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Assessment and comparison of three years of Terra and Aqua MODIS Aerosol Optical Depth Retrieval (C005) in Chinese terrestrial regions

Lili Wang [a], Yuesi Wang [a,*], Jinyuan Xin [a], Zhanqing Li [b], Xiaoyuan Wang [a]

[a] LAPC, 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 latest MODIS aerosol optical depth (AOD) retrieval algorithm (C005) based on analyses of global AERONET data for both Terra and Aqua satellites has gradually supplanted the older algorithm (C004) since 2006. However, due to few AERONET sites in China, assessing applications of MODIS products over Chinese terrestrial regions for both Terra and Aqua is very necessary, including evaluating and comparing differences between Terra and Aqua. In this study, three years of Terra and Aqua AODs (C005) were analyzed over Chinese terrestrial regions using long-term and large-scale ground-based network observation data, from the Chinese Sun Hazemeter Network (CSHNET). The results show that C005 MODIS aerosol products (C005) have enough accuracy over China, with the same correlation coefficient (R) ~0.86, the slope ~1.006 and 0.990, the offset ~−0.043 and −0.038, 53% and 50% of collocated data within the expected errors for Terra and Aqua, respectively, though there existed differences in different ecosystems and geographic locations. Overall, the MODIS products underestimated by 0.03 or 9% for Terra, 0.02 or 6% for Aqua, and more underestimation (11–16%) was noted in summer and autumn, which is based on annual and seasonal means of all sites. For different Angstrom exponent (α) ranges, the MODIS underestimated by 0.03 or 8% at the moderate α, and 0.07 or 27% for the fine (α>1.5) and coarse (α<0.5) modes, which dominated for both Terra and Aqua. Remarkably, there are no very significant differences between Terra and Aqua AODs based on long-term statistical Terra and Aqua AODs for different Angstrom exponent (α) ranges and regional monthly averages Over China, which confirms that either the Terra or Aqua estimate of AOD over China is a valid representation of the daily average, though there may be a diurnal cycle near aerosol emission regions. Moreover, the magnitude of the differences of regional monthly mean Terra and Aqua AODs varied from region to region and increased with aerosol loading, but there was no significantly consistent negative or positive bias between Terra and Aqua AODs in each region over China.

1. Introduction

Aerosols have an important climatic influence through direct and indirect radiative forcing (Houghton et al., 2001; Satheesh et al., 2005) and cloud processes (Devara et al., 1998; Rosenfeld and Lensky 1998). Aerosols also influence air quality and therefore affect human health, such as supporting cardiovascular and respiratory diseases at $PM_{2.5}$ (particulate matter, or aerosol particles, with aerodynamic diameter ≤2.5 μm) (Dockery and Pope 1994; Pope Iii et al., 2002), and reduce visibility (Samet et al., 2000). Due to the lack of accurate information on the global distribution of aerosol properties, it is very difficult to quantify its net effects.

The twin Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites were launched under the auspices of the NASA Earth Observing System (EOS) program to obtain daily remote measures of aerosols over the land and ocean, and to better understand the global aerosol budget. These data would then be used to estimate the

* Corresponding author. Tel.: +86 1082080530; fax: +86 1062041393.
E-mail address: wys@mail.iap.ac.cn (Y. Wang).

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contribution of anthropogenic emissions to the aerosol budget and to radiative forcing. The Terra satellite was first launched on December 18, 1999 and began observing that morning when it crossed the equator during the daytime at about 10:30 AM local time. The Aqua satellite was launched on May 4, 2002 for observing in the afternoon, and crossed the equator during the daytime at about 1:30 PM local time. The MODIS aerosol products, which provide the ability to monitor spatial and temporal characteristics of the global aerosol field, obtain aerosol properties over both land (Kaufman et al., 1997) and ocean (Tanré et al., 1997), using seven well calibrated spectral channels (0.47–2.1 μm). The MODIS aerosol products including different collections–002, 003, 004, 005 (C002, C003, C004, C005)–have been comprehensively validated over land on a global scale (Chu et al., 2002; Remer et al., 2005; Levy et al., 2007) by observations through the Aerosol Robotic Network (AERONET) (Holben et al., 1998). In addition, due to different channels (Barnes et al., 2004; Xiong et al., 2004; Xiong and Barnes 2006) and equatorial crossing times for these two satellites, possible differences between Terra and Aqua MODIS aerosol products over land and ocean have been investigated (Ichoku et al., 2005; Kaufman et al., 2005; Ignatov et al., 2006; Remer et al., 2006a), although the aerosol algorithms applied to the two MODIS sensors are identical.

In recent decades, in concert with a rapidly developing economy, aerosol loading in China has become heavier(Chang et al., 2009), and this has had serious effects on climate and environment change (Xu 2001; Menon et al., 2002; Huebert et al., 2003; Buzorius et al., 2004; Yu et al., 2007). MODIS aerosol products have been applied to analyze these effects in China by an increasing number of scientists (Li et al., 2005; Zhao et al., 2006). MODIS aerosol products have been extensively validated with data over China (Xia et al., 2004; Li et al., 2007; Mi et al., 2007; Wang et al., 2007) using the AERONET and the CSHNET (Xin et al., 2007) data. However, as of yet, most of the published studies used only Terra data, with little assessment of Aqua MODIS aerosol products. Furthermore, through analyzing AERONET data, Kaufman et al. (2000) demonstrated that Terra and Aqua aerosol measurements can represent the diurnal average aerosol over the world for applications to climate study, and Ichoku et al. (2005) have confirmed this conclusion in global scale. However, it is still unknown over Chinese terrestrial regions. Thus assessment and comparison of Terra and Aqua MODIS AOD retrievals over China are necessary, especially for the latest algorithm of C005.

In this paper, the MODIS AOD retrievals at 550 nm wavelength on both Terra and Aqua satellites were assessed over a period of three years (August, 2004–July, 2007) and compared with CSHNET-derived AOD data over China, with attention to different ecosystems, geographic locations, seasons and Angstrom Exponent ranges. In addition, aerosol distribution over China is analyzed based on the three-year mean MODIS AODs over China and regional monthly MODIS means from Terra and Aqua satellites, respectively.

2. Data

2.1. The Chinese Sun Hazemeter Network

The Chinese Sun Hazemeter Network (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. A description of the network and the instruments utilized can be found in Xin et al. (2006, 2007). Fig. 1 shows the locations of the 25 sites in the CSHNET. Nineteen CERN (Chinese Ecosystem Research Network) stations represented the typical ecosystems of China which are located in relatively remote areas in order to represent large-scale regional background conditions of certain ecosystems (e.g. desert and semi-desert regions, agricultural areas, forest ecosystems, and coastal regions). The hazemeters measured AODs at three wavelengths (405 nm, 500 nm and 650 nm), and the measurement period was from 10 AM to 2 PM (local time), which encompasses the passing time of both the Terra and Aqua satellites. Measurements were taken three times every half an hour and at least 15–20 times a day; weather conditions and cloud coverage were synchronously recorded during the measurement periods, but no observations were made if the cloud amount was greater than four-fifths. The LED hazemeters were uniformly calibrated by Langley plot calibration and instrument inter-comparisons on an annual basis; observations showed good agreement with CIMEL Sun photometer values used in the AERONET (Xin et al., 2006, 2007). To compare with MODIS data, the values of the CSHNET data at 550 nm were interpolated on a log–log plot assuming linearity at 500 nm and 650 nm, using the formula $\ln(\tau_a) = a \times \ln(\lambda) + b$, where τ_a is the aerosol optical depth and λ is the wavelength (Eck et al., 1999; Zhao et al., 2002; Remer et al., 2005). The spatial and temporal distribution and seasonal variations of aerosol optical properties of the CSHNET have been described in the work of Xin and Wang et al. (Xin et al., 2007; Wang et al., 2008). Table 1 shows geographic and ecological information and aerosol features in each CSHNET site.

2.2. The MODIS aerosol products

The MODIS aerosol algorithm is actually two independent algorithms, one for deriving aerosols over land (Kaufman et al., 1997) and the other for aerosols over the ocean (Tanré et al., 1997). In this paper, MODIS aerosol products over land were evaluated, and C005 level 2 MODIS aerosol products produced at a spatial resolution of a 10 × 10 km pixel array were used from the Terra and Aqua MODIS sensors. Compared to C004, the latest algorithm (C005) has four major changes (Jethva et al., 2007): 1) the new algorithm uses updated aerosol models based on the results found by Dubovik et al. (2002) and derived using “subjective cluster analysis” of AERONET Level-2 data which yielded three fine-dominated models and one spheroid dust model with new geographic distribution of fine-dominated models; 2) the look-up-table (LUT) calculations in C005 are based on a combination of MIE code (Wiscombe, 1980) and RT3 radiative transfer code (Evans and Stephens, 1991), which jointly account for the effects of polarization; 3) the new algorithm no longer assumes that the 2.1 μm channel is transparent to aerosols, and; 4) the SWIR relationships used to estimate surface reflectance in the visible channels ($\rho_{0.66}{}^{s}$ $\rho_{0.47}{}^{s}$) from the reflectance in the 2.1 μm channel ($\rho_{2.1}{}^{s}$) are parameterized depending in part on “green-ness” of the target (Normalized Difference Vegetation Index($NDVI_{swir}$), based on 1.24 μm and

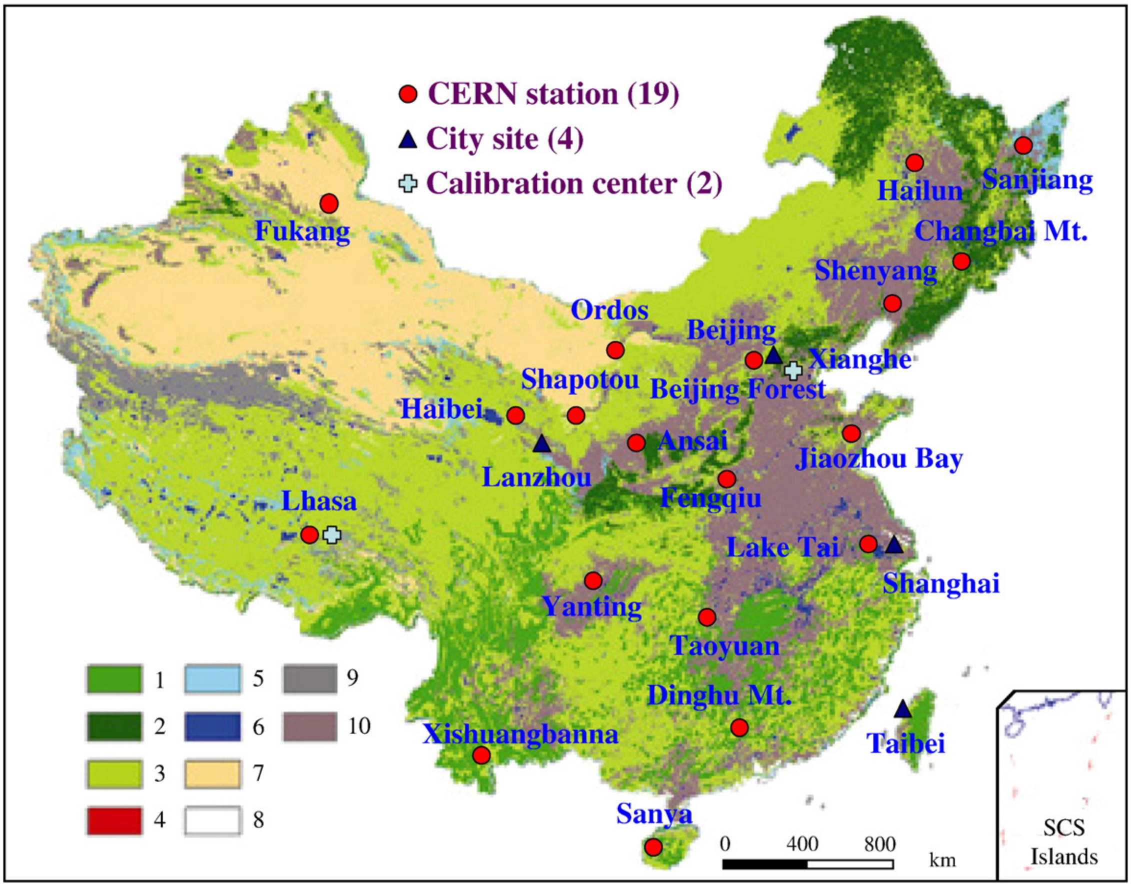

Fig. 1. Geographical locations of observation sites in the Chinese Sun Hazemeter Network (CSHNET). The map of land cover type of Chinese terrestrial ecosystem is from Pan et al. (2005). The legend codes are as follows: 1. tropic and sub-tropic forests; 2. temperate forests; 3. grassland/shrub; 4. mangrove; 5. swamp/marsh; 6. river/lake; 7. desert; 8. tundra; 9. glacier/bare rock; 10. cultivation.

2.1 μm) and scattering angles(θ), $\rho_{0.66}{}^{s}=f(\rho_{2.12}{}^{s},\mathrm{NDVI}_{swir},\theta)$, $\rho_{0.47}{}^{s}=g(\rho_{0.66}{}^{s})$. Details of the latest algorithm and main changes have been described in Remer et al. (Remer et al., 2006b; Levy et al., 2007). MODIS AODs are at wavelengths of 470 nm and 660 nm, and AODs at a wavelength of 550 nm were interpolated from the 470 nm and 660 nm retrieval values (Remer et al., 2005).

3. Results and discussion

3.1. Assessment of the Terra and Aqua MODIS AODs (C005) by the CSHNET over China

The CSHNET AOD data were matched with the MODIS AOD retrievals in time and space following the method in Ichoku et al. (2002) (CSHNET observations within ±30 min of MODIS overpasses and MODIS data including at least five pixels at a 50-km area centered over CSHNET sites). Additionally, the CSHNET observations with standard deviations (SD)>0.05 were deleted to reduce validation errors due to heterogeneity and questionable data. Fig. 2 shows the modified scatterplots with the MODIS data and CSHNET observations (all collocated data sorted according to the CSHNET AODs which are classed at the interval of 0.05), instead of the actual scatterplots due to a large volume of data (three years' worth of values). A similar method was used by Ichoku et al. (2005) and Remer et al. (2005). Over China, at the largest AOD values ($\tau>1.2$, both Terra and Aqua), wide fluctuation was found, which is probably associated with less samples and greater spatial and temporal variation in AOD. For Terra, the percentage of MODIS AOD within the expected errors (R^2) was about 55% for low AOD values ($\tau<0.6$), and about 65% for moderate AOD values. However, for Aqua, R^2 percentages were about 55% for both the low and moderate AOD values. More tendencies to underestimation both for Terra and Aqua MODIS AODs were showed in Fig. 2. The linear regression analysis of all the actual MODIS and CSHNET collocated data showed the same $R\sim0.86$, and differing slopes (sl) ~1.006 and 0.990, and offsets ~−0.043 and −0.038 for Terra and Aqua, respectively. These values were in their excepted error ranges; 53% and 50% of collocated data were within the expected errors for Terra and Aqua, respectively. Overall, there does not appear to be any clear difference in performance between Terra AOD and Aqua AOD. Compared to C004 (evaluated by Ichoku et al., 2005 and Wang et al., 2007), the new MODIS algorithm C005 is much better and improved upon the earlier version particularly by correcting past overestimations at low AOD values, e.g., the R for C005

Table 1
Geographic and ecological information and aerosol features in each CSHNET site.

Site	Ecosystem/ geographic region	Ecosystem	Longitude	Latitude	Altitude (m)	Aerosol features
Lhasa	Tibetan Plateau	Alpine shrub-grassland	91.33	29.67	3688	Low AOD; large continental/dust aerosols
Haibei		Alpine meadow	101.32	37.45	3230	Low AOD; fine smoke aerosols in autumn/winter, large continental or dust aerosols in spring/summer
Shapotou	Northern desert regions	Desert	104.95	37.45	1357	Dust aerosols
Ordos		Sandy grassland	110.18	39.48	1300	Fine smoke aerosols in autumn/winter, large continental or dust aerosols in spring/summer
Fukang		Oasis in the transition zone	87.92	44.28	470	
Ansai		Arid agrarian land	109.31	36.85	1208	
Hailun	Remote northeastern corner of China	Agriculture	126.63	47.43	240	Low AOD (except for Shenyang); fine smoke aerosols in autumn/ winter, continental aerosols in spring/summer
Sanjiang		Marsh/farmland	133.52	47.58	56	
Changbai Mt.		Temperate forest	128.63	42.40	736	
Shenyang		Suburban farmland	123.63	41.52	31	
Beijing Forest	Forest regions	Warm temperate forest	115.43	39.96	1130	Smoke in autumn/winter, dust in spring/summer
Dinghu Mt.		Subtropical evergreen forest	112.53	23.17	300	High AOD, urban/industrial pollution except sea salt in summer
Xishuangbanna		Tropical rainforest	101.27	21.90	570	Smoke in spring, low AOD in summer/autumn due to rain
Sanya	Lake and coastal regions	Tropical marine ecosystem	109.47	18.22	3	Low AOD; sea salt except pollution aerosols in spring
Jiaozhou Bay		Marginal sea	120.18	35.90	6	High AOD; urban/industrial pollution; while dust in spring/ summer
Lake Tai		Freshwater lake	120.22	31.40	6	High AOD; urban/industrial pollution, smoke, soil dust, sulphate
Shanghai	Cities	Urban	121.75	31.12	5	High AOD
Lanzhou		Urban	103.82	36.07	1520	High AOD, smoke and dust in winter/spring; urban/industrial in summer/autumn
Beijing		Urban	116.37	39.97	44	High AOD, smoke and little dust in winter and spring; urban/ industrial in summer and autumn
Xianghe		Suburban	116.96	39.75	40	
Fengqiu	Farmland regions	Agriculture	114.40	35.00	68	High AOD, industrial and anthropogenic aerosols, mineral and soil dust
Yanting		Agriculture	105.45	31.27	420	
Taoyuan		Agriculture	111.45	28.92	78	

relative to C004 increasing from 0.72 to 0.87, sl from 0.78 to 1.02, offset decreasing from 0.11 to −0.05, and percentage within the expected errors increasing from 44% to 83%, resulting from evaluating Terra AOD and CSHNET AOD during August 2004–June 2006, which is consistent with the findings by Li et al. (2007).

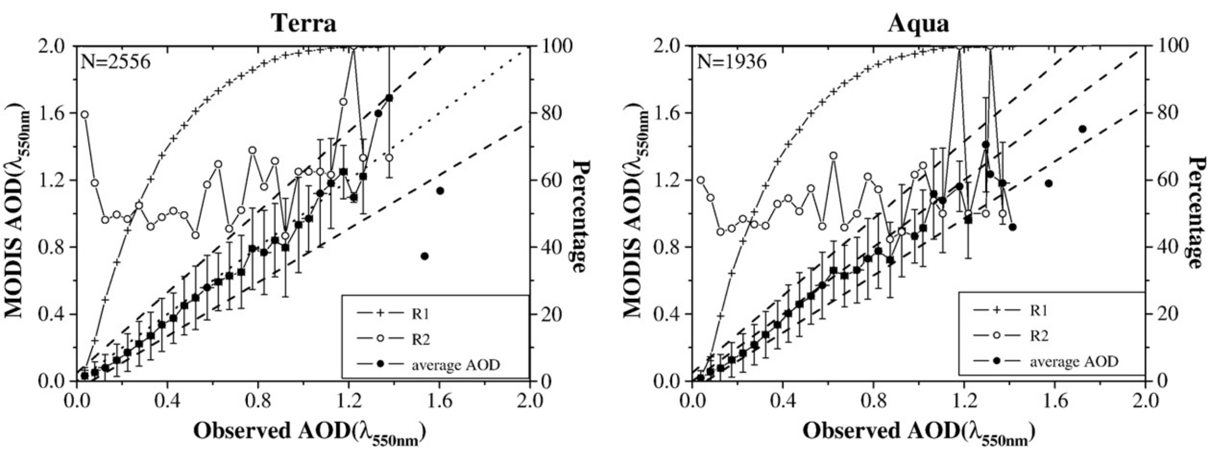

Fig. 2. Comparisons of $\tau_{aCSHNET}$ and τ_{aMODIS} at a wavelength of 550 nm from Terra and Aqua over China. The data are sorted according to the collocated CSHNET AODs which are classed at the interval of 0.05. Dashed lines represent $y = 0.05 + 1.15x$ and dotted lines $y = -0.05 + 0.85x$, which are the expected error lines issued by NASA. Vertical bars and horizontal bars represent the standard deviations (SD) of AOD classes for MODIS and CSHNET, respectively. $R1$ is the cumulative percentage of data points in each class and $R2$ is the percentage of MODIS AOD within the expected error lines in each class. N is the total number of collocated data points.

Table 2
Statistical values for the assessment of the Terra and Aqua MODIS AOD values and those of the CSHNET at different sites in the CSHNET, including the number of points (Number), correlation coefficient (*R*), linear regression slope (Sl) and offset, the root mean square errors (RSME), and the percentage of MODIS AOD values falling within the expected error lines (R^2).

Site	Terra						Aqua					
	N	*R*	RMSE	Sl	Offset	R^2	*N*	*R*	RMSE	Sl	Offset	R^2
Lhasa	57	0.57	0.06	1.02	−0.040	68.4	26	0.36*	0.08	0.83	−0.041	50.0
Haibei	78	0.68	0.06	0.63	0.024	71.8	54	0.62	0.08	0.88	0.006	72.2
Shapotou	18	0.71	0.08	0.68	0.120	83.3	9	0.58*	0.07	0.33	0.156	75.0
Ordos	151	0.80	0.10	0.68	−0.008	62.3	101	0.82	0.09	0.95	−0.047	66.3
Fukang	83	0.77	0.12	1.30	0.046	47.0	69	0.77	0.12	1.37	0.035	46.4
Ansai	140	0.60	0.18	0.58	0.016	37.1	31	0.80	0.09	0.96	−0.024	48.4
Hailun	128	0.53	0.15	0.47	−0.050	14.1	97	0.75	0.14	0.77	−0.092	10.3
Sanjiang	95	0.82	0.13	0.96	−0.093	32.6	86	0.77	0.13	1.01	−0.099	37.2
Changbai Mt.	99	0.84	0.08	0.84	−0.039	59.6	64	0.82	0.09	0.83	−0.041	60.9
Shenyang	223	0.90	0.16	0.94	−0.097	39.0	212	0.87	0.17	0.86	−0.064	42.0
Beijing Forest	257	0.92	0.09	0.94	−0.045	65.0	146	0.89	0.09	0.92	−0.048	50.7
Dinghu Mt.	52	0.91	0.11	1.07	−0.061	88.5	43	0.82	0.15	0.95	−0.006	76.7
Xishuangbanna	133	0.91	0.22	0.80	−0.118	9.0	160	0.92	0.19	0.79	−0.094	14.4
Sanya	53	0.82	0.14	0.56	0.062	41.5	64	0.86	0.12	0.59	0.057	53.1
Jiaozhou Bay	153	0.89	0.16	1.14	−0.062	69.3	100	0.85	0.16	0.88	0.05	68.0
Lake Tai	45	0.54	0.18	0.78	0.216	48.9	29	0.66	0.17	0.71	0.271	44.8
Shanghai	83	0.81	0.30	1.25	0.108	22.9	67	0.61	0.31	0.67	0.404	31.3
Lanzhou	78	0.19*	0.28	0.21	0.353	42.3	50	0.19*	0.22	0.17	0.368	46.0
Beijing	127	0.90	0.16	0.98	0.106	51.2	59	0.82	0.18	0.84	0.161	45.8
Xianghe	128	0.90	0.17	0.76	−0.011	49.2	115	0.87	0.17	0.89	−0.037	50.4
Fengqiu	141	0.93	0.11	1.14	−0.034	84.4	150	0.87	0.13	1.06	0.011	72.7
Yanting	84	0.94	0.13	1.13	−0.099	76.2	70	0.95	0.12	1.02	−0.061	80.0
Taoyuan	150	0.87	0.13	0.98	−0.001	75.3	135	0.87	0.14	1.06	−0.034	65.2

*Correlation is insignificant at the 0.01 level.

The statistical correlation analyses between the two sets of data over different ecosystems and Geographic regions in China are shown in Table 2. The regional assessment results revealed significant differences in different sites for the same satellite; however, for the same site, the differences between the two satellites were smaller than those across different regions. For Terra and Aqua, the best retrieval regions were farmland sites in central and central-southern China, and in temperate and subtropical forests, with *R* ~0.82–0.95, R^2 ~61%–89%, and the values of sl and offset falling within the expected error ranges. The poorest retrieval was obtained in the eastern inland lakes, remote northeast regions, tropical rainforests and urban regions with R^2 ~9%–51%, and large variations of slopes to 1 or large offsets. Because the slopes represent systematic biases if differing from 1 (mainly due to aerosol model assumptions, instrument calibration, etc.) and the offsets represent the errors in the surface reflectance estimates (Chu et al., 2002), the slopes and offsets can reflects the probable causes leading to retrieval errors.. Significantly, in the Tibet Plateau and the northern arid and semiarid regions (except in Shapoto which had too little collocated data for analyses), there were some improvements in statistical values when compared to C004 which has been evaluated by Wang et al., 2007, especially offsets ~0.01–0.05 which indicate that the new algorithm at least partially corrected for influence by surface reflectance. In conclusion, the reasons for the improvement in the AOD retrievals could be the introduction of the parameterized reflectance relationships into the algorithm and new aerosol models based on Dubovik et al. (2002), especially improvement for surface reflectance estimate except for eastern inland lakes and urban regions. However, the single scattering albedo (SSA) assumed by the C005 over most Chinese regions is 0.90 for the whole year, which cannot reflect the true SSA or aerosol properties in different regions and in different seasons over China (Lee et al., 2007; Li et al., 2007; Mi et al., 2007), as showing at Table 1, which probably introduces the errors to the retrieval algorithm.

The seasonal and annual means over all of the regions, as well as the spatial correlation coefficients (*R*) between MODIS and CSHNET based on the seasonal and annual means in different sites, are listed in Table 3. For seasonal averaged

Table 3
The seasonal and annual means of AOD_{Terra}, AOD_{Aqua}, and AOD_{CSHNET} based on values of all CSHNET sites, corresponding relative errors [RE = (AOD_{MODIS} − AOD_{CSHNET}) / AOD_{CSHNET} × 100%] and spatial correlation coefficients (*R*) based on seasonal and annual mean co-located values between MODIS and CSHNET AODs for both Terra and Aqua during three years.

	Terra				Aqua			
	CSHNET	MODIS	RE (%)	Spatial *R*	CSHNET	MODIS	RE (%)	Spatial *R*
Spring	0.39	0.40	3	0.88	0.37	0.40	8	0.87
Summer	0.34	0.30	−12	0.89	0.28	0.25	−11	0.89
Autumn	0.33	0.28	−15	0.87	0.32	0.27	−16	0.94
Winter	0.25	0.22	−12	0.91	0.29	0.27	−7	0.95
Annual mean	0.35	0.32	−9	0.90	0.34	0.32	−6	0.92

values of all sites, the MODIS data revealed underestimation by 7–16%, except for data collected in spring, for both Terra and Aqua, and using annual means resulted underestimations of 0.03 or 9% and 0.02 or 6% for Terra and Aqua, respectively. The spatial R between the MODIS and CSHNET values based on the seasonal and annual means in different sites were greater than 0.87 for both Terra and Aqua, which should be helpful in improving the $PM_{2.5/10}$ retrieval levels by AOD distribution in China. The results of the MODIS as compared to the CSHNET at different sites, for the four seasons are depicted in Fig. 3. Because snow is the main land cover in winter in north regions of China, there were no MODIS data in these regions. The trend of MODIS overestimation or underestimation for both Terra and Aqua at one site is almost the same; however, there were significant differences across ecosystems and geographic locations for the same satellite and same season. Specifically, the MODIS underestimated in the Tibetan Plateau area, northwest (except for Fukang), forests (except for Dinghu Mt.), and northeast of regions of China, and overestimated in city regions and eastern lake regions of China. Moreover, the differences between the MODIS and the CSHNET data were different across the four seasons in farmland sites in central-southern China. As mentioned above, in spring, the MODIS data revealed slightly overestimation by 3–8% for both Terra and Aqua; and the results of the MODIS as compared to the CSHNET at different sites during this period showed overestimation in urban cities, eastern coastal and lake regions of China, and farmland regions in central-southern China; in addition, the analysis in next Section 3.2 showed the MODIS values were slight overestimations at the moderate α in spring for both Terra and Aqua; thus, the overestimation in spring may caused by wrong aerosol models assumption in some degree.

3.2. Comparison of the Terra and Aqua MODIS AODs (C005) over China

The three-year (August 2004–July 2007) mean AODs at 550 nm wavelength over China based on the MODIS 1 × 1°level-3 monthly mean products from Terra and Aqua are showed in Fig. 4(a) and (b), respectively; Fig. 4(c) shows the differences in AOD between the two satellites. The distributions of the three-year means of Terra and Aqua both show the largest AODs (over 0.4) centered in the central, east, southeast, and northwest of China, which is caused by many anthropogenic sources of aerosol in southeast and dust aerosols in northwest. The lowest AOD values centered in the Qinghai–Tibet Plateau and the far northeast corner of China, which is in accordance with the results from Xin et al. (2007) and Wang et al. (2008). In Chinese terrestrial regions, the difference between Terra and Aqua was about −0.05–0.05, except in some northwest regions that displayed larger differences, and the AODs observed by Terra were slightly higher than those observed by Aqua, particularly in south and north China and lower in most other regions of China. Overall, the differences in performance between Terra and Aqua, which may be caused by a true diurnal signal or retrieval errors, are not very significant. Through analyzing AERONET data, Kaufman et al. (2000) posed a conclusion: "each polar orbiting satellite that measure aerosol should be able to represent the daily average impact of aerosol on climate, independent of morning or afternoon orbit." Is it true over China? Then, we will confirm it through comparing long-term statistical Terra and Aqua AODs based on different Angstrom exponent (α) ranges and regional monthly average.

Firstly, the Angstrom exponent (α) was calculated using log-linear fitting with three wavelengths (405 nm, 500 nm and 650 nm) of the CSHNET (Kim et al., 2004), and, in general, the Angstrom exponent ranged from 0.0 to 2.0 with smaller Angstrom exponents corresponding to larger aerosol particle sizes (Dubovik et al., 2002; Kim et al., 2004). Terra and Aqua AODs were averaged according to three α ranges calculated through CSHNET AODs at three wavelengths (405 nm, 500 nm and 650 nm). The comparison results of the MODIS and CSHNET data are shown in Fig. 5. Significantly, the MODIS values for both Terra and Aqua underestimated the AOD values relative to those of the CSHNET in all three α ranges. The differences were 0.03 or 8% at the moderate α level and higher at 0.06–0.08 or 21–33% for $\alpha > 1.5$ (fine mode dominated aerosols) and $\alpha < 0.5$ (coarse mode dominated aerosols). However, the differences between the Terra and Aqua values for the three α ranges were smaller (0.005–0.015), which is not significant difference, and the Terra values were a little lower than the corresponding Aqua values. Therefore, MODIS would underestimate the average AOD over China by about 0.03–0.07 from both Terra and Aqua together, which is approximately consistent with MODIS expected errors ($\pm 0.05 \pm 0.15$*AOD) over land.

To assess the seasonal trends of AOD based on different α ranges, monthly means of MODIS AODs and (CSHNET–MODIS) differences are depicted in Fig. 6. The seasonal trends of Terra and Aqua AODs for different α ranges are similar, and there were no significant differences between them. The MODIS values were almost all lower than the CSHNET values for all three α divisions and both satellites. However, the MODIS values were slight overestimations at the moderate α in spring for both Terra and Aqua, and at the low α in winter only for Terra. However, there was a significant seasonal change trend: high AOD values in spring and summer and low AOD values in winter for the three α divisions and both satellites, a finding which corresponds to the results found by Ichoku et al. (2005).

Regional monthly mean Terra and Aqua MODIS AODs, and their differences (Terra − Aqua) at 550 nm wavelength over different ecological regions are shown in Fig. 7. The regional means were derived from MODIS level 2 aerosol products from Terra and Aqua and the regions were 50 km × 50 km centered at different sites in the CSHNET. These were (a) on the Tibetan Plateau, (b) at the northern desert region, (c) in the remote northeast corner of China, (d) in the forest region, (e) in the lake and coastal regions of China, (f) in the city regions and (g) in the farmland region. To make data more representative, regional monthly mean AODs for both Terra and Aqua were eliminated if calculated from fewer than three days of AOD data. Due to snow and sparse vegetation, no data were available for winter in the Tibetan Plateau, northwest or northeast of China; in addition, sometimes there were no data in south of China due to rain in summer. Consistent with the distribution of ground-based observations by Xin et al. (2007), in most parts of China, both Terra and Aqua AODs were at maximum levels in spring or summer and at a minimum in autumn or winter, especially in northern regions. The higher regional monthly mean values, ranging from 0.3 to 1.5, were found in the central, east and southeast regions of China, which are densely populated and

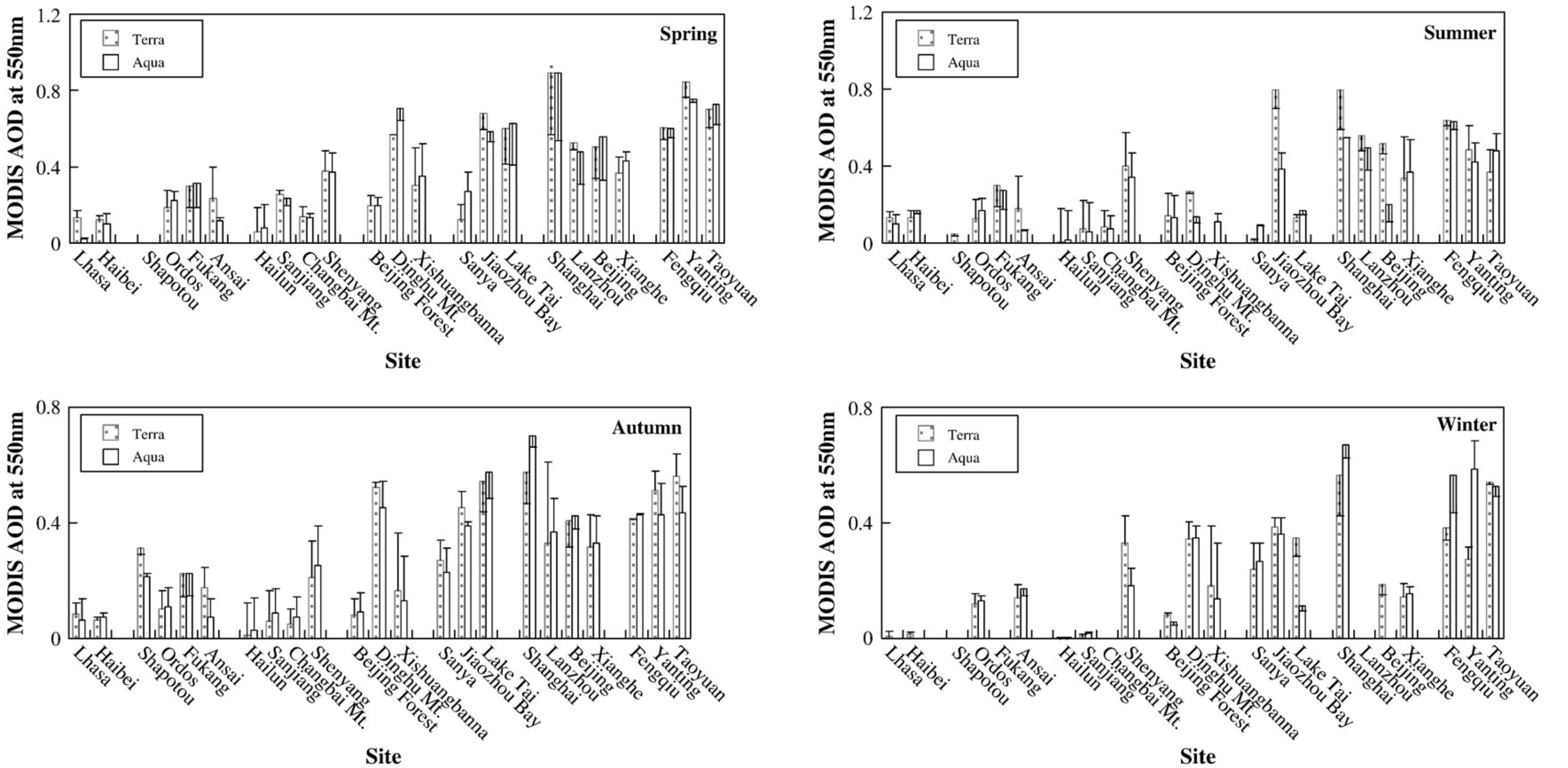

Fig. 3. Comparison of the MODIS AOD values at 550 nm with the CSHNET at different sites for the four seasons. The bars represent the Terra and Aqua MODIS regional means computed from a 50 km area centered at the CSHNET sites; the vertical spikes are the corresponding average (CSHNET–MODIS) differences and represent the MODIS underestimation or overestimation with respect to CSHNET data, depending on whether they project above or below the top of the bar.

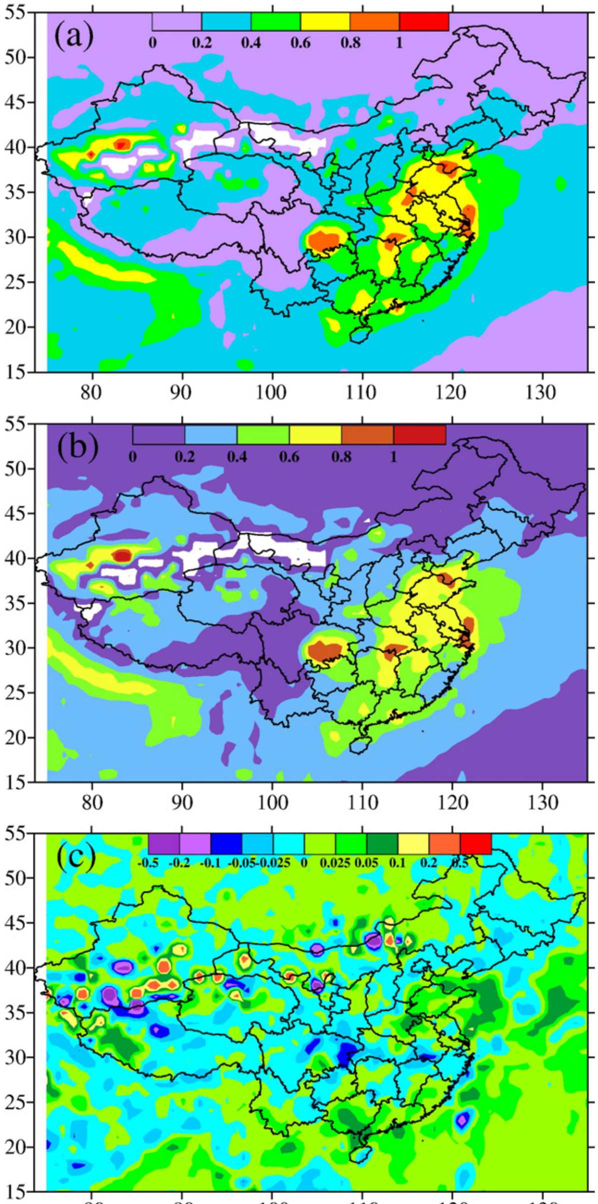

Fig. 4. The three-year (August 2004–July 2007) mean AODs at 550 nm wavelength over China derived from MODIS 1°×1° level-3 monthly mean products. (a)Terra; (b)Aqua; (c) (Terra − Aqua) differences.

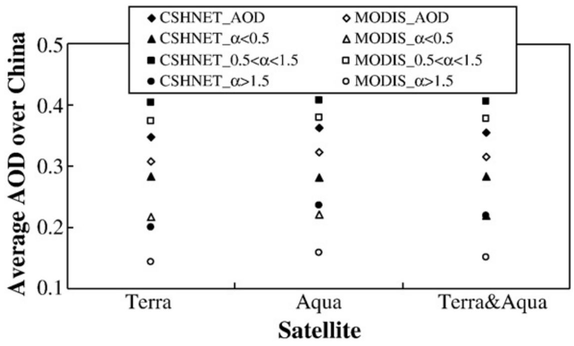

Fig. 5. Plots of average AOD values from Terra, Aqua and CSHNET over China, calculated from all collocated data and sorted according to three Angstrom exponent (α) ranges which were calculated with CSHNET AODs at three wavelengths (405 nm, 500 nm and 650 nm).

industrialized regions. The lower values, ranging from 0.05 to 0.6, were found in the northwest, northeast and south areas of China as well as on the Tibet Plateau. The annual Terra AOD was slightly lower by 0.003 or 0.6% than Aqua AOD, with an RMSE of 0.033, based on monthly means for all sites, which is a consistent trend with the founding by Ichoku et al. (2005) over land; in addition, for mean regional (Terra − Aqua) differences ($MD_{(T-A)}$), the Tibetan Plateau, northeast of China, temperate and subtropical forests, and eastern coastal regions showed a slight negative bias for Terra of 0.002–0.033; and the rest of regions demonstrated a slight positive bias for Terra of 0.002–0.052 (Fig. 4). The differences between regional monthly mean Terra and Aqua AODs were changing throughout the year at each region, and there was no significantly consistent negative or positive bias between the two satellites. Differences between Terra and Aqua could be caused by either a strong diurnal signal or low density of data, or retrieval errors. Overall, there is no statistically significant difference between long-term Terra and Aqua monthly average AODs in each region over China, which supports the founding by Kaufman et al. (2000), though a diurnal cycle can exist near aerosol emission sources that may have a strong diurnal signal, e.g., from biomass burning emissions (Prins et al., 1998). Interestingly, the magnitude of the differences of regional monthly mean Terra and Aqua AODs varied from region to region and increased with aerosol loading, which supports the founding by Ichoku et al. (2005), e.g., low ($MD_{(T-A)}$ ~−0.026–0.024, RMSE ~0.042–0.081) in northwest, remote northeast and south China and the Tibet Plateau with overall $AOD_{AM}^{Terra}<0.40$, and high ($MD_{(T-A)}$ ~−0.033–0.052, RMSE ~0.111–0.225) in central, east and southeast China with $AOD_{AM}^{Terra}>0.45$.

4. Conclusions

The Terra and Aqua MODIS AOD Retrieval (C005) data were assessed and compared over Chinese terrestrial regions comprising different ecosystems and geographic locations, four seasons and three α ranges, using three years of the CSHNET data. The analyses show the better agreement between Terra and Aqua MODIS data and CSHNET data, than that obtained using the older MODIS version (C004). The large retrieval improvement across almost all sites was likely due to the new parameterized reflectance relationship and new aerosol models, especially the improvement in Tibetan Plateau and northern arid and semiarid regions. For Terra and Aqua, the best retrieval regions were farmland sites in central and central-southern China, and temperate and subtropical forest regions, with R~0.82–0.95, R^2~61%–89%; the poorest retrieval was found in eastern inland lakes, remote northeast regions, tropical rainforests and urban regions with R^2~9%–51%, and larger offsets ~0.06–0.4 due to cloud coverage, surface reflectance or aerosol modes. Overall, compared to the CSHNET data, both Terra and Aqua MODIS data underestimate the average AOD over China by about 0.03–0.07, which is approximately consistent with MODIS expected errors (±0.05±0.15*AOD) over land. Remarkably, the differences

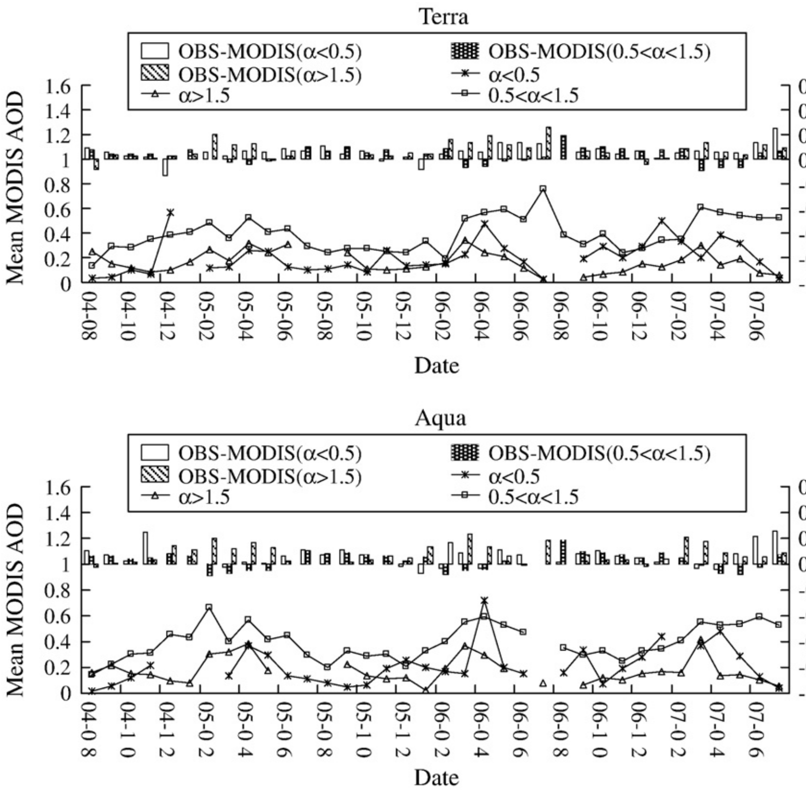

Fig. 6. Time series of monthly mean MODIS AODs and CSHNET–MODIS differences. The means were calculated from all collocated data and sorted according to three CSHNET α ranges.

between Terra and Aqua in different seasons or α ranges were found to be much smaller than those comparing MODIS to CSHNET presented above.

In most parts of China, the regional monthly means from Terra and Aqua show that AODs are at a maximum in spring or summer and at a minimum in autumn or winter. Moreover, the distributions of Terra and Aqua show the lowest AOD values (AOD_{AM}^{Terra}<0.4; AOD_{RM} ~0.05–0.6) centered in the Qinghai–Tibet Plateau and the far northeastern corner of China and Hainan Island, while the largest AOD values (AOD_{AM}^{Terra}>0.45; AOD_{RM} ~0.3–1.5) were centered in central, east, southeast and northwest China, which may be due to many anthropogenic sources of aerosol in southeast and dust aerosols in northwest. The differences between Terra and Aqua AOD average values are not very significant based on long-term statistical Terra and Aqua AODs for different Angstrom exponent (α) ranges and regional monthly averages, thus, either the Terra or Aqua estimate of AOD over China is a valid representation of the daily average, although Terra values are slightly lower than Aqua ones. Moreover, the magnitude of the differences of regional monthly mean Terra and Aqua AODs varied from region to region and increased with aerosol loading, but there was no significantly consistent negative or positive bias between Terra and Aqua AODs in each region over China.

Finally, the analyses in this paper indicate the increased usefulness of the MODIS AOD products both for Terra and Aqua over Chinese Terrestrial regions, in turn providing evidence of their applicability and encouraging further research examining MODIS data obtained over China.

Acknowledgments

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References

Barnes, W.L., Xiong, X., Salomonson, V.V., 2004. MODIS instrument status and operational activities. Proc. SPIE 5542 (14). doi:10.1117/12.558185.
Buzorius, G., McNaughton, C.S., Clarke, A.D., Covert, D.S., Blomquist, B., Nielsen, K., Brechtel, F.J., 2004. Secondary aerosol formation in continental outflow conditions during ACE-Asia. J. Geophy. Res. 109 (D24203). doi:10.1029/2004JD004749.
Chang, D., Song, Y., Liu, B., 2009. Visibility trends in six megacities in China 1973–2007. Atmos. Res 94 (2), 161–167.
Chu, D.A., Kaufman, Y.J., Ichoku, C., Remer, L.A., Tanré, D., Holben, B.N., 2002. Validation of MODIS aerosol optical depth retrieval over land. Geophys. Res. Lett. 29 (12), 8007.
Devara, P.C.S., Pandithurai, G., Raj, P.E., Maheskumar, R.S., Dani, K.K., 1998. Atmospheric aerosol–cloud-stability relationship as observed with optical and radio remote sensing techniques. Atmos. Res. 49 (1), 65–76.
Dockery, D.W., Pope, C.A., 1994. Acute respiratory effects of particulate air pollution. Annu. Rev. Public Health 15 (1), 107–132.

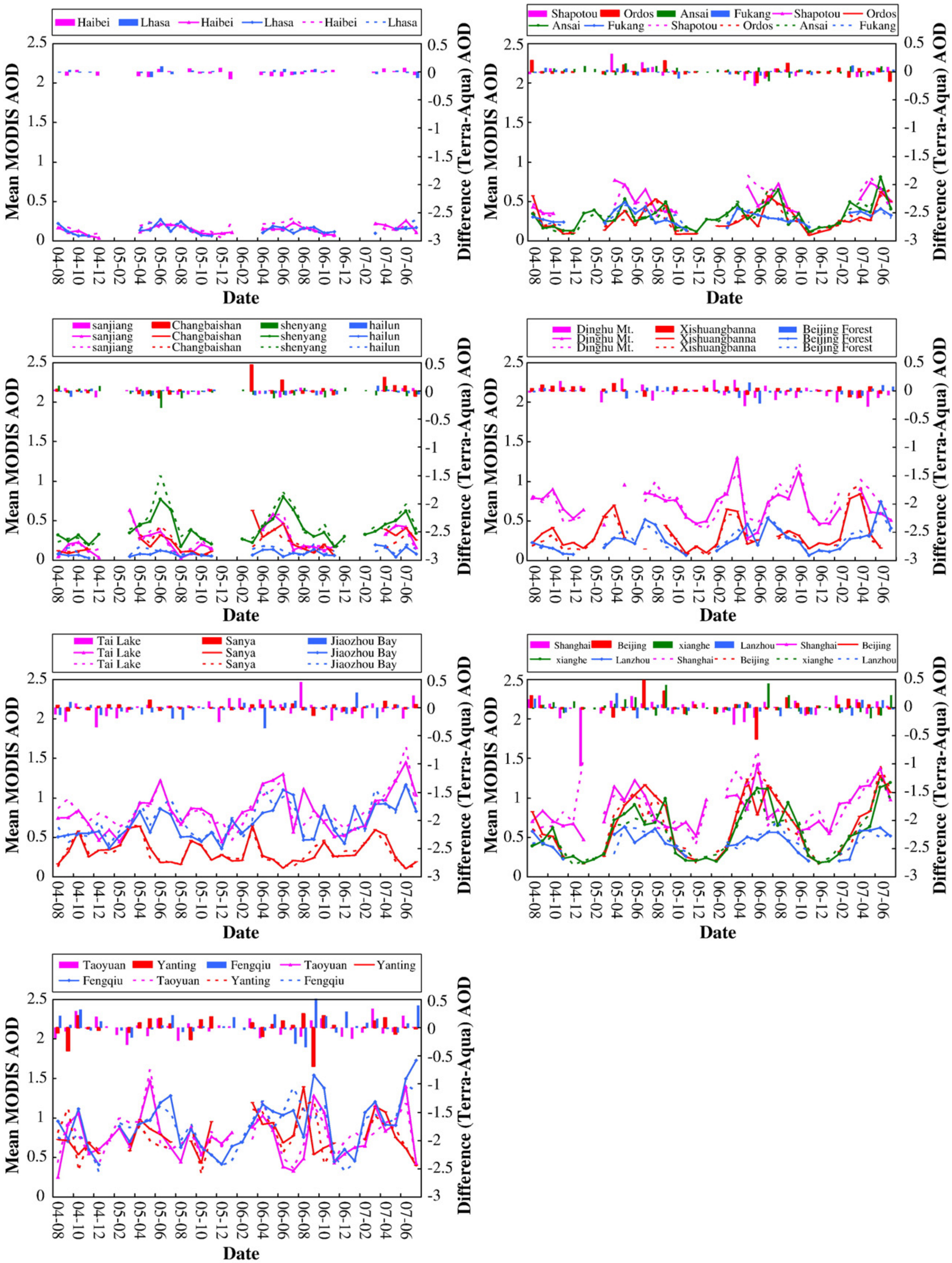
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Table 4
The annual means and standard deviations of AOD_{Terra}, mean regional (Terra − Aqua) differences ($MD_{(T-A)}$) of AODs based on monthly means at 550 nm, and root mean squared errors (RMSE) between Terra and Aqua in different CSHNET sites and over different ecosystems from July 2004 to June 2007.

Site	AOD_{AM}^{Terra}	$MD_{(T-A)}$	RMSE
Lhasa	0.141 ± 0.056	−0.002	0.042
Haibei	0.144 ± 0.055	−0.016	0.053
Shapotou	0.523 ± 0.152	0.002	0.117
Ordos	0.276 ± 0.164	0.003	0.081
Fukang	0.301 ± 0.087	0.003	0.048
Ansai	0.317 ± 0.156	0.013	0.071
Hailun	0.086 ± 0.044	−0.023	0.048
Sanjiang	0.248 ± 0.164	−0.005	0.051
Changbai Mt.	0.226 ± 0.145	−0.023	0.113
Shenyang	0.390 ± 0.166	−0.026	0.081
Beijing Forest	0.260 ± 0.157	−0.007	0.069
Dinghu Mt.	0.697 ± 0.218	−0.024	0.131
Xishuangbanna	0.327 ± 0.201	0.024	0.059
Sanya	0.319 ± 0.156	0.004	0.049
Jiaozhou Bay	0.679 ± 0.212	−0.033	0.111
Lake Tai	0.830 ± 0.261	−0.024	0.154
Shanghai	0.854 ± 0.246	−0.020	0.225
Lanzhou	0.445 ± 0.137	−0.011	0.097
Beijing	0.662 ± 0.353	0.012	0.163
Xianghe	0.554 ± 0.326	0.023	0.136
Fengqiu	0.914 ± 0.334	0.052	0.185
Yanting	0.773 ± 0.234	0.011	0.191
Taoyuan	0.770 ± 0.296	−0.008	0.146
All sites	0.475 ± 0.107	−0.003	0.033

Dubovik, O., Holben, B., Eck, T.F., Smirnov, A., Kaufman, Y.J., King, M.D., Tanre, D., Slutsker, I., 2002. Variability of absorption and optical properties of key aerosol types observed in worldwide locations. J. Atmos. Sci. 59 (3), 590–608.
Eck, T.F., Holben, B.N., Reid, J.S., Dubovik, O., Smirnov, A., O'Neill, N.T., Slutsker, I., Kinne, S., 1999. Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols. J. Geophy. Res. 104 (D24), 31333–31350.
Evans, K.F., Stephens, G.L., 1991. A new polarized atmospheric radiative transfer model. J. Quant. Spectrosc. Radiat. Transfer 46 (5), 413–423.
Holben, B.N., Kaufman, Y.J., Eck, T.F., Slutsker, I., Tanre, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J., 1998. AERONET — a federated instrument network and data archive for aerosol characterization. Remote Sens. Environ. 66 (1), 1–16.
Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., 2001. Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge.
Huebert, B.J., Bates, T., Russell, P.B., Shi, G., Kim, Y.J., Kawamura, K., Carmichael, G., Nakajima, T., 2003. An overview of ACE-Asia: strategies for quantifying the relationships between Asian aerosols and their climatic impacts. J. Geophy. Res. 108 (D23). doi:10.1029/2003JD003550.
Ichoku, C., Chu, D.A., Mattoo, S., Kaufman, Y.J., Remer, L.A., Tanre, D., Slutsker, I., Holben, B.N., 2002. A spatio-temporal approach for global validation and analysis of MODIS aerosol products. Geophys. Res. Lett. 29 (12), 8006. doi:10.1029/2001GL013206.
Ichoku, C., Remer, L.A., Eck, T.F., 2005. Quantitative evaluation and intercomparison of morning and afternoon MODIS aerosol measurements from the Terra and Aqua satellites. Geophy. Res. 110 (D10S03). doi:10.1029/2004JD004987.
Ignatov, A., Minnis, P., Miller, W.F., Wielicki, B.A., Remer, L., 2006. Consistency of global MODIS aerosol optical depths over ocean on Terra and Aqua CERES SSF data sets. J. Geophy. Res. 111 (D14202). doi:10.1029/2005JD006645.
Jethva, H., Satheesh, S.K., Srinivasan, J., 2007. Assessment of second-generation MODIS aerosol retrieval (Collection 005) at Kanpur, India. Geophys. Res. Lett. 34 (L19802). doi:10.1029/2007GL029647.
Kaufman, Y.J., Tanré, D., Remer, L.A., Vermote, E.F., Chu, A., Holben, B.N., 1997. Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. J. Geophy. Res. 102 (17), 17051–17068.
Kaufman, Y.J., Holben, B.N., Tanre, D., Slutsker, I., Smirnov, A., Eck, T.F., 2000. Will aerosol measurements from Terra and Aqua polar orbiting satellites represent the daily aerosol abundance and properties? Geophy. Res. Lett. 27 (23), 3861–3864.
Kaufman, Y.J., Tanre, L.A., Kleidman, D., Mattoo, R., Levy, S., Eck, R.C., Holben, T.F., Ichoku, B.N., Martins, C., Koren, J.V., 2005. A critical examination of the residual cloud contamination and diurnal sampling effects on MODIS estimates of aerosol over ocean. IEEE Trans. Geosci. Remote Sens. 43 (12), 2886–2897.
Kim, D.H., Sohn, B.J., Nakajima, T., Takamura, T., Takemura, T., Choi, B.C., Yoon, S. C., 2004. Aerosol optical properties over east Asia determined from ground-based sky radiation measurements. J. Geophy. Res. 109 (D02209).
Lee, K.H., Li, Z.Q., Wong, M.S., Xin, J.Y., Wang, Y.S., Hao, W.M., Zhao, F.S., 2007. Aerosol single scattering albedo estimated across China from a combination of ground and satellite measurements. J. Geophy. Res. 112 (D22S15). doi:10.1029/2007JD009077.
Levy, R.C., Remer, L.A., Mattoo, S., Vermote, E.F., Kaufman, Y.J., 2007. Second-generation operational algorithm: retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance. J. Geophy. Res. 112 (D13211). doi:10.1029/2006JD007811.
Li, C.C., Mao, J.T., Lau, A.K.H., Yuan, Z.B., Wang, M.H., Liu, X.Y., 2005. Application of MODIS satellite products to the air pollution research in Beijing. Sci. China D Earth Sci. 48 (Supp. II), 209–219.
Li, Z.Q., Niu, F., Lee, K.H., Xin, J.Y., Hao, W.M., Nordgren, B., Wang, Y.S., Wang, P.C., 2007. Validation and understanding of Moderate Resolution Imaging Spectroradiometer aerosol products (C5) using ground-based measurements from the handheld Sun photometer network in China. J. Geophy. Res. 112 (D22S07). doi:10.1029/2007JD008479.
Menon, S., Hansen, J., Nazarenko, L., Luo, Y., 2002. Climate effects of black carbon aerosols in China and India. Science 297 (5590), 2250–2253.
Mi, W., Li, Z.Q., Xia, X.A., Holben, B., Levy, R., Zhao, F.S., Chen, H.B., Cribb, M., 2007. Evaluation of the Moderate Resolution Imaging Spectroradiometer aerosol products at two Aerosol Robotic Network stations in China. J. Geophy. Res. 112 (D22S08). doi:10.1029/2007JD008474.
Pan, Y., Shi, P.J., Zhu, W.Q., Gu, X.H., Fan, Y.D., Li, J., 2005. Measurement of ecological capital of Chinese terrestrial ecosystem based on remote sensing. Sci. China D Earth Sci. 48 (6), 786–796.
Pope Iii, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. J. Am. Med. Assoc. 287 (9), 1132–1141.
Prins, E.M., Feltz, J.M., Menzel, W.P., Ward, D.E., 1998. An overview of GOES-8 diurnal fire and smoke results for SCAR-B and 1995 fire season in South America. J. Geophy. Res. 103 (D24), 31821–31835.
Remer, L., Kaufman, Y.J., Tanré, D., Mattoo, S., Chu, D.A., Martins, J., Li, R.-R., Ichoku, C., Levy, R.C., Kleidman, R.G., Eck, T.F., Vermote, E., Holben, B.N., 2005. The MODIS aerosol algorithm, products, and validation. J. Atmos. Sci. 62 (4), 947–973.
Remer, L.A., Kaufman, Y.J., Kleidman, R.G., 2006a. Comparison of three years of Terra and Aqua MODIS aerosol optical thickness over the global oceans. IEEE Geosci. Remote Sens. Lett. 3 (4), 537–540.
Remer, L.A., Tanré, D., Kaufman, Y.J., 2006. Algorithm for remote sensing of tropospheric aerosol form MODIS: Collection 5. http://modis-atmos.gsfc.nasa.gov/MOD04_L2/.
Rosenfeld, D., Lensky, I.M., 1998. Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. Bull. Am. Meteorol. Soc. 79 (11), 2457–2476.
Samet, J.M., Zeger, S.L., Dominici, F., Curriero, F., Coursac, I., Dockery, D.W., Schwartz, J., Zanobetti, A., 2000. The national morbidity, mortality, and air pollution study. Part II: morbidity and mortality from air pollution in the United States. Research Report 94. Health Effects Institute, Cambridge MA.
Satheesh, S.K., Moorthy, K.K., Satheesh, S.K., Moorthy, K.K., 2005. Radiative effects of natural aerosols: a review. Atmos. Environ. 39 (11), 2089–2110.
Tanré, D., Kaufman, Y.J., Herman, M., Mattoo, S., 1997. Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. J. Geophy. Res. 102 (D14), 16971–16988.
Wang, L.L., Xin, J.Y., Wang, Y.S., Li, Z.Q., Liu, G.R., Li, J., 2007. Evaluation of the MODIS aerosol optical depth retrieval over different ecosystems in China during EAST-AIRE. Atmos. Environ. 41 (33), 7138–7149.
Wang, Y.S., Xin, J.Y., Li, Z.Q., Wang, S.G., Wang, P.C., Hao, W.M., Nordgren, B., Chen, H.B., Wang, L.L., Sun, Y., 2008. Seasonal variations in aerosol optical

Fig. 7. Time series of regional monthly mean Terra–MODIS AODs and the (Terra − Aqua) differences at 550 nm wavelength over different ecological regions. The regional means are derived from the MODIS level 2 aerosol products of Terra and Aqua, and the regions are 50 km × 50 km centered at different sites in the CSHNET. Solid lines represent Terra MODIS AODs, and dashed lines represent Aqua MODIS AODs, and the bars represent the (Terra − Aqua) differences. (a) on the Tibetan Plateau; (b) at northern desert regions; (c) in the northeast of China; (d) at forest regions; (e) in lake and coastal regions of China; (f) in city regions; and (g) at farmland regions.

properties over China. Atmos. Chem. Phys. Discuss. 8, 1–23 www.atmos-chem-phys-discuss.net/8/1/2008/.

Wiscombe, W.J., 1980. Improved Mie scattering algorithms. Appl. Opt. 19 (9), 1505–1509.

Xia, X.A., Chen, H.B., Wang, P.C., 2004. Validation of MODIS aerosol retrievals and evaluation of potential cloud contamination in East Asia. J. Environ. Sci. 16 (5), 832–837.

Xin, J.Y., Wang, Y.S., Li, Z.Q., Wang, P.C., Wang, S.G., Wen, T.X., Sun, Y., 2006. Introduction and calibration of the Chinese sun hazemeter network. Environ. Sci. 27 (9), 1–6 (In Chinese).

Xin, J.Y., Wang, Y.S., Li, Z.Q., Wang, P., Hao, W.M., Nordgren, B.L., Wang, S., Liu, G., Wang, L., Wen, T., Sun, Y., 2007. AOD and Angstrom exponent of aerosols observed by the Chinese Sun Hazemeter Network from August 2004 to September 2005. J. Geophy. Res. 112 (D05203). doi:10.1029/2006JD007075.

Xiong, X., Barnes, W., 2006. An overview of MODIS radiometric calibration and characterization. Adv. Atmos. Sci. 23 (1), 69–79.

Xiong, X., Chiang, K.F., Sun, J., Che, N., Barnes, W.L., 2004. Aqua MODIS first year on-orbit calibration and performance. Proc. SPIE 5234 (391). doi:10.1117/12.510580.

Xu, Q., 2001. Abrupt change of the mid-summer climate in central east China by the influence of atmospheric pollution. Atmos. Environ. 35 (30), 5029–5040.

Yu, X.N., Cheng, T.T., Chen, J.M., Liu, Y., 2007. Climatology of aerosol radiative properties in northern China. Atmos. Res. 84 (2), 132–141.

Zhao, T.X.P., Stowe, L.L., Smirnov, A., Crosby, D., Sapper, J., McClain, C.R., 2002. Development of a global validation package for satellite oceanic aerosol optical thickness retrieval based on AERONET observations and its application to NOAA/NESDIS operational aerosol retrievals. J. Atmos. Sci. 59 (3), 294–312.

Zhao, C.S., Tie, X.X., Lin, Y.P., 2006. A possible positive feedback of reduction of precipitation and increase in aerosols over eastern central China. Geophys. Res. Lett. 33 (L11814). doi:10.1029/2006GL025959.