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Evaluation of the MODIS aerosol optical depth retrieval over different ecosystems in China during EAST-AIRE

Lili Wang[a], Jinyuan Xin[a], Yuesi Wang[a,*], Zhanqing Li[b], Guangren Liu[a], Jing Li[a]

[a]*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, PR China*
[b]*Department of Meteorology, The University of Maryland, College Park, MD 20782, USA*

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Abstract

The accuracy of the Moderate Resolution Imaging Spectroradiometer's (MODIS) aerosol products is still uncertain in China, due to a lack of validation by long-term and large-scale ground-based observations. In this paper, the MODIS aerosol optical depth (AOD) product is evaluated using Chinese Sun Hazemeter Network (CSHNET) data as ground truths over different ecological regions in China during the East Asian Study of Tropospheric Aerosols—an International Regional Experiment (EAST-AIRE). The evaluation results show very large differences in the MODIS AOD retrieval between different ecosystems and geographic locations. The most agreement between the MODIS data and that of the CSHNET was in farmland sites in central-southern China, where high correlation ($R > 0.82$) and large percentages ($R2 > 72\%$) within the expected error lines issued by NASA were found. In temperate forest, coastal regions, and northeast and central farmlands, there appeared moderate agreement, with $R\sim 0.64$–0.80 and 45–73% of retrieval data falling within the expected errors. The poorest agreement existed in northern arid and semiarid regions, in remote northeast farmlands, in the Tibetan and Loess Plateau, and in southern forests, with 13–54% of retrieval data falling within the expected errors. In addition, the MODIS AOD retrievals were significantly overestimated in the northern arid and semiarid regions and underestimated in remote northeast farmlands and southern forests.

Keywords: MODIS; CSHNET; Aerosol optical depth (AOD); Ecosystem; China

1. Introduction

China is the largest country in Asia and the third largest in the world, possessing a vast territory and a large variety of ecosystems (Wu, 1980; Sun, 2005). In recent decades, with a rapidly developing economy, expanding anthropogenic activity and urbanization, fast-growing industry, and increasing levels of large-scale agriculture, aerosol loading in China has become more and more heavy. Furthermore, the lack of accurate information on the distribution of aerosol properties in China has a very important influence on estimating the Earth's radiative balance and global climate change (Huebert et al., 2003; Li, 2004; Seinfeld et al., 2004), since aerosols have a substantial climatic influence through direct and indirect radiative forcing and cloud processes (Satheesh and Moorthy, 2005;

*Corresponding author. Tel.: +86 10 82080530; fax: +86 10 62041393.
E-mail address: wys@dq.cern.ac.cn (Y. Wang).

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Rosenfeld and Lensky, 1998). Satellite remote sensing has provided a powerful means of assessing the distribution of aerosols over the world (Kaufman et al., 2002; King et al., 1999), allowing scientists to research microphysical and optical properties, as well as regional and seasonal characterization of aerosols on a global scale, which provides basic data for climate change research.

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a sensor onboard the NASA EOS (Earth observing system) Terra satellite, which provides an available and convenient method for aerosol remote sensing (Salomonson et al., 1989; Barnes et al., 1998) due to a high spatial resolution and a near-daily global coverage of data. The MODIS aerosol products, which provide the ability to monitor spatial and temporal characteristics of the global aerosol field, retrieve aerosol properties over both land (Kaufman et al., 1997a) and ocean (Tanre et al., 1997) using seven well-calibrated spectral channels (0.47–2.1 μm). The MODIS aerosol products have been comprehensively validated over land on a global scale (Chu et al., 2002; Remer et al. 2005) by observations through the Aerosol Robotic Network (AERONET) (Holben et al., 1998). However, global validation does not provide a representative measure of the accuracy of MODIS aerosol products over China, since there are so few AERONET stations in this country (Li, 2004), plus there exists a wide variety of ecosystems, complex surface conditions, and many different aerosol types. Other validations taken by Chinese scientists (Mao et al., 2002; Li et al., 2003, 2005; Chen and Yang, 2005; Xia et al., 2004; Xia, 2006) have done in some regions, such as Beijing, Hong Kong, and Taiwan. However, due to the lacked large-scale and long-term data, the accuracy of the MODIS aerosol products is even more uncertain over China.

Under the aegis of the East Asian Study of Tropospheric Aerosols—an International Regional Experiment (EAST-AIRE), the Chinese Sun Hazemeter Network (CSHNET), which includes 25 stations in different ecological and geographic regions over China, has been successfully established since August 2004 (Xin et al., 2006). In this paper, CSHNET-derived aerosol optical depth data are used as ground truths to evaluate the MODIS aerosol optical depth (AOD) retrieval in China. The analysis will focus on the impact of different ecosystems, seasons and aerosol types upon MODIS AOD retrieval uncertainties.

2. Data and methodology

2.1. The CSHNET

The CSHNET was initiated in August 2004, and was the first large-scale observation project to measure aerosol optical properties and their spatial and temporal variations throughout China. Fig. 1 shows the locations of the 25 sites in the CSHNET. Nineteen CERN (Chinese Ecosystem Research Network) stations represent the typical ecosystems of China, and are located in relatively remote areas in order to represent large-scale regional background conditions of certain ecosystems (e.g. arid and semiarid regions, agriculture, forest ecosystems and coastal regions). The network uniformly uses the LED (light-emitting diode) hazemeter, also called a sun hazemeter (Brooks and Mims, 2001; Acharya, 2005), which has been deployed in other field campaigns, such as the Southern African Regional Science Initiative (SAFARI) campaign (Hao et al., 2005). The hazemeters measure AODs at three wavelengths (405, 500 and 650 nm), and the measurement period is from 10 AM to 2 PM (local time), which encompasses the passing time of the Terra satellite. Measurements are taken three times every half an hour and at least 15–20 times a day; weather conditions and cloud amount are synchronously recorded during the measurement periods, but no observations are made if the cloud amount is greater than four-fifths. The LED hazemeters are uniformly calibrated by the Langley plot calibration and instrument intercomparisons on an annual basis, and observations have shown good agreement with CEMIL Sun photometers used in the AERONET (Xin et al., 2006, 2007). The latest systematic calibration of all hazemeters deployed in China was carried out in August 2006 at Lhasa and the hazemeters had degraded by about 10% over 2 years. Xin et al. (2006, 2007) and Wang et al. (2006) have introduced in detail aspects such as running mode, calibration approaches, running conditions, and some new features concerning the spatial and temporal distribution of aerosol optical properties to the CSHNET.

2.2. The MODIS aerosol products

The MODIS aerosol algorithm is actually two entirely independent algorithms, one for deriving aerosols over land (Kaufman et al., 1997a) and the other for aerosols over the ocean (Tanre et al.,

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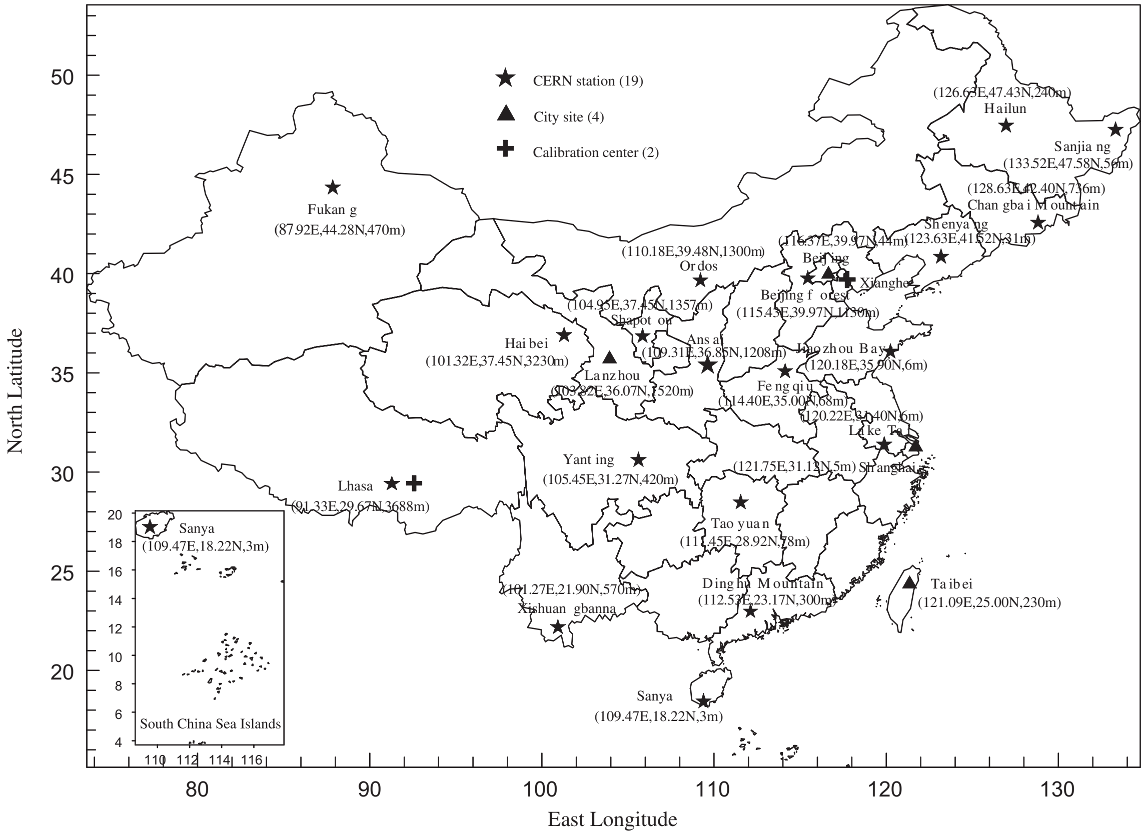

Fig. 1. Geographical locations of observation sites in the CSHNET sites.

1997). In this paper, MODIS aerosol products over land are evaluated. The data analysis in this paper uses data from the MODIS sensor aboard the Terra satellite from Collection 4 level 2 MODIS aerosol products, which are produced at a spatial resolution of a 10×10 km pixel array. The MODIS retrievals of AODs over land at wavelengths of 0.47 and 0.66 μm employ primarily three spectral channels (0.47, 0.66 and 2.1 μm) (Kaufman et al., 1997a) at a resolution of 500 m. First, cloud-free pixels are selected using the multi-spectral MODIS cloud mask. Then, the 'dark-object' method is applied to the MODIS aerosol retrieval algorithm (Kaufman et al., 1997a, b, 2000). The basic assumption of the algorithm is that if the surface is densely vegetated, then the empirical formulae (Kaufman et al., 1997c) $\rho_{0.47\ \mu m}/\rho^*_{2.1\ \mu m} = 0.25$ and $\rho_{0.66\ \mu m}/\rho^*_{2.1\ \mu m} = 0.5$ are used to estimate the surface reflectance (ρ) at 0.47 μm and at 0.66 μm from the measurements (ρ^*) at 2.1 μm. In addition, to minimize the error, $\rho^*_{2.1\ \mu m}$ is limited to less than 0.25 and the darkest 20% and brightest 50% of $\rho^*_{0.66\ \mu m}$ are discarded to eliminate cloud contamination and cloud shadowing effects (Remer et al., 2005). Finally, after aerosol models have been chosen, AODs at wavelengths of 0.47 and 0.66 μm can be estimated using look-up tables. Aerosol type selection was done using the ratio of path radiances (Kaufman et al., 1997a), $\rho_{0.66\ \mu m}/\rho_{0.47\ \mu m}$, to make a decision whether the aerosol is pure dust, non-dust, or mixed. AOD at a wavelength of 550 nm is interpolated from the 0.47- and 0.66-μm retrieval values (Remer et al., 2005). The detailed mechanics of the MODIS land algorithm can be found in Remer et al. (2005).

2.3. Data processing

This study uses the products of the Collection 4 level 2 MODIS AODs and CSHNET-derived AOD data during the period of August 2004 to July 2006. CSHNET-derived AOD data are cloud-screened by manual record tables and chosen under such weather conditions with free cloud or cloud amounting to less than a half (in order to assure no cloud within a field of sun/view angle of 30°) (Wang et al., 2006). The values of the CSHNET

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data at 550 nm are interpolated on a log–log plot assuming linearity with 500 and 650 nm, using the formula $\ln(\tau_a) = a \times \ln(\lambda) + b$, where τ_a is the AOD and λ is the wavelength (Zhao et al., 2002; Eck et al., 1999; Remer et al., 2005). To estimate the aerosol size distribution and types, the Angstrom exponent (α) is calculated using a log-linear fitting through three wavelengths (405, 500 and 650 nm) of the CSHNET (Kim et al., 2004). In general, the Angstrom exponent ranges from 0.0 to 2.0, with smaller Angstrom exponents corresponding to larger aerosol particle sizes (Dubovik et al., 2002; Kim et al., 2004). The CSHNET AOD data are matched with the MODIS AOD retrievals in time and space following the method of Ichoku et al. (2002). Data from the CSHNET were averaged within ± 30 min of the satellite's passing and the MODIS data were averaged over a 50 km area centered at the ground stations (including at least five pixels). In an effort to reduce validation errors due to heterogeneity and questionable data, the CSHENT observations with standard deviation (SD) > 0.05, which only accounts for 11% of all collocated data, are excluded from the evaluation. Statistical correlation analyses between the two sets of data were carried out, and the percentages of collocated data falling within the expected errors of $\Delta\tau_a = \pm 0.05 \pm 0.15\tau_a$ over land issued by NASA (Remer et al., 2005) were calculated in order to evaluate the MODIS AOD retrieval over different ecosystems in China.

Table 1
Statistical values for the evaluation of the MODIS AOD with that of the CSHNET, including the number of points (N), correlation coefficient (R), linear regression slope and offset, and the root mean square errors (RSME)

Site	N	R	RSME	Slope	Offset
Lhasa	4	0.25	0.09	0.67	0.14
Haibei	7	−0.41	0.13	−0.8	0.33
Shapotou	30	0.47	0.32	0.91	0.29
Ordos	60	0.71	0.18	1.19	0.04
Fukang	159	0.67	0.21	1.35	0.12
Hailun	62	0.52	0.1	0.5	0.002
Sanjiang	75	0.53	0.17	0.91	0.04
Changbai Mt.	74	0.36	0.18	0.74	0.08
Beijing Forest	156	0.81	0.12	0.89	−0.02
Xishuangbanna	106	0.85	0.22	0.64	−0.05
Dinghu Mt.	36	0.75	0.19	0.7	0.06
Jiaozhou Bay	168	0.77	0.25	0.8	0.24
Sanya	55	0.76	0.1	0.64	0.13
Lake Tai	71	0.64	0.11	0.76	0.17
Shenyang	150	0.74	0.16	0.78	0.05
Ansai	86	0.48	0.22	0.57	0.004
Fengqiu	112	0.69	0.18	0.69	0.22
Taoyuan	108	0.82	0.14	0.81	0.06
Yanting	77	0.92	0.15	0.82	0.03

3. Results and discussion

Separate discussions according to individual CSHNET stations located in different ecosystems and geographic regions will be presented. Figs. 4–9 show scatterplots between the MODIS data and CSHNET observations, matched in space and time. The data were sorted into three types according to Angstrom exponents calculated through CSHNET AODs at three wavelengths (405, 500 and 650 nm). Linear regression statistics are provided in Table 1. Fig. 2 shows the ratios of the number of all collocated data to that of CSHNET and the percentages of collocated points within the expected error range of $\Delta\tau_a = \pm 0.05 \pm 0.15\tau_a$ for all 19 stations and Fig. 3 shows the same but divided across the four seasons.

Fig. 4 shows the evaluation results of AODs at a wavelength of 550 nm between the CSHNET and the MODIS data at the sites of Lhasa and Haibei located on the Tibet Plateau, which are alpine-shrub–grassland and meadow ecosystems, respectively. Both sites are at high altitudes on the plateau, where winters are very long and snow is the main land cover, leading to no MODIS data during this period. In other seasons, due to less rain and vegetation, pixel points satisfying the 'dark-object' condition are so sparse in the 50 × 50 km that an inadequate number of points were available for comparison. The number of collocated data only accounts for no less than 4% of that of CSHNET observed data. As shown in the figure, both sites have so few collocated data that the validation results are rather questionable and are less representative and reliable. In Fig. 3, except in summer, there are no collocated data in other seasons. Both sites have very clean air with low and stable AODs (mean yearly AOD is less than 0.15) (Xin et al., 2007), which contributes to larger retrieval errors (Remer et al., 2005). Therefore, the MODIS algorithm cannot deal well with this area, and it is very necessary to establish a new algorithm to fit the 'bright-object' surface and clean air conditions.

Fig. 5 shows the same results as Fig. 4 but at the sites of Shapotou, Orods and Fukang in the northern arid or semiarid regions. The Shapotou site is located in the arid region of the Tengger Desert, the Orods site is located in a sandy grassland

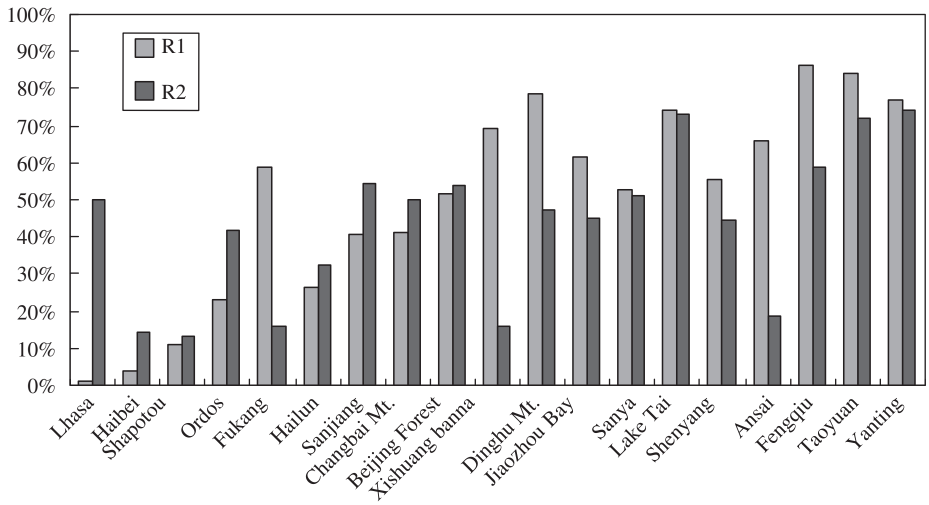

Fig. 2. Ratios of the number of all collocated data to that of the CSHNET data ($R1$) and percentages of collocated data falling within the expected error lines ($R2$) at different sites in the CSHNET.

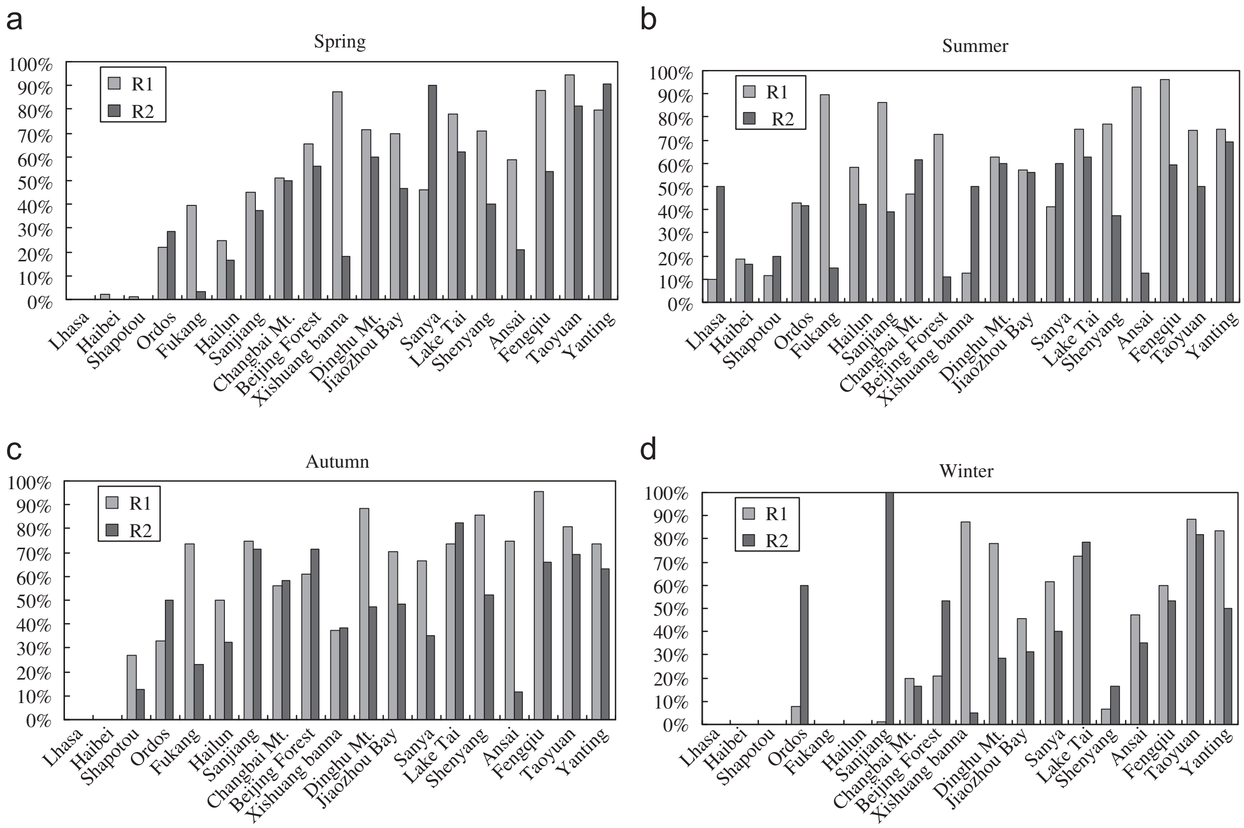

Fig. 3. Ratios of the number of all collocated data to that of the CSHNET data ($R1$) and percentages of collocated data falling within the expected error lines ($R2$) at different sites in the CSHNET for the four seasons.

ecosystem in a semiarid region, and the Fukang site is situated at an oasis transition zone in the inland desert in northwestern China. Clearly, the MODIS data are significantly overestimated in all three sites and all plots show large scattering. The ratios of the number of collocated data to that of CSHNET data

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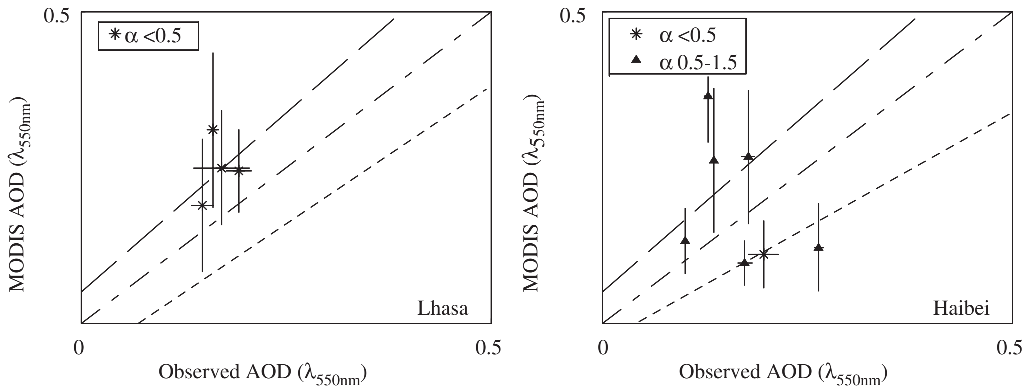

Fig. 4. $\tau_{aCSHNET}$ versus τ_{aMODIS} at a wavelength of 550 nm at sites on the Tibet Plateau. Dashed lines represent $y = 0.05 + 1.15x$ and dotted lines $y = -0.05 + 0.85x$, which are the expected error lines issued by NASA. Vertical bars represent the spatial standard deviations (SD) in the MODIS-derived AOD; horizontal bars represent the temporal SD in the CSHNET-derived AOD, with SD$\leqslant$0.05; and α represents the Angstrom exponent.

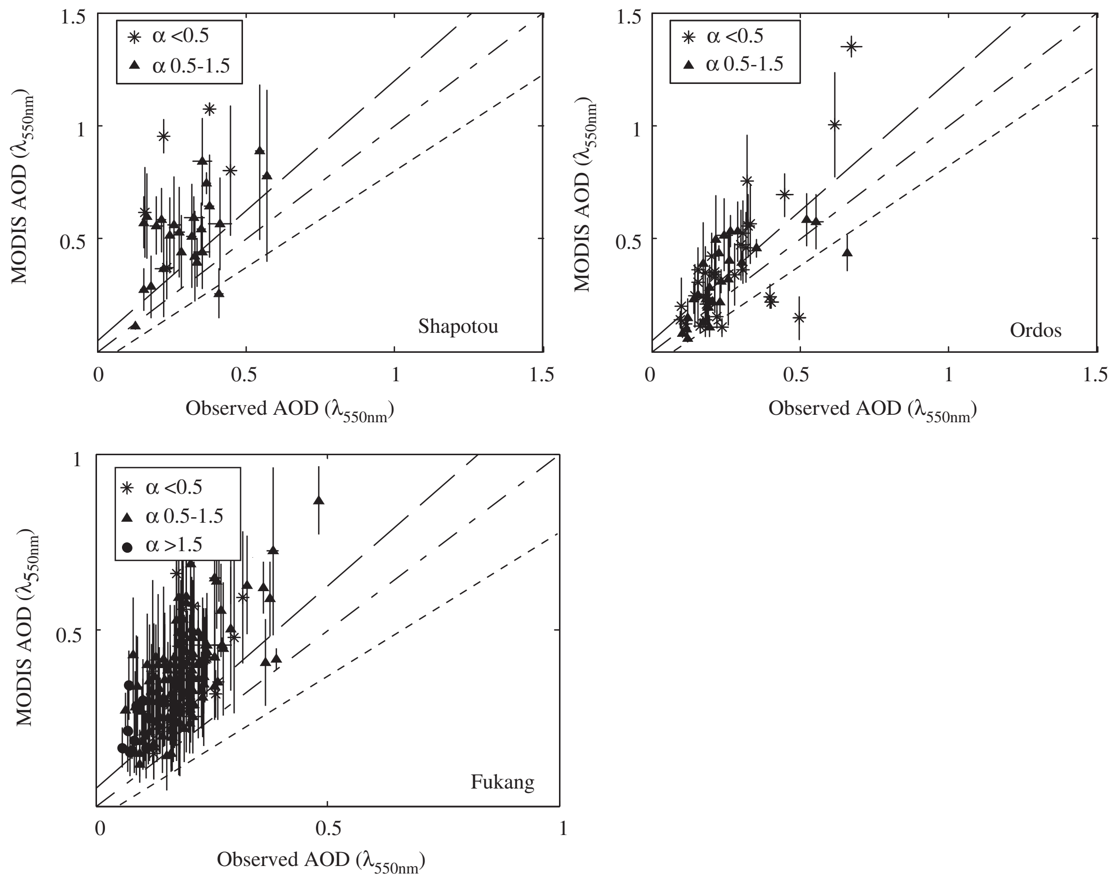

Fig. 5. $\tau_{aCSHNET}$ versus τ_{aMODIS} at a wavelength of 550 nm at northern desert sites. Dashed lines represent $y = 0.05 + 1.15x$ and dotted lines $y = -0.05 + 0.85x$, which are the expected error lines issued by NASA. Vertical bars represent the spatial standard deviations (SD) in the MODIS-derived AOD; horizontal bars represent the temporal SD in the CSHNET-derived AOD, with SD$\leqslant$0.05; and α represents the Angstrom exponent.

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are 11%, 23% and 59%, and the percentages within the expected error lines are 13%, 42% and 16%, respectively, which is more than the pre-launch expectations of 66% issued by NASA (Remer et al., 2005). The ratios and percentages in all sites are even less in spring and winter. The low correlation coefficients are found at all three sites, with R ranging from 0.47 to 0.71. Slopes of the linear regression lines show variations about 1 by more than 10%, which show the larger systematic biases of the MODIS retrieval (Chu et al., 2002). As shown in the figure, the spatial standard deviation of the MODIS is large, which highlights the fact that the MODIS retrievals have larger errors for different pixel points in the same region due to sparse vegetation. At the two latter sites, due to agricultural and pastoral activities surrounding the regions, the dominant aerosol types show a seasonal change indicated by the Angstrom exponent distribution (figure not shown), which reveals a fine mode in autumn and winter due to fossil fuel and biomass burning being the preferred heating methods of local farmers and inhabitants, and a coarse mode in other seasons. The large errors of the MODIS retrieval are also because of incorrect assumptions in the aerosol models. In conclusion, due to a less densely vegetated surface and aerosol type seasonal change, there is a poor MODIS retrieval in this arid/semiarid region, and the 'dark-object' algorithm does not perform well.

Fig. 6 shows the same results as those at the Hailun and Sanjiang sites but for a remote northeast corner of China. Both are farmland ecosystem on a plain, and Sanjiang is also a wetland ecosystem. Because winter is very long in this area and snow is the main land cover during winter, there is little MODIS data for Hailun and Sanjiang and the ratios of the number of collocated data to that of CSHNET data are only 26% and 41%, respectively. MODIS data are underestimated overall, especially at the Hailun site, and the percentages within the expected errors are low (32% and 55%, respectively). Furthermore, the scattering and spatial standard deviation of the MODIS data are both large. The two sites are situated in the far northeast corner of China and are exposed to clear air with relatively low AOD (annual mean <0.2) (Xin et al., 2007), and in addition, due to fossil fuel and biomass burning for warmth in winter and spring, there is a seasonal shift in aerosol type (Xin et al., 2007), which enlarges the MODIS retrieval errors. As far as the seasons are concerned, the agreement between the two sets of data is also rather poor across the board. Therefore, MODIS retrieval AOD algorithm can be better corrected because surface reflectance and aerosol models in general vary regularly.

The comparison results at forest sites are shown in Fig. 7. Although the four sites are all forest ecosystems, the comparison results are distinctly different, due to differences in geographic location distribution. There is a poor correlation and a large scattering over Changbai Mt., which is a temperate forest located in Northeast China. In contrast, a much higher correlation coefficient of 0.8, a slope of 0.88, and a percentage within errors of 54% are

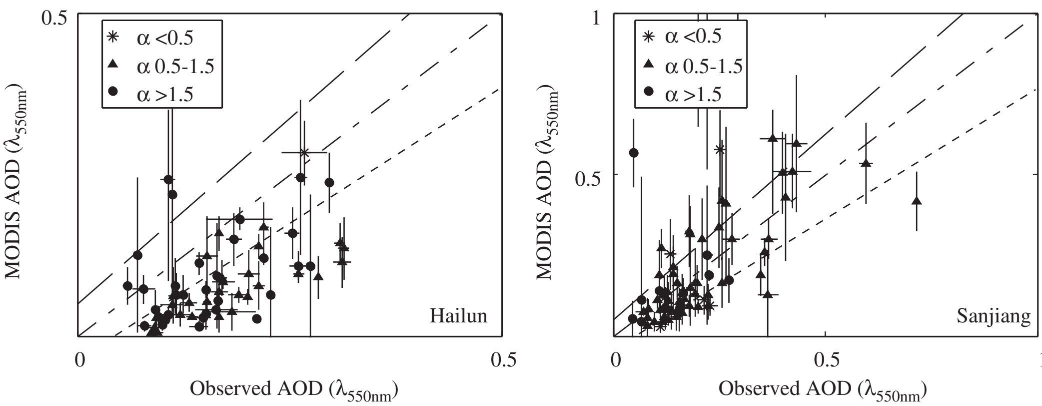

Fig. 6. $\tau_{aCSHNET}$ versus τ_{aMODIS} at a wavelength of 550 nm at sites in the remote northeast corner of China. Dashed lines represent $y = 0.05 + 1.15x$ and dotted lines $y = -0.05 + 0.85x$, which are the expected error lines issued by NASA. Vertical bars represent the spatial standard deviations (SD) in the MODIS-derived AOD; horizontal bars represent the temporal SD in the CSHNET-derived AOD, with SD$\leqslant$0.05; and α represents the Angstrom exponent.

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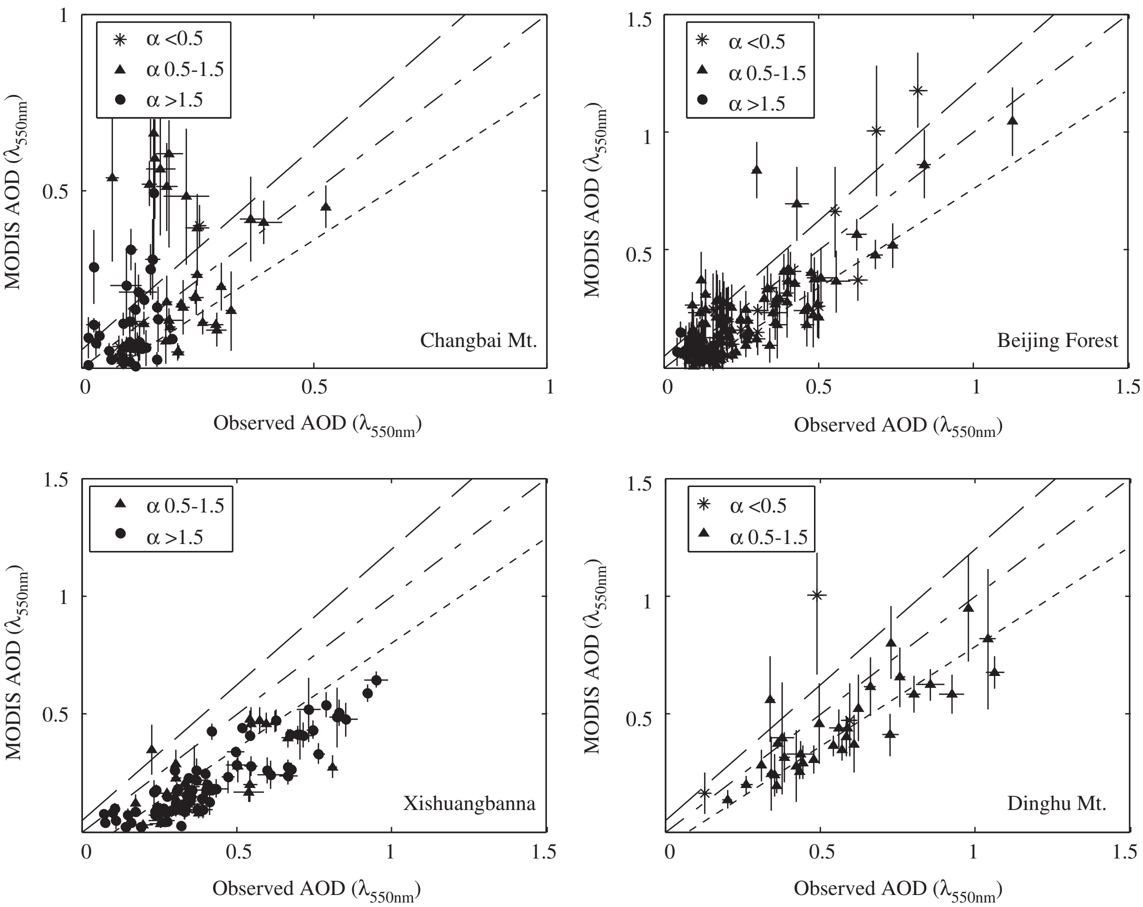

Fig. 7. $\tau_{aCSHNET}$ versus τ_{aMODIS} at a wavelength of 550 nm at forest sites. Dashed lines represent $y = 0.05 + 1.15x$ and dotted lines $y = -0.05 + 0.85x$, which are the expected error lines issued by NASA. Vertical bars represent the spatial standard deviations (SD) in the MODIS-derived AOD; horizontal bars represent the temporal SD in the CSHNET-derived AOD, with SD$\leqslant$0.05; and α represents the Angstrom exponent.

found at the Beijing Forest site, which is warm temperate forest ecosystem to the west of Beijing City. This is due to a densely vegetated surface and more pixels fitting the 'dark-object' conditions, although a lot of smoke and soot due to fossil fuel and biomass burning reduces the size of dominant aerosols in autumn and winter (Cao et al., 2005), and dust storm transportation and local soil dust emission increases the size in spring and summer (Zhou et al., 2004). As shown in the figure, the MODIS retrieval results underestimate at Dinghu Mt., a subtropical evergreen forest ecosystem located at the Pearl River Delta and about 84 km away from Guangzhou in southern China, and at Xishuangbanna, a tropical rainforest ecosystem in Yunnan Province in southwestern China. For the former, this is because of complexities in aerosol types, and for the latter because of special environment conditions typical of tropical rainforests. Aerosols at Dinghu Mt. are influenced by environment pollution due to the rapid regional industrial development (Wu, 2003; Li et al., 2003; Li, 2004) and large-particle sea salt transportation by southeast winds, while at Xishuangbanna the errors of the MODIS retrieval are due to high humidity, more cloud and rain, and uncertainty of organic aerosol elimination (Xin et al., 2007). Therefore, although the densely vegetated surface of the forest ecosystem fits the 'dark-object' conditions, complexities of aerosol types and special environment conditions exacerbate the accuracy of the MODIS retrieval results.

Fig. 8 shows a comparison of results at sites along the coastal regions of China. The Jiaozhou Bay and

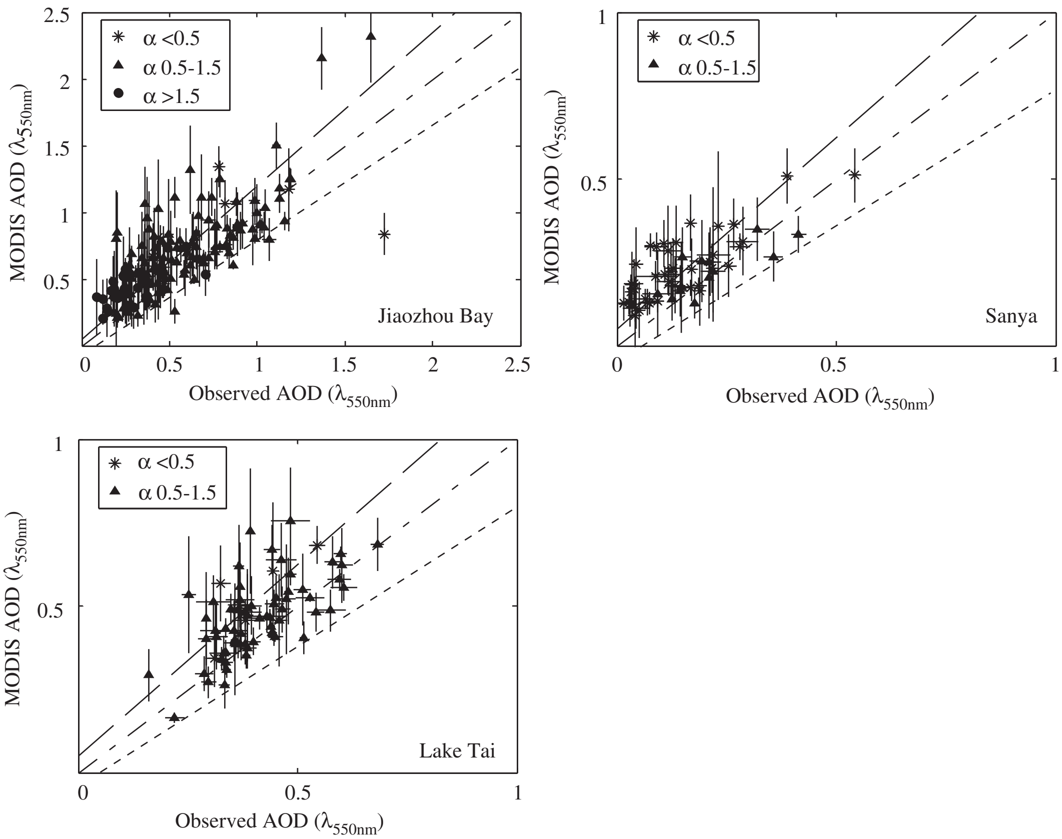

Fig. 8. $\tau_{aCSHNET}$ versus τ_{aMODIS} at a wavelength of 550 nm at sites along coastal regions of China. Dashed lines represent $y = 0.05 + 1.15x$ and dotted lines $y = -0.05 + 0.85x$, which are the expected error lines issued by NASA. Vertical bars represent the spatial standard deviations (SD) in the MODIS-derived AOD; horizontal bars represent the temporal SD in the CSHNET-derived AOD, with SD$\leqslant$0.05; and α represents the Angstrom exponent.

Sanya sites are both marine ecosystems located on the west coast of the Yellow Sea and the South China Sea, respectively, while the Lake Tai site is about 130 km west of Shanghai, which is located along the eastern shore of China. Compared with coastal sites, due to stable aerosol types, the MODIS retrieval at the Lake Tai site shows better agreement with the ratio (the number of collocated data to that of CSHNET data) of 74%, with a percentage (within the errors) of 73%, R value of 0.64, a RSME of 0.11 and a slope of 0.76. However, the offset is 0.17, significantly greater than the expected value of 0.05, which is due to water pollution in Lake Tai adding to the satellite retrieval errors. The Jiaozhou Bay and Sanya sites are both in coastal regions, where comparison results show moderate agreement. However, at Jiaozhou Bay site, due to seawater full of sand and a large change of aerosol modes, parts of the MODIS retrievals are systematically overestimated.

Fig. 9 shows the results at five agricultural sites. The MODIS AOD retrievals perform well except at the Ansai site, which is located in the typical loess hill-gullied region of the Loess Plateau. The MODIS retrieval result is underestimated against that of the CSHNET and only 19% of collocated data are within the errors at the Ansai site. This is mainly due to less vegetation and a shift of dominant aerosol types indicated by the Angstrom exponent distribution (figure not shown)—a coarse mode aerosol by dust in spring and a fine mode aerosol by fossil fuels and biomass burning in autumn and winter. Compared with farmland sites (Fengqiu, Taoyuan and Yanting, located in remote areas of central China), plots at the Shenyang site, 35 km south of Shenyang City, show large scattering and only 45% of retrievals falling within expected errors. This can be attributed to complexities of aerosol compositions (Cao et al., 2005) and the surface conditions changing before and after the

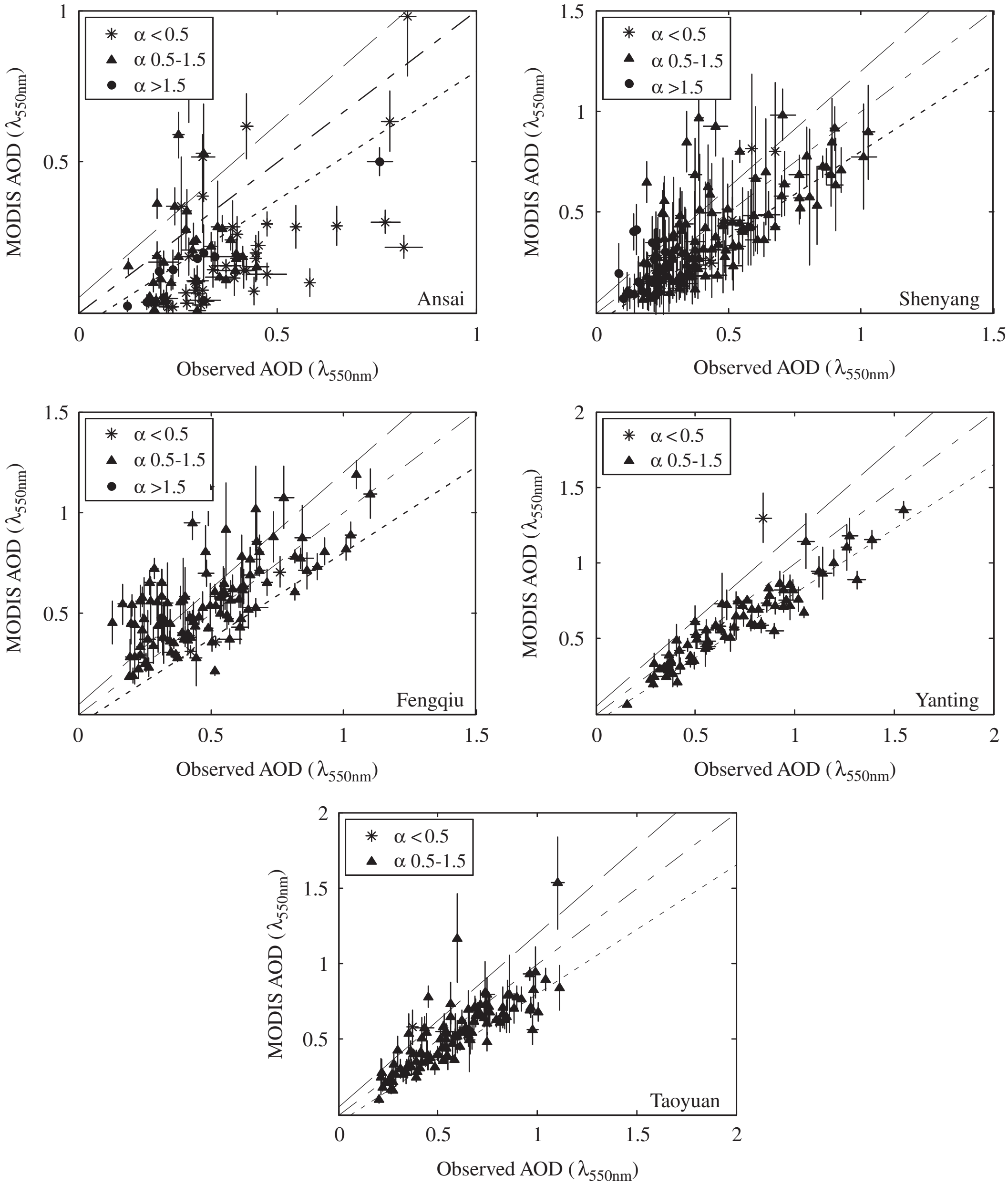

Fig. 9. $\tau_{aCSHNET}$ versus τ_{aMODIS} at a wavelength of 550 nm at agricultural sites. Dashed lines represent $y = 0.05 + 1.15x$ and dotted lines $y = -0.05 + 0.85x$, which are the expected error lines issued by NASA. Vertical bars represent the spatial standard deviations (SD) in the MODIS-derived AOD; horizontal bars represent the temporal SD in the CSHNET-derived AOD, with SD$\leqslant$0.05; and α represents the Angstrom exponent.

growing season. High correlation ($R > 0.7$) and large percentages ($R2 > 59\%$) within errors are found at farmland sites in the central regions of China, in particular at Yanting and Taoyuan ($R > 0.82$ and $R2 > 72\%$), where dense and homogeneous vegetation are the main land cover over four seasons and aerosol types are relatively stable.

4. Summary and conclusions

In this study, the accuracy of the MODIS AOD retrieval over different ecosystems in China using the CSHNET observations have been evaluated. Nineteen CERN sites located in relatively remote areas represented large-scale regional background

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conditions of certain ecosystems in China, which are favorable for evaluation against the MODIS data. Overall, the comparison results show the MODIS AOD retrievals lack the ability to accurately represent true observations in China, and thus cannot be well applied there. This can be attributed to a complexity of surface conditions and aerosol types, and to seasonal changes of surface reflectance and aerosol modes over different ecological and geographic regions. The MODIS AOD retrievals perform well over 'dark-object' surfaces (some farmland and forest sites), but poorly over 'bright-object' surfaces (deserts, arid regions and plateaus). The MODIS was found to produce poor retrievals in these regions, where the air is clear and the AOD rather low, such as in the remote northeast corner of China and in the Tibetan Plateau. The analysis in this paper indicates the need for systematic modification of the MODIS algorithm over different ecosystems and during different seasons in China.

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