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Validation of MODIS aerosol retrievals and evaluation of potential cloud contamination in East Asia

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Abstract: MODIS aerosol retrievals onboard Terra/Aqua and ground truth data obtained from AERONET (Aerosol Robtic Network) solar direct radiance measurements are collocated to evaluate the quality of the former in East Asia. AERONET stations in East Asia are separated into two groups according to their locations and the preliminary validation results for each station. The validation results showed that the accuracy of MODIS aerosol retrievals in East Asia is a little worse than that obtained in other regions such as Eastern U.S., Western Europe, Brazil and so on. The primary reason is due to the improper aerosol model used in MODIS aerosol retrieval algorithm, so it is of significance to characterize aerosol properties properly according to long term ground-based remote sensing or other relevant *in situ* observations in order to improve MODIS retrievals in East Asia. Cloud contamination is proved to be one of large errors, which is demonstrated by the significant relation between MODIS aerosol retrievals versus cloud fraction, as well as notable improvement of linear relation between satellite and ground aerosol data after potential cloud contamination screened. Hence, it is suggested that more stringent clear sky condition be set in use of MODIS aerosol data. It should be pointed out that the improvement might be offset by other error sources in some cases because of complex relation between different errors. Large seasonal variation of surface reflection and uncertainties associated with it result in large intercepts and random error in MODIS aerosol retrievals in northern inland of East Asia. It remains to be a big problem to retrieve aerosols accurately in inland characterized by relatively larger surface reflection than the requirement in MODIS aerosol retrieval algorithm.

Keywords: MODIS; aerosol retrieval; validation; AERONET

Introduction

Satellite retrieval of aerosol properties (the composition, size, and total content) is thought to be the unique approach to obtain spatio-temporal distribution of aerosols with high resolution on a global scale (King, 1999). It is partly realized with the launch of Earth Observation System's (EOS) Terra and Aqua satellite in 1999 and 2002, respectively (Kaufman, 1997). Aerosol optical depth (τ_a) at 440 and 660 nm wavelengths (and interpolates at 550 nm) over vegetated land surfaces and at seven spectral bands over oceans are retrieved operationally based on Moderate Resolution Imaging Spectroradiometer (MODIS) measurements onboard Terra and Aqua. Validation of MODIS τ_a, whether on a global or regional scale, is absolutely necessary before these data are utilized to test our understanding of aerosol's role in climate system. It may be achieved through inter-comparison between different satellite aerosol retrievals, for example, AVHRR, TOMS, MISR, POLDER, and MODIS, etc. or comparison against ground truth data. Three papers concerning validation method, validation of MODIS τ_a over ocean and land, respectively, were published in Geophysical Research Letter in 2002 (Ichoku, 2002; Chu, 2002; Remer, 2002). Mao *et al*., (Mao, 2002) also carried out preliminary validation research in Beijing. Generally speaking, the MODIS aerosol retrievals over land and ocean meet the expectation with unprecedented accuracy. However, lack of comprehensive validation of MODIS in East Asia hinders us in reaching more convincing conclusion since East Asia is one of major aerosol source regions of, not only anthropogenic productions, but also natural emissions. Fortunately, a few AERONET (Aerosol Robtic Network) stations have been established in recent years, as part of the international research and monitoring activities and as part of supporting validation analysis of remote sensing from satellite system, which provides us opportunities to carry out validation research on MODIS retrievals in East Asia. In this study, we will focus on this issue based on AERONET aerosol data and corresponding MODIS aerosol retrievals from 2001 to the present in East Asia. In the validation, much attention has also been paid to cloud contamination on MODIS aerosol retrievals, because cloud contamination remains to be one of large errors by theory and validation researches (Mishchenko, 1999; Zhao, 2003); furthermore, it is made possible by cloud observations contained in MODIS data.

1 Validation data sets

Ground truth data are from AERONET, a network

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consisting in automatic CIMEL Sun/sky radiometers. AERONET was initiated by NASA Earth Observing System (EOS) in Africa and expanded rapidly with the support of many local governments and institutions. AERONET sunphotometers derive τ_a at 340, 380, 440, 500, 670, 870, and 1020 nm wavelengths with accuracy of 0.01—0.02 from direct solar spectral radiance measurements(Holben, 2001). We use AERONET cloud screening data (Level 1.5; Smirnov, 2000). Ground truth data of τ_a at 470 and 660 nm wavelengths corresponding to MODIS aerosol retrievals over land are deduced according to a second polynominal fit to ln (τ_a) and ln(λ) data at CIMEL working wavelengths, as proposed by Eck *et al*.(Eck, 1999).

AERONET stations used in the validation are listed in Table 1, and also included are their locations. The stations are separated into two groups according to their locations and preliminary validation results for each station. The first region includes stations located in Japan, South Korea, and China Taiwan. The remaining three stations signed by star represent northern inland of East Asia and are appointed to be the second region. Notable difference in validation results for the two regions will be demonstrated in the consequent analysis.

Table 1 AERONET stations and their exact locations used in the validation. Stations are separated into two groups according to their locations and the preliminary validation results for each station(signed with and without star)

Site	Longitude	Latitude	Site	Longitude	Latitude
Shirharma	135.36	33.69	Seoul _ SNU	126.95	37.46
Taiwan	121.10	24.90	Osaka	135.59	34.65
Anmyon	126.32	36.52	Beijing*	116.58	39.78
Yulin*	109.72	38.28	Dalanzadgad*	104.42	43.58

MODIS on Terra and Aqua level 2 aerosol retrievals are collocated with AERONET within a time/space window (± 0.5 h for AERONET and a circle with 50 km radius for MODIS). The window is in consistency with previous validation researches(Chu, 2002). At least 2 out of possible 5 AERONET measurements and at least 5 out of 25 possible MODIS aerosol retrievals are required to make each match-up data point. The spatial and temporal average and standard deviation are calculated for each match-up data point.

2 Evaluation approach

Generally speaking, the quality of satellite aerosol retrievals depends on the observation accuracy(e.g., errors in calibration and radiometric digitization) and the uncertainties associated with such as aerosol model assumption, cloud contamination, and surface reflection, and so on. Under the single scattering approximation of the radiative transfer equation in a clear-sky condition, the satellite retrievals may be obtained from the equation below.

$$\tau_a = 4\mu_s\mu_v \frac{\rho - \rho_R - \rho_S T}{\omega P_a}.$$

Where τ_a is the aerosol optical depth; ρ, ρ_R, and ρ_S are the satellite measured apparent reflectance, Rayleigh scattering contribution, and diffuse surface reflectance, respectively. T is the total atmospheric transmittance; ω and P_a are the aerosol single-scattering albedo and phase function; μ_s and μ_v are the cosines of solar and view zenith angles. From the equation, we can see that the errors are mainly from uncertainty in ρ (due to radiometric and calibration errors, and cloud contamination), surface ρ_S, ω and P_a assumption since all other terms are reasonably well known.

MODIS aerosol retrieval accuracy is evaluated by linear regression results between collocated MODIS and AERONET aerosol data. Four parameters including A (slope), B (intercept), δ (standard deviation), and R (relation coefficient) are presented in the comparison. The former two coefficients represent systematic errors. A nonzero intercept means the algorithm is biased at low τ_a values, which may result from the additive errors (as shown in equation) associated with uncertainties from calibration, surface reflection, and cloud contamination. A slope not equal to unity is mainly produced by incorrect assumptions in ω and P_a, which is dominant when aerosol loading is high. The standard deviation represents random errors(Zhao, 2002).

3 Primary validation results

The validation results are presented in term of the first and second region for MODIS onboard Terra and Aqua, respectively.

Fig.1 presents the validation results for MODIS onboard Terra for the first region(a), and the second region(b). A total of 196 and 73 match-up points satisfied the requirements of validation condition, respectively. The results are compared with those obtained in other regions reported in the literature(Chu, 2002; Table 2). Obviously, the slopes are smaller and the intercepts are(absolute value) larger in East Asia. The slopes for the first region are only 0.66 and 0.63 for the 440 and 670 nm wavelengths. The largest intercept even approaches to 0.17 at 670 nm in the second region, beyond 4 times compared with the largest intercept(0.04 at 470 nm in Western Europe) obtained in other regions. Large systematic errors in East Asia are accompanied by large random errors, especially for the second region. It has random error 2—4 times larger than the first region and other regions. The preliminary validation results for Aqua are presented by Fig. 2. Similarly, much less than unity of slopes are obtained for Aqua, although they are relatively larger with comparison of those discussed above for Terra. The intercepts are also larger than those reported in the literature. The standard deviations in the second region are 0.23 at 470 nm and 0.20 at 660 nm, respectively, close to those obtained in the same region for Terra.

As pointed out in the evaluation approach, the slope is mainly determined by assumption of aerosol properties used in

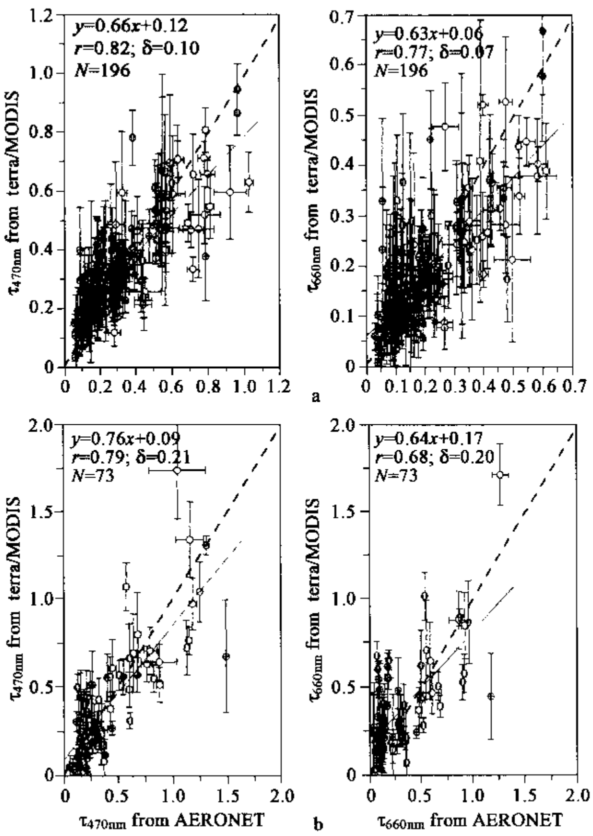

Fig. 1 Scatterplots of aerosol optical depth from AERONET and Terra/MODIS. Corresponding linear regression results including slope, intercept, correlation coefficient and standard deviation are presented. N is the total number. Dashed lines represent 1 : 1 relationship (left) 470 nm, (right) 660 nm for all available match-up data. The short bar means spatial or temporal standard deviation for AERONET (horizontal axes) and MODIS aerosol optical depth (vertical axes), respectively. The first and second region is shown in a, b, respectively

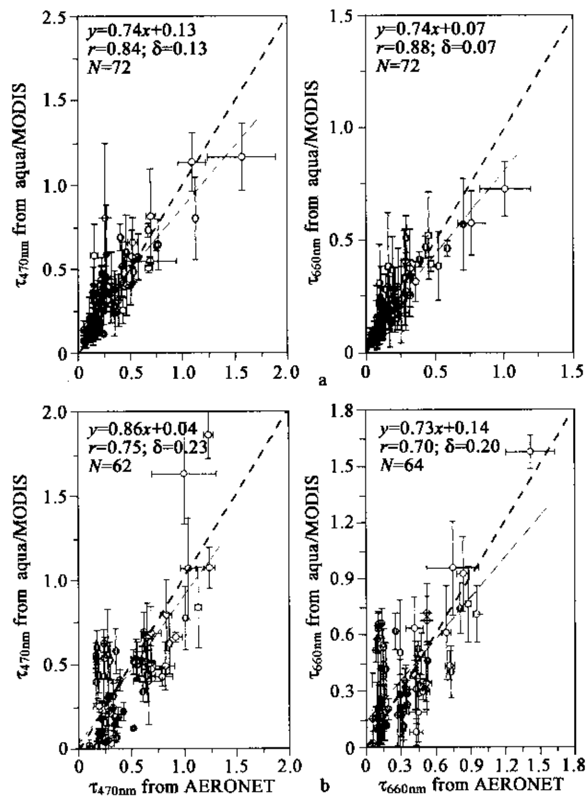

Fig. 2 The same as Fig. 1, but for MODIS aerosol retrievals onboard Aqua in the first region (a), and in the second region (b)

Table 2 Validation results of MODIS/Terra in East Asia and comparison with validations in other regions as reported in the literature (Chu, 2002)

	470 nm				670 nm			
Region	A	B	R	δ	A	B	R	δ
Eastern U.S.	1.05	-0.01	0.94	0.07	0.89	-0.01	0.85	0.06
Brazil	1.06	-0.01	0.98	0.09	0.85	0.01	0.94	0.08
Western Europe	0.92	0.04	0.92	0.07	0.93	0.01	0.90	0.05
Southern Africa	0.90	-0.02	0.93	0.10	0.92	0.03	0.92	0.06
East Asia 1(Terra)	0.66	0.12	0.82	0.10	0.63	0.06	0.77	0.07
East Asia 2(Terra)	0.76	0.09	0.79	0.21	0.64	0.17	0.68	0.20
East Asia 1(Aqua)	0.74	0.13	0.84	0.13	0.74	0.07	0.88	0.07
East Asia 2(Aqua)	0.86	0.04	0.75	0.23	0.73	0.14	0.70	0.20

MODIS retrievals. Actually, ground-based sun/sky radiometer observations can provide not only validation data as for satellite remote sensing, but also estimation of columnar aerosol properties (aerosol optical depth, size distribution, scattering phase function, and single-scattering albedo, etc.). The danger that aerosol climatology (summarized according to *in situ* observations at ground level) does not represent the whole atmospheric column or the properties of the ambient aerosol may be avoided if aerosol model established based on long-term ground-based sun/sky radiometer observations is used. Dynamical aerosol models for the smoke aerosol and for aerosol resultant from industrial/urban pollution in Eastern U.S. and Brazil have been established based on long-term AERONET data, which are utilized in MODIS aerosol retrievals (Remer, 1998). Hence, it is reasonable there are good consistencies between AERONET and MODIS aerosol data in these regions. On the contrary, the sources of aerosols in East Asia are very complex. Anthropogenic productions and natural emissions have their own distinctive optical properties and contribute to aerosol loading with seasonal variation, resulting in tremendous variation of aerosol properties. It is not an easy task to characterize the aerosol properties properly unless there are long-term observations in East Asia. So it is not surprising that MODIS aerosol retrievals in East Asia only show moderate agreement with ground truth data since there is a long way to go as for aerosol characterization in East Asia. A larger effect of surface inhomogeneity or sub-pixel water contamination on MODIS retrievals resulted in larger systematic errors in continental coasts (Chu, 2002), which probably contributes to the large systematic errors in the first region of East Asia since some AERONET stations are located near coast region. However, The slopes of preliminary regression analysis between MODIS and ground aerosol data for each station are similar as those described above. Additionally, base on those collocated data points without sub-pixel water contamination, we do not find obvious improvement in regression relation. Hence, we can state that it is aerosol model that plays dominant role in determining the slopes of regression relation between satellite and ground aerosol data in the first region.

The large random errors in second region have close relation with large surface reflection. Actually, the surface reflectance at 2100 nm is always much larger than the criteria required in MODIS aerosol algorithm in most cases. So large estimation uncertainties of surface reflectance in the visible channels are unavoidable since the relationship between the reflectance in the visible channels and the 2100 nm channel is significantly more chaotic for $\rho_{2100} > 0.15$. So it is particularly important to improve MODIS aerosol retrieval algorithm under the condition of high surface reflection.

Cloud contamination is one of large errors in AVHRR (advanced very high resolution radiometer) and VIRS (visible/infrared scanner) aerosol retrieval products (Zhao, 2003; Mishchenko, 1999). More accuracy in cloud discrimination is anticipated since MODIS offers observations with higher spatial and spectral resolution. Whether there are still residual clouds contaminating MODIS aerosol retrievals after the standardized cloud mask procedure for MODIS? We will focus on this issue in next section in detail.

4 Evaluation of sub-pixel cloud contamination

Generally, residual cloud or cloud shadow in the field-of-view will produce false higher aerosol signal. Hence, it is particularly important to evaluate cloud contamination carefully. It will be studied according to two checks. The first is to check whether there is a significant relation between cloud fraction (CF) and MODIS aerosol retrievals, i.e., to check whether MODIS τ_a increases with the increase of CF; the second is to check whether the regression results will be improved if stringent clear-sky condition is used in regression analyses. If and only if the answers for both checks are positive, we can say for sure that sub-pixel residual clouds do contaminate MODIS aerosol retrievals.

Fig.3 presents the cloud fraction bin and corresponding average of MODIS τ_a obviously, the significant positive relation between CF and MODIS τ_a is observed. However, it is not enough to state that this trend is caused by sub-pixel cloud contamination, but not by potentially real aerosol signal due to clouds (indirect effect) or a combination of them (Zhao, 2003).

Fig.4 presents the MODIS/Terra validation results for those match-up points with CF less than 30% for the first region (a) and the second region (b). The reason why 30% is used in the presentation is based on the validation results for each bin of CF. It is shown that for CF less than 10%, 20% and 30%, the regression results demonstrate little difference between each other; however, they degraded significantly if data points with CF larger than 30% are used in the

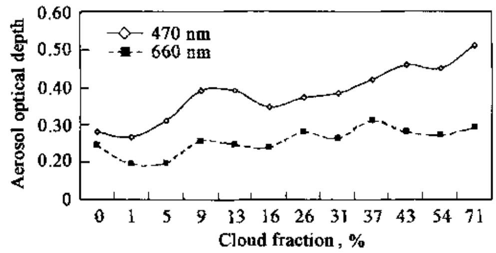

Fig. 3 The average of MODIS aerosol optical depth at 470 nm (solid line with diamond) and 660 nm (dash line with square) wavelengths corresponding to each bin of cloud fraction

validation. Only 64 and 37 data points are obtained for the first and second region, respectively. Fig. 5 presents the similar results for MODIS onboard Aqua. In general, the systematic errors decrease as demonstrated by increasing slopes towards unity and declining intercepts, also, random error decreases after potential cloud contamination filtered. In order to demonstrate the results more clearly, Table 3 presents the improvements in systematic deviations corresponding three cases with different aerosol loading for MODIS onboard Terra and Aqua. The systematic error is defined as $\Delta\tau = A\tau_{AERONET} + B - \tau_{AERONET}$. Three cases with $\tau_{AERONET}$ equal to zero, the average, and unity are presented. Apparently, with stringent clear-sky used in the validation, the averages of aerosol optical depth decrease notably, except for Aqua in the second region. It is not out of expectation, since sub-pixel cloud contamination always produces false higher aerosol signal. Significant improvement in MODIS aerosol retrievals occurs after cloud contamination screened in most cases, which also meet our anticipation. However, there are also some exceptions. 6 out of 16 cases for middle and high aerosol loading shows increased systematic errors. Zhao *et al*. (Zhao, 2003) also found this phenomenon in the validation of VIRS aerosol retrievals. The systematic error at large aerosol optical depth is mainly due to the improper assumptions in the aerosol properties. Hence, it looks like that the systematic errors caused by the cloud contamination and by improper assumption of aerosol properties are in opposite sign. As seen in the discussion above, the improper assumption of aerosol properties (mainly the single-scattering albedo) caused smaller aerosol optical depth retrievals; hence, the residual cloud probably offsets the systematic error caused by improper characterization of aerosols. As a result, after the minimization of cloud contamination, the systematic error caused by the improper assumption of aerosol properties is expanded due to no offset from cloud contamination. Additionally, only one out of 8 cases for 660 nm for middle and high aerosol loading shows unexpected results, as for the 470 nm, it is 5 out of 8 cases. It is indicative of different improvements for 440 and 670 nm wavelengths, which seems to be inconsistency with the expectation since the wavelength dependence of cloud optical depth is very weaker and the similar improvements for both channels should be obtained after sub-pixel cloud contamination is minimized. The cause of the inconsistent improvements in the two channels is still not clear. It has been pointed out the balance between the improper assumption of aerosol properties and residual cloud contamination in MODIS aerosol retrievals. As a matter of fact, the inconsistent improvements between 470 and 660 nm wavelengths are probably related to the different aerosol signal and potential diverse effects of uncertainties associated with such as surface reflection, calibration, etc between both wavelengths.

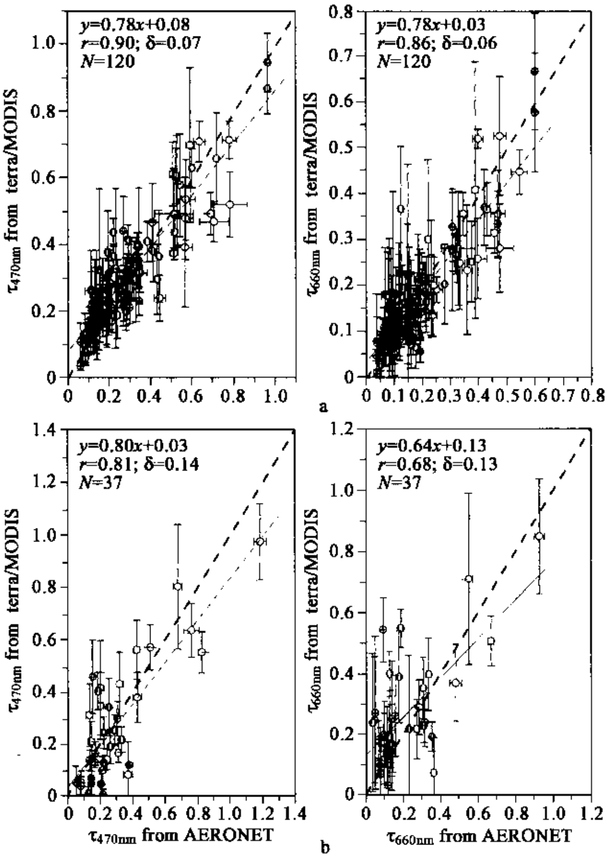

Fig. 4 The same as Fig. 1, but for all match-up points with cloud fraction less than 30% in the first region (a), and in the second region (b)

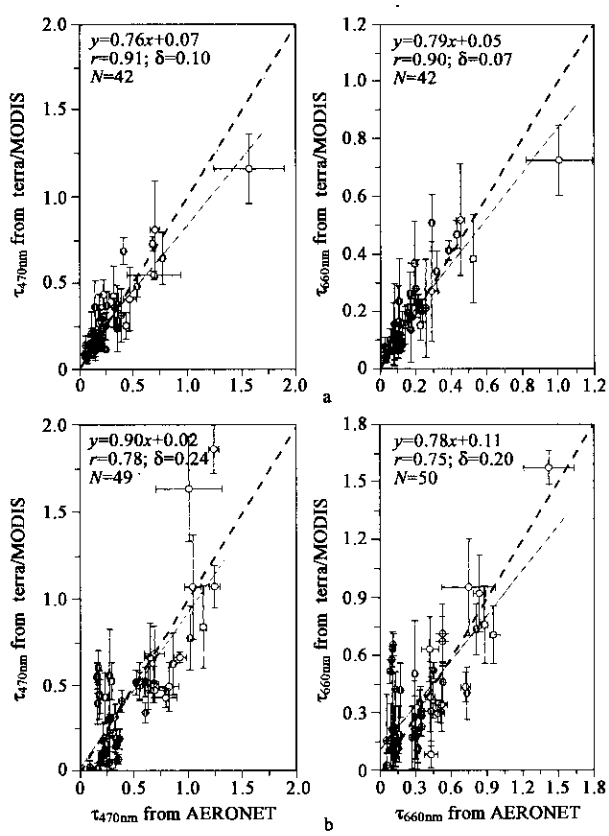

Fig. 5 The same as Fig. 2, but for all match-up points with cloud fraction less than 30% in the first region (a), and in the second region (b)

Table 3 The systematic errors corresponding to different aerosol loading for MODIS onboard Terra and Aqua

Sat	Cloud	Region	470 nm	660 nm	Systematic errors					
					470 nm			660 nm		
			$\bar{\tau}_{AERONET}$	$\bar{\tau}_{AERONET}$	Low	Middle	High	Low	Middle	High
Terra	All CF	First	0.31	0.20	0.12	0.015	-0.22	0.06	-0.014	-0.27
		Second	0.43	0.32	0.09	-0.013	-0.15	0.17	0.055	-0.19
Aqua	All CF	First	0.33	0.21	0.13	0.044	-0.13	0.07	0.015	-0.19
		Second	0.47	0.35	0.04	-0.026	-0.10	0.14	0.046	-0.13
Terra	CF < 30%	First	0.29	0.19	0.08	0.016	-0.14	0.03	-0.012	-0.19
		Second	0.32	0.24	0.03	-0.034	-0.17	0.13	0.044	-0.23
Aqua	CF < 30%	First	0.30	0.18	0.07	-0.002	-0.17	0.05	0.012	-0.16
		Second	0.47	0.37	0.02	-0.027	-0.08	0.11	0.029	-0.11

Notes: The systematic error is defined as $\Delta\tau = A\tau_{AERONET} + B - \tau_{AERONET}$. Parameters A and B are slope and intercept of the linear regression line, respectively. Low, Middle, and High represent three aerosol loading cases, corresponding to aerosol optical depth equal to zero, the average and unity, respectively. Hence, the corresponding systematic errors are B, $A\bar{\tau}_{AERONET} + B - \bar{\tau}_{AERONET}$, and $A + B - 1$, respectively. The results are presented for each region. The description in detail is referred to the text

It is demonstrated that there are complex relations between different errors in MODIS aerosol retrievals. In certain cases, there is some balance between different errors, so it is not absolutely necessary result that better retrievals should be obtained after only one error is eliminated. Anyway, residual cloud contamination is identified in the MODIS aerosol retrievals.

5 Conclusions and discussion

MODIS aerosol retrievals in East Asia are evaluated by comparison with AERONET aerosol observations. With cloud information contained in MODIS data, we also checked potential effects of sub-pixel contamination on MODIS aerosol retrievals.

The preliminary validation results showed a moderate agreement between MODIS and AERONET aerosol optical depth. It is of significance to improve characterization of aerosol optical properties in East Asia, in order to improve MODIS aerosol retrieval. It may be achieved through analysis of long-term ground-based remote sensing data or other relevant in situ observations, just as demonstrated by the researches in Eastern U.S. and Brazil, and so on.

With the minimization of sub-pixel contamination, the quality of MODIS aerosol retrievals is improved notably, which demonstrates that sub-pixel contamination remains to be one of large errors and should be treated carefully. It seems that more stringent clear-sky condition is required in use of MODIS aerosol data, at least in East Asia.

Seasonal variation and uncertainties of surface reflection in northern inland of East Asia produce large random errors in MODIS aerosol retrievals. It is particularly important to improve MODIS aerosol retrieval algorithm in these regions.

There are complex relations between different errors. The improvement made after one error is eliminated may be offset by other errors, so it is more suitable to take all potential errors into consideration comprehensively.

The validation study points out the potential reasons resulting in errors of MODIS aerosol retrievals. Focus on these errors and improve MODIS aerosol retrievals will be done based on long-term ground-based observations.

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