	0.04
18	0.910	0.010	0.510	0.13
19	0.17	0.07	0.24	0.06
21	0.17	0.08	0.110	0.09
24	0.110	0.06	0.15	0.03
25	0.20	0.07	0.220	0.08
27	0.220	0.05	0.25	0.03
31	0.08	0.09	0.05	0.05
33	0.33	0.03	0.420	0.05
37	0.620	0.00	0.48	0.08
41	0.29	0.09	0.25	0.07
42	0.86	−0.010	0.80	0.09
43	0.78	0.00	0.90	0.04
44	0.60	−0.020	0.85	0.03

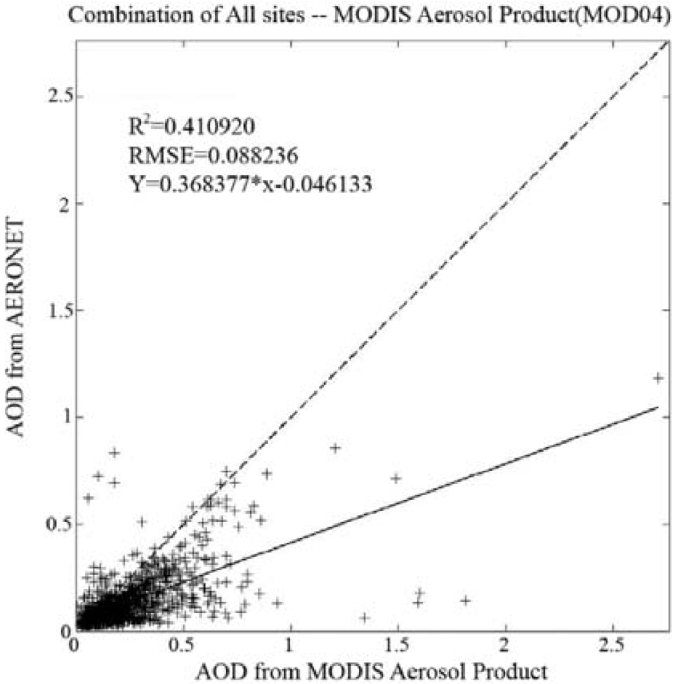

Figure 4. Comparison of MOD04 collection-4 AODs and the AERONET measurements at all 25 sites.

The critical parameters of the algorithm, such as the percentage of the clear observations and aerosol models, were also evaluated. It is interesting to find out that this algorithm is not very sensitive to the aerosol models probably because of the clear atmosphere conditions over North America. It may not be valid for turbid atmospheres over other regions of the world. A more extensive validation globally is still needed.

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