

Validation and understanding of Moderate Resolution Imaging Spectroradiometer aerosol products (C5) using ground-based measurements from the handheld Sun photometer network in China

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Received 30 January 2007; revised 6 May 2007; accepted 24 May 2007; published 31 October 2007.

[1] The Moderate Resolution Imaging Spectroradiometer (MODIS) currently provides the most extensive aerosol retrievals on a global basis, but validation is limited to a small number of ground stations. This study presents a comprehensive evaluation of Collection 4 and 5 MODIS aerosol products using ground measurements from the Chinese Sun Hazemeter Network (CSHNET). The Collection 5 product uses a new method to determine the surface reflectance and a new aerosol model to retrieve aerosol optical thickness (AOT). Substantial improvement was found in the Collection 5 AOT product relative to the Collection 4 AOT product. Overall, the correlation coefficient of regression with ground measurements increased from 0.66 to 0.84 for all data points. The offset is reduced from 0.179 to 0.047, and the slope is improved from 0.74 to 0.98. At individual sites, the improvement varies with surface and atmospheric conditions. In general, both versions of the MODIS aerosol product tend to overestimate AOT over deserts/semideserts, tend to underestimate AOT over forests, and are more accurate over agricultural and suburban sites. The poorest retrievals occur over urban areas. The land cover dependence of aerosol retrievals was traced to the estimation of surface reflectance. The selection of the aerosol type is another major factor contributing to the discrepancies. Errors caused by both factors are subject to considerable variations with season and location due to land cover changes and varying fractions of coarse and fine mode aerosols, as well as the changing amount of scattering and absorbing aerosols.

Citation: Li, Z., F. Niu, K.-H. Lee, J. Xin, W.-M. Hao, B. Nordgren, Y. Wang, and P. Wang (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. Geophys. Res.*, 112, D22S07, doi:10.1029/2007JD008479.

1. Introduction

[2] Aerosol radiative forcing is widely recognized as the largest source of uncertainty among all sources of forcing to the Earth's climate system [Intergovernmental Panel on Climate Change, 2001]. Reduction of this uncertainty requires a substantially improved knowledge of basic aerosol optical properties on a global basis, such as aerosol optical thickness (AOT), single scattering albedo (SSA) and asymmetry factor, especially over aerosol-laden regions.

[3] This task cannot be fulfilled without the use of remote sensing data which provides global coverage on a continuous basis. While numerous global aerosol products exist, the majority are only available over dark oceans, e.g., those

retrieved from conventional meteorological sensors such as the Advanced Very High Resolution Radiometer (AVHRR) [Nakajima and Higurashi, 1998; Mishchenko et al., 1999, 2003; Stowe et al., 2002; Ignatov et al., 2004], and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) [Wang et al., 2005]. Because of the small number of spectral channels and thus highly limited information content, the data sets usually contain large uncertainties partially due to inherent assumptions made in the retrieval algorithms [Jeong et al., 2005]. AOT retrievals are available over land from the Moderate Resolution Imaging Spectroradiometer (MODIS) [Kaufman et al., 1997a; Remer et al., 2005], the Multiangle Imaging Spectroradiometer (MISR) [Diner et al., 2005; Kahn et al., 2005], the Total Ozone Mapping Spectrometer (TOMS) [Torres et al., 2002] and the Sea-viewing Wide Field-of-view Sensor (SEAWIFS) [Hsu et al., 2004]. Validation of the MODIS AOT retrievals against the global ground-based measurements from the Aerosol Robotic Network (AERONET) [Holben et al., 1998] generally show inferior quality over land [Chu et al., 2002; Ichoku et al., 2002] than over the oceans [Remer et al., 2005]. Two factors were identified as causes of the bulk of the errors, namely, surface reflectance and aerosol type governing, in

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particular, aerosol absorption. Validation of the MODIS AOT retrievals against the global ground-based measurements from the Aerosol Robotic Network (AERONET) [Holben *et al.*, 1998] generally shows slopes less than unity in the regressions between MODIS retrieved AOD (Y axis) and AERONET measured AOD (X axis) AOT, and positive offsets over land [Chu *et al.*, 2002; Ichoku *et al.*, 2002]. This implies that MODIS tends to underestimate AOD for large AODs values and overestimate for small AODs. The latter (overestimation) is presumably caused by errors in accounting for the influence of surface reflectance.

[4] The surface reflectance problem is more acute for bright surface. Three approaches can be used to overcome this problem. One is the MISR approach which relies on the contrast due to variable path lengths [Kahn *et al.*, 2005]. The second approach is to use reflectances at shorter wavelengths where the surface albedo are generally darker [Hsu *et al.*, 2004]. The third approach involves using a combination of measurements made in the ultraviolet and visible regions [Jeong and Li, 2005].

[5] To remedy the identified problems, substantial modifications were introduced to the second-generation aerosol retrieval algorithm applied to MODIS data [Levy *et al.*, 2007a, 2007b]. In C4, surface reflectances in the blue and red bands are estimated as one quarter and one half of surface reflectances in the SWIR band. However, in C5, their relations are not fixed ratio but depend on the scattering angle and the NDVI. The aerosol models used in C5 are also modified on the basis of AERONET observations. Six aerosol models were derived including two models that represent very clean conditions, one coarse-dominated model and three fine mode models. Since only three bands are used to retrieve aerosols over land, it is hard to decide which fine mode should be used. So the fine mode model is preassigned on the basis of the location and season. The coarse model used in C5 is nonspherical model instead of a spherical model used in C4. Atmosphere is no longer considered as being transparent in the SWIR band in C5 algorithm.

[6] However, the modifications hinge on AERONET measurements that provide essential aerosol optical data for the correction of the atmospheric effects. Since the AERONET sites are mostly located in the US and Europe, improvements may thus have regional biases depending on the amount of data used in tuning the algorithm. Unfortunately, heavy aerosol loading usually occurs over under-sampled regions of the globe whose impact on the estimation of global aerosol radiative forcing is more significant than elsewhere.

[7] China is among the heavy aerosol-laden regions of the world with few ground-truth measurements [Li *et al.*, 2003; Li, 2004]. Prior to 2004, only sporadic aerosol data were available for short periods of time ($\sim$ a couple of months), together with one AERONET site in the center of Beijing [Eck *et al.*, 2005; Xia *et al.*, 2005, 2006]. Thanks to the East Asian Study of Tropospheric Aerosols: an International Regional Experiment (EAST-AIRE), established in 2004 as a joint research venture between US and China [Li *et al.*, 2007a], continuous aerosol measurements have been made across China using both automated and handheld Sun photometers. The automated Cimel-318 instruments are deployed at three sites as part of the AERONET. They

have collected data continuously since 2004 in northern (Xianghe, near Beijing), southeastern (Taihu, near Shanghai) and western (Namco, near Lhasa) China. A preliminary analysis of AERONET data revealed some distinct aerosol features unique to the region [Li *et al.*, 2007b]. Use of the AERONET measurements to validate the MODIS aerosol products is the subject of a companion paper by Mi *et al.* [2007]. This study will make use of handheld Sun photometers, simply referred to as hazemeter [Hao *et al.*, 2005], data that have a greater spatial coverage but less optical information. The data were acquired at 25 stations across China as a part of the EAST-AIRE observation network [Xin *et al.*, 2007]. A detailed description of the data is given in the following section.

[8] The main objectives of this study are to evaluate both versions of the MODIS aerosol product and to understand any discrepancies between satellite retrievals and ground observations. Given the meagerness of ground-based measurements, the evaluation and understanding of any problems are crucial to improve satellite retrievals in this region in order to fill a big gap existing in global aerosol-related studies. The paper is structured as follows. The data sets employed are introduced in section 2. Section 3 compares the two latest versions of the MODIS aerosol products. Section 4 presents comparisons between satellite retrievals and ground measurements. Also reported in this section are the investigations into the causes for the discrepancies with the main focus on surface reflectance and single scattering albedo (SSA). The study is concluded in section 5.

2. Data

2.1. MODIS Aerosol Products

[9] The MODIS instrument is on board two NASA Earth Observation System (EOS) platforms, i.e., the Terra and Aqua satellites. The Terra satellite is on a descending orbit flying southward across the equator around 1030 local solar time (LST), while the Aqua satellite is on an ascending orbit flying northward around 1330 LST. MODIS data are coincident with CSHNET hazemeter data acquired from 1000 to 1400 LST on a half-hourly basis. While the MODIS has 36 channels ranging from 0.41 to 14 μm at different spatial resolutions (250 m, 500 m and 1 km), seven channels are used for aerosol retrievals, namely 0.47, 0.55, 0.66, 0.86, 1.24, 1.67 and 2.12 μm . Three of the channels (0.47, 0.66 and 2.12 μm) are used for retrieving aerosol parameters over land, while the remaining channels are used for retrieving aerosol parameters over ocean, cloud masking and other procedures.

[10] It is worth noting that the cloud screening method used for aerosol retrievals [Remer *et al.*, 2005; Martins *et al.*, 2002] is not the same as that used for generating MODIS cloud products [Ackerman *et al.*, 1998]. This is to avoid misclassification of heavy aerosols as clouds. After nominal cloud screening, the remaining potentially clear pixels are subject to further screening by eliminating the brightest 50% and darkest 25% of the pixels over land in an attempt to eliminate cloud contamination and cloud shadowing effects. As a result, the resolution of the MODIS aerosol product was degraded to 10 km.

[11] There are two MODIS aerosol retrieval algorithms developed for use over oceans [Tanré *et al.*, 1997] and land

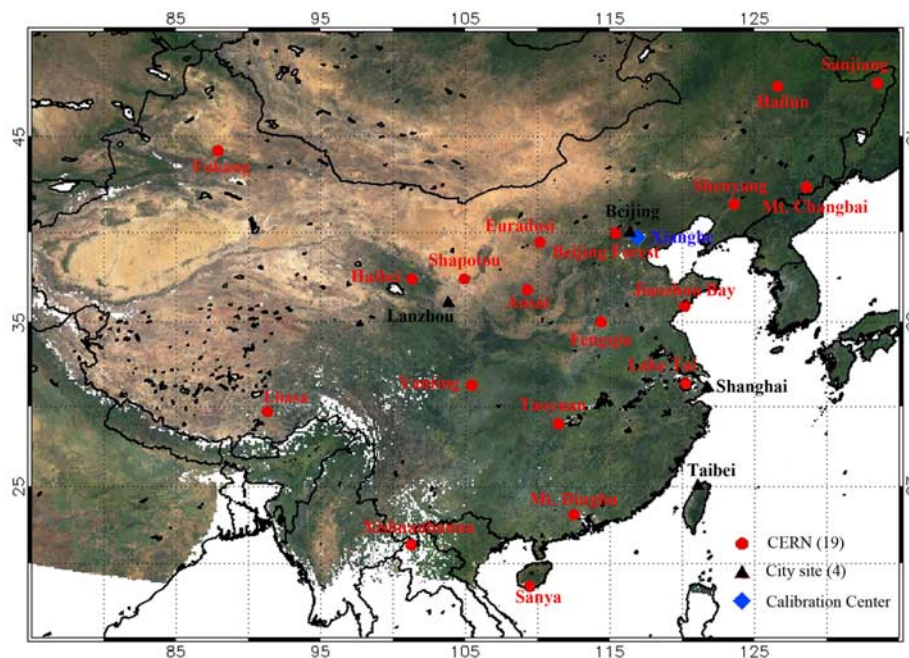


Figure 1. Locations of hazemeter sites in China.

[Kaufman *et al.*, 1997a]. This study is concerned with the land algorithm that has been modified the most since the original version was proposed before launch [Kaufman *et al.*, 1997a]. The algorithm has been improved over the years with two milestone versions described by Remer *et al.* [2005] and Levy *et al.* [2007a], leading to two distinct products denoted as Collections 4 (C004) and 5 (C005). C004 provides the most complete global aerosol data retrieved from Terra and Aqua platforms since their launches with an expected uncertainty of $0.05 + 0.15$ AOT at $0.55 \mu\text{m}$. While the expected accuracy is met in general, significantly larger errors are found in certain regions [Chu *et al.*, 2002; Remer *et al.*, 2005; Levy *et al.*, 2005]. An outstanding common problem was a systematic overestimation of AOT under the condition of low aerosol loading, in comparison with the AERONET ground-based retrievals. On a global scale, the two types of AOT data are related by $\text{AOT}_{\text{MODIS}} = 0.1 + 0.9 \text{AOT}_{\text{AERONET}}$. Over regions where there are no, or few, ground measurements that could, otherwise, be used to train the algorithm, errors remain largely unknown.

[12] In general, AOT retrievals are mainly influenced by two factors: surface reflectance and aerosol type. Except in the presence of large coarse-mode aerosols, atmospheric transmittance due to aerosols is generally high, allowing the retrieval of surface reflectance at longer wavelength channels. In C004 retrievals, the MODIS algorithm assumes constant ratios of surface reflectance at red and blue channels versus that at $2.12 \mu\text{m}$. In C005 retrievals, the ratios are modified to be functions of the scattering angle and the normalized difference vegetation index derived from reflectances at 1.24 and $2.12 \mu\text{m}$ channels [Levy *et al.*, 2007a]. Aerosol type selection was also refined by taking advantage of aerosol optical properties, especially

the single scattering albedo, retrieved from the AERONET [Levy *et al.*, 2007b]. Since the AERONET has a highly variable density around the world, the improvement varies considerably from region to region. For example, a fixed model with $\text{SSA} = 0.9$ is still assumed over the vast territory of China except along a very narrow strip in the east coastal region.

2.2. Hazemeter Data

[13] The handheld Sun photometers have been deployed in other field campaigns such as the SAFARI in Africa [Hao *et al.*, 2005]. A nationwide aerosol observation network, the Chinese Sun Hazemeter Network (CSHNET), was established in 2004 and includes 25 stations distributed across China (Figure 1) representing different ecological and geographic regions [Xin *et al.*, 2007]. Daily continuous measurements of aerosol optical depths at 3 wavelengths (405 nm, 500 nm, 650 nm) have been made since August 2004. This is the first large-scale attempt at collecting aerosol observations in China. Before this, only spotty measurements of unknown or undocumented quality were made.

[14] Many new features concerning the spatial and temporal variations of AOT and particle size were found through the analyses of data acquired so far [Xin *et al.*, 2007]. Those relevant to this study are summarized as follows. Overall, AOT is larger in central and southeast China. There are many anthropogenic sources of aerosols in southeast China. In winter, the majority of observation sites in northern China are under the influence of coal burning and biomass and fossil fuel burning which produce heavy loadings of fine-mode aerosols. From spring to summer, many eastern stations experienced rises in AOT and decreases in Angstrom exponent, α , due to the humidity-

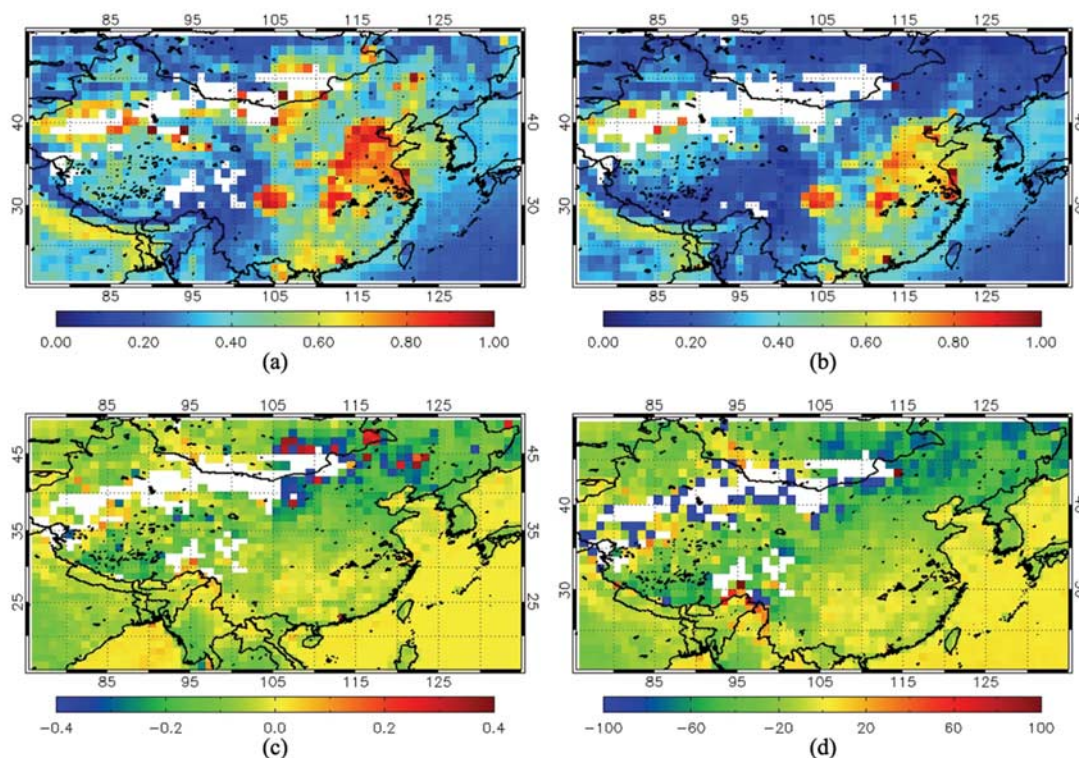


Figure 2. Annual mean AOT from MODIS collection (a) C4, (b) C5, (c) their absolute difference ($C5 - C4$), and (d) relative difference $(C5 - C4) / C4 \times 100$ (%).

swelling effect [Jeong *et al.*, 2007]. Desert or desert-like stations in western China are more affected by the coarse-mode mineral dust aerosols, with a maximal loading in spring. Many sites in eastern China show aerosol properties characteristic of mixtures of pollutants, mineral aerosols, and smoke aerosols.

[15] In addition to initial calibrations using the AERONET facilities at the NASA Goddard Space Flight Center, the hazemeters were further calibrated against the Cimel Sun photometer in China from time to time by means of both instrument intercomparisons and the Langley method [Xin *et al.*, 2007]. The results show the slope of the regression line between the two sets of AOD is close to 1.0 at 405 nm, 500 nm and 650 nm. The hazemeter results are generally consistent with the CIMEL results with discrepancies on the order of 2% to 6%. There is a slight tendency of overestimation of AOD, but the overestimation is within the range of measurement uncertainty except for 880nm channel that is not used in this study. To further reduce the calibration error due to instrument degradation, systematic calibration of all hazemeters deployed in China was carried out in August 2006 at Lhasa through side-by-side comparisons against a newly calibrated Cimel-318 Sun photometer. Overall, the hazemeters degraded by about 10% over 2 a, which is much less than the discrepancies found between satellite and ground retrievals as shown in this study. Despite the efforts in calibration, the hazemeters may still suffer from significant errors associated with calibration. Continual and rigorous calibration will be implemented pending available resources.

[16] The hazemeter data are matched with the satellite retrievals in time and space following the method of Ichoku *et al.* [2002]. Data from the ground-based hazemeters were averaged within 30 min of the satellite overpass times and are compared with the means of the MODIS retrievals within a 25-km radius around each ground station.

3. Comparisons Between the Two Collections of MODIS Aerosol Product

[17] The distributions of the yearly mean AOT from MODIS C004 and C005 during one whole year of 2005, and their differences are presented in Figure 2. Overall, AOT shows rather dramatic changes across China. Large AOT (>0.7) occurs over east-central China and the Sichuan basin. The lowest AOT (<0.2) is seen over the Qinghai-Tibet plateau. Intermediate values ($0.3 \sim 0.6$) are observed in southern China and northwest China. Detailed regional features will be discussed later on the basis of hazemeter ground observations. The two versions of the MODIS products have substantial differences that are larger in the north than in the south. Over almost half of China in the north, their differences range from -20% to -50% . In general, the C005 retrievals are less than the C004 retrievals, as is seen more clearly in the scatterplot and histogram of Figures 3a and 3b. Peaks in the histograms of AOT are similar (~ 0.28) for both product versions, but the C004 data have a greater number of AOT > 0.3 than the C005 data. The majority of the differences fall within $-0.2 \sim 0.0$, as seen from the histogram of their differences in Figure 3c.

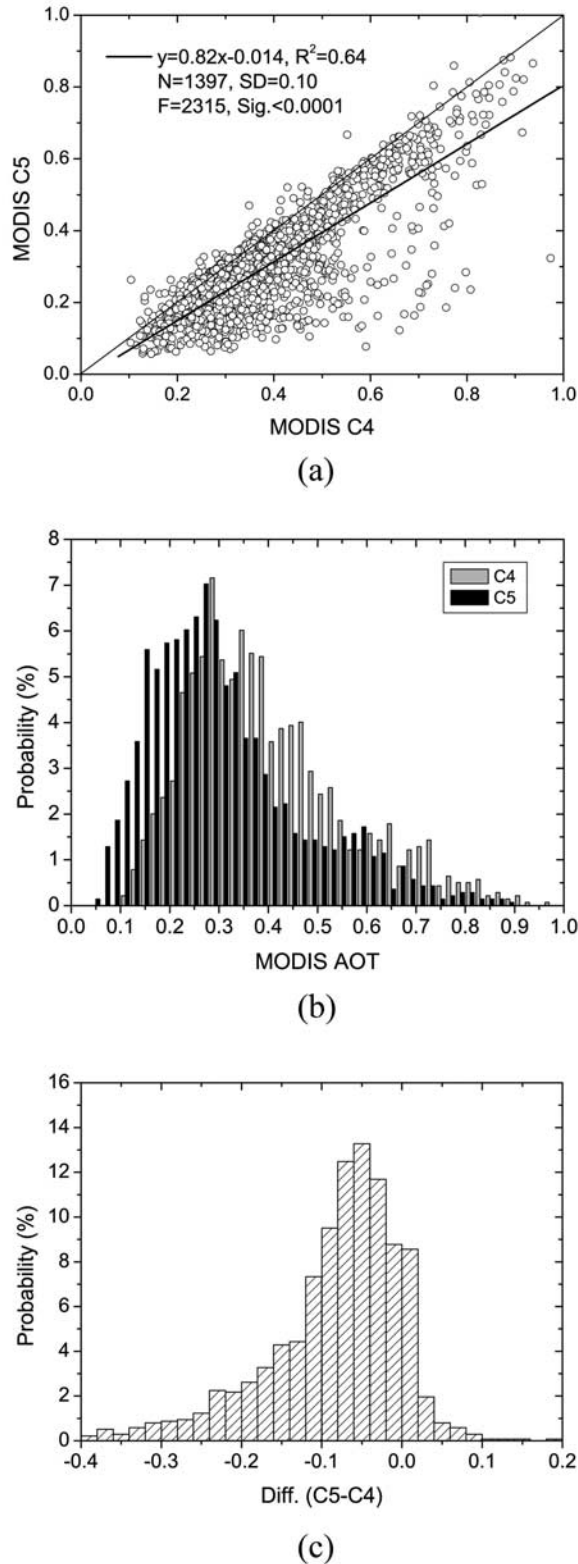


Figure 3. (a) Scatterplot of AOT from MODIS collections C004 and C005, (b) histogram of AOT from MODIS collections C004 and C005, and (c) histogram of AOT differences between MODIS collections C004 and C005.

[18] Given that surface reflectance plays an important role in aerosol retrievals over land, surface reflectances across the region were estimated from MODIS Level 1 seasonal composites of minimum reflectances that used nominal atmospheric corrections employing surface topography, an assumed AOT = 0.2 and an aerosol of the continental type. From the seasonal minimum reflectance data, annual minimum reflectance at the two visible channels (0.47 μm and 0.66 μm) and SWIR channel (2.12 μm) are shown in Figures 4a–4c. While the values are not precise because of assumed aerosol properties, it is sufficient to view their gross spatial patterns. Evident is the very bright surface covering a large fraction of northern and northwest China, rendering the region unsuitable, or marginally suitable for aerosol retrievals, especially in the red channel.

[19] As stated earlier, the MODIS algorithm retrieves surface reflectance at shorter wavelengths (0.47 μm and 0.66 μm) from the longer wavelength (2.12 μm). Fixed empirical ratios ($\rho_{0.47}/\rho_{2.12} = 0.25$ and $\rho_{0.66}/\rho_{2.12} = 0.5$) were used in the C004 algorithm [Kaufman *et al.*, 1997b]. The ratios over the study area are plotted in Figures 4c and 4d. Figures 4c and 4d show strong spatial variations with values differing significantly from the constants used in the C004 algorithm. In general, the ratios are larger than the assumed values, leading to underestimation of surface reflectances and overestimation of AOT. This is especially the case for the blue band ratio that is quite different from the assumed value over the study region. Even for dark pixels ($\rho_{2.12} < 0.2$) and dense green vegetated areas as seen in Figures 4c and 1, the ratios deviate significantly from the assumed values.

[20] To estimate more precisely the reflectances and their ratios, clear-sky MODIS data are matched with ground measurements for AOT < 0.2. To do a precise atmospheric correction, we would need a complete set of aerosol optical properties, namely, AOT, single scattering albedo and asymmetry factor. Since the effect of assuming different aerosol models on atmospheric correction decreases with decreasing AOT, the correction was done only for AOT < 0.2 and assuming the continental aerosol model. In a sensitivity test, correction was performed for AOT < 0.1 but little difference in the results was found.

[21] The resulting surface reflectances at the blue, red and SWIR bands are shown in Figure 5 for all the sites and for all seasons. The reflectances have linear relationships and the correlation coefficient is much larger between the red and SWIR channels than that between the blue and SWIR channels. The data scattering around the linear regression lines indicates retrieval uncertainties, which are substantial for the blue channel. The regression coefficients, slopes and the offsets are subject to change with season, with the greatest correlation found during the summer and the worse correlation found during the winter.

[22] As demonstrated by Levy *et al.* [2007a], the variation of the ratios is partially caused by their dependence on the vegetation condition and the viewing geometry. In order to validate the parameterizations used to account for these two factors, the ratios were compared with the vegetation index and the scattering angle as shown in Figure 6. Also plotted are the linear regression fit between the ratio and the two

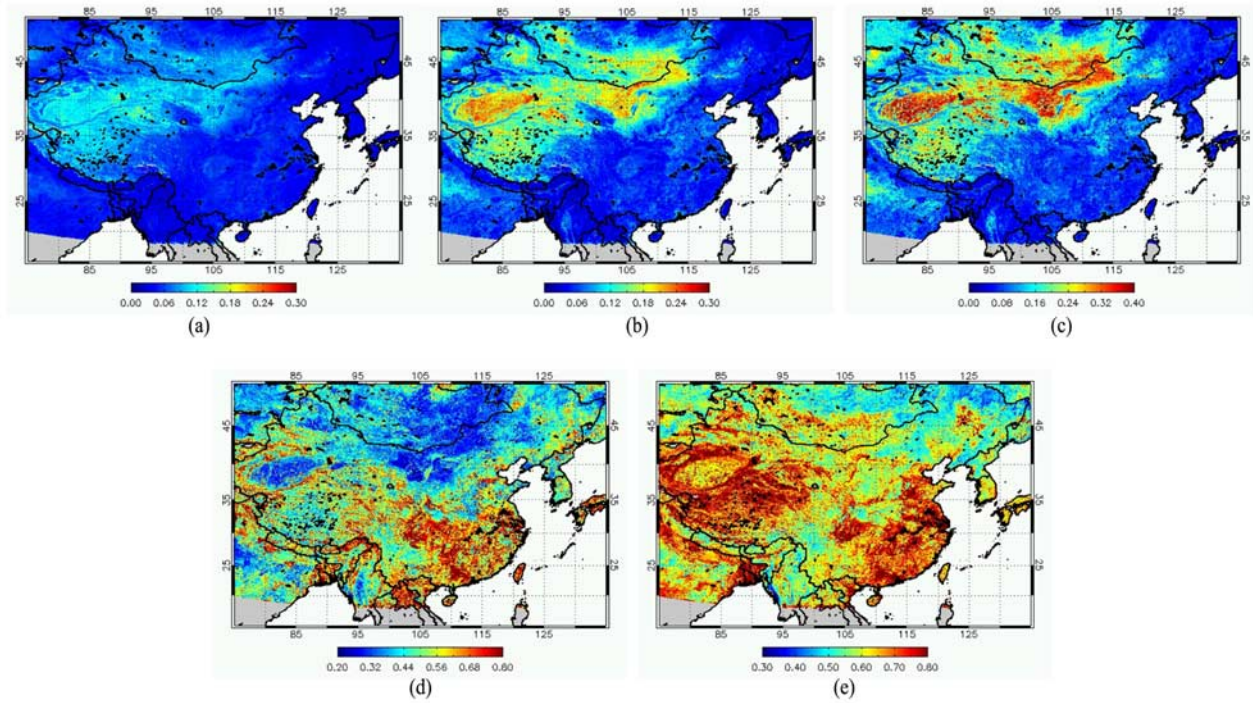


Figure 4. Annual minimum reflectance at (a) $0.47 \mu\text{m}$, (b) $0.66 \mu\text{m}$, and (c) $2.12 \mu\text{m}$ and VIS/SWIR ratios of (d) $0.47/2.12$ and (e) $0.66/2.12$.

variables, namely, NDVISWIR and the scattering angle (Θ), defined as follows:

$$NDVISWIR = \frac{\rho_{1.24} - \rho_{2.12}}{\rho_{1.24} + \rho_{2.12}}$$

$$\Theta = \cos^{-1}(-\cos \theta_0 \cos \theta + \sin \theta_0 \sin \theta \cos \phi)$$

where θ_0 , θ and ϕ are the solar zenith, viewing zenith and relative azimuth angles, respectively. The reflectance ratios have moderate correlations with the two variables, but the dependence is weak for the scattering angle, especially for the red channel.

4. Comparisons Between AOT From the Hazemeters and MODIS

[23] Figure 7 is a scatterplot showing the comparisons of AOT from ground measurements at all sites in China (differentiated by different symbols) and the MODIS retrievals AOT from Collection 4 (Figure 7, left) and Collection 5 (Figure 7, right), respectively. Clearly, the Collection 5 aerosol product is superior to the Collection 4 aerosol product. In the comparison with Collection 4, there is a large positive offset ($O = 0.179$) and small slope less than 1 ($S = 0.74$), which is consistent with the results from previous studies. When the aerosol optical depth is small, the satellite-retrieved AOT is overestimated. In comparison with Collection 5, the offset is much smaller (0.047), and slope is close to unity (0.98). The correlation coefficients are 0.66 ($R^2 = 0.44$) to 0.84 ($R^2 = 0.72$) for C004 and C005, respectively. Note that the expected error

of the MODIS retrieval is given by $0.05 \pm 0.15 * \text{AOT}$. About 45.70% of the C004 retrievals fall within this range, which increases to 56.74% in the C005.

[24] Another useful measure of the data quality is the variability of AOT as denoted by the standard deviations (SD) computed from samples over space (MODIS/50 km) and time (hazemeters/0.5 a). In principle, AOT over a 50-km² domain does not vary much except over regions near major emission sources, which is not the case for the hazemeter sites that are all located in remote areas. Had the variability driven by the natural variability, SDs from MODIS and hazemeters would have similar distributions and magnitudes, provided that the spatial and temporal scales are matched. SD for individual data points are marked as the bars in Figure 7. Figure 8 shows three histograms of the SD computed from C004 and C005 and the hazemeters. There are marked differences between the histograms in terms of both distribution and magnitude. The SDs from the two MODIS products are substantially larger than that from the hazemeters, while SDs from the C005 are significantly smaller than the C004. The long tail of SD from MODIS results primarily from the artifacts of the retrievals that are addressed in subsequent sections. While the vast majority of the SD computed from hazemeter AOD data are very small (e.g., 80% with $\text{SD} < 0.03$), a handful of data does have exceptionally large SD for which the data quality are questionable. If we limit our analyses to $\text{SD} < 0.05$ for hazemeter data, and $\text{SD} < 0.1$ for MODIS data, the agreements between satellite retrievals and ground observations would be improved, as seen from Figure 7 (bottom), e.g., the R^2 for C005 increasing from 0.72 to 0.75, S from 0.98 to 0.99, and O decreasing from 0.048 to 0.039.

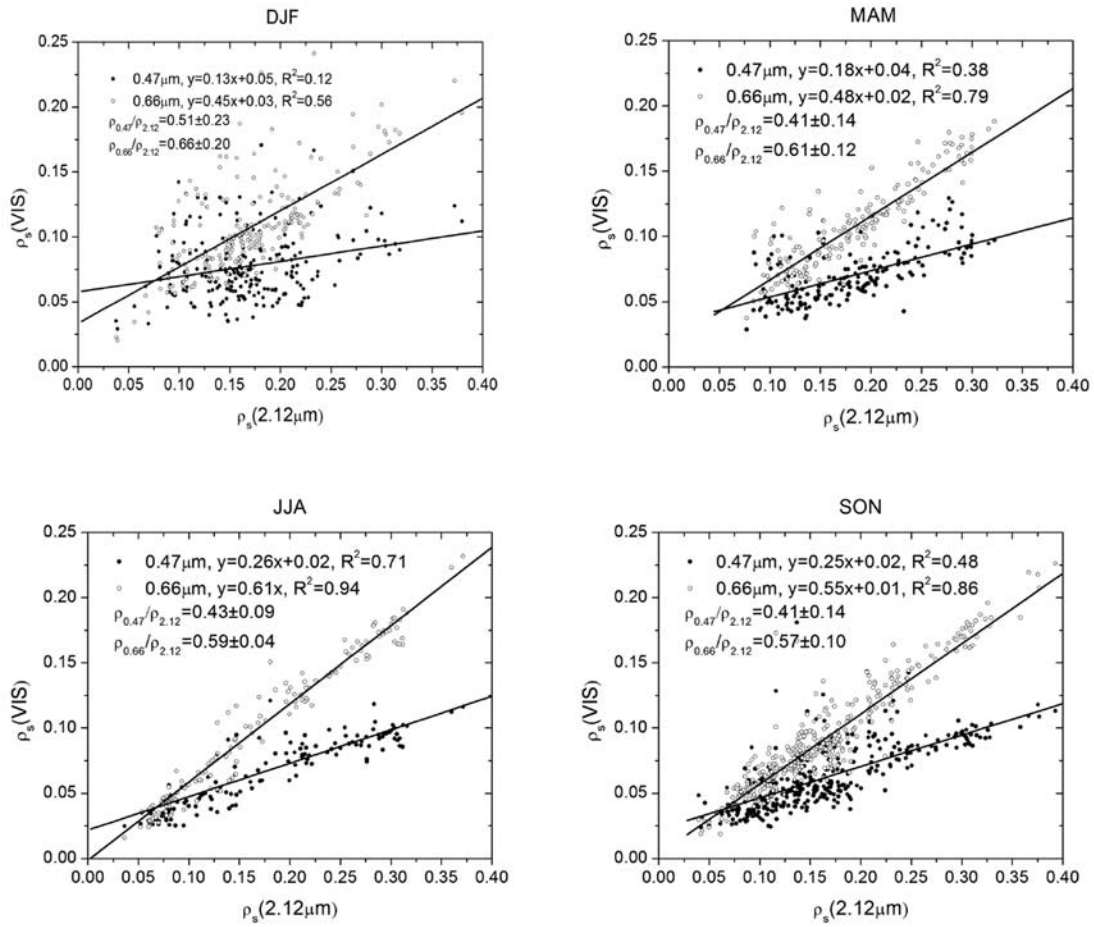


Figure 5. Relationships between surface visible and SWIR reflectances derived from MODIS TOA radiances following atmospheric corrections using ground-based hazemeter AOT data (AOT < 0.2). Linear regressional fits are plotted for four seasons.

[25] As expected, the performance of the MODIS retrieval varies from station to station.

[26] Figure 9 presents the statistics of the comparisons with MODIS Collections 4 and 5 for individual sites. For

almost all sites, the correlation is better for C005 than for C004, with the mean R^2 value increasing from 0.37 for C004 to 0.55 for C005. The values for some sites, for example, Beijing Forest and Xianghe, are close to 0.9.

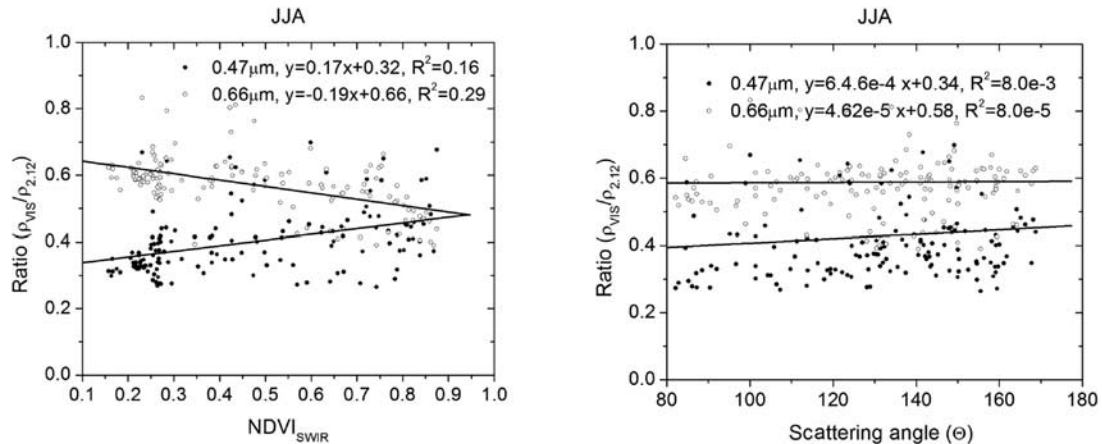


Figure 6. Scatterplot of the reflectance ratios (VIS/SWIR) versus the (left) NDVISWIR and (right) scattering angle.

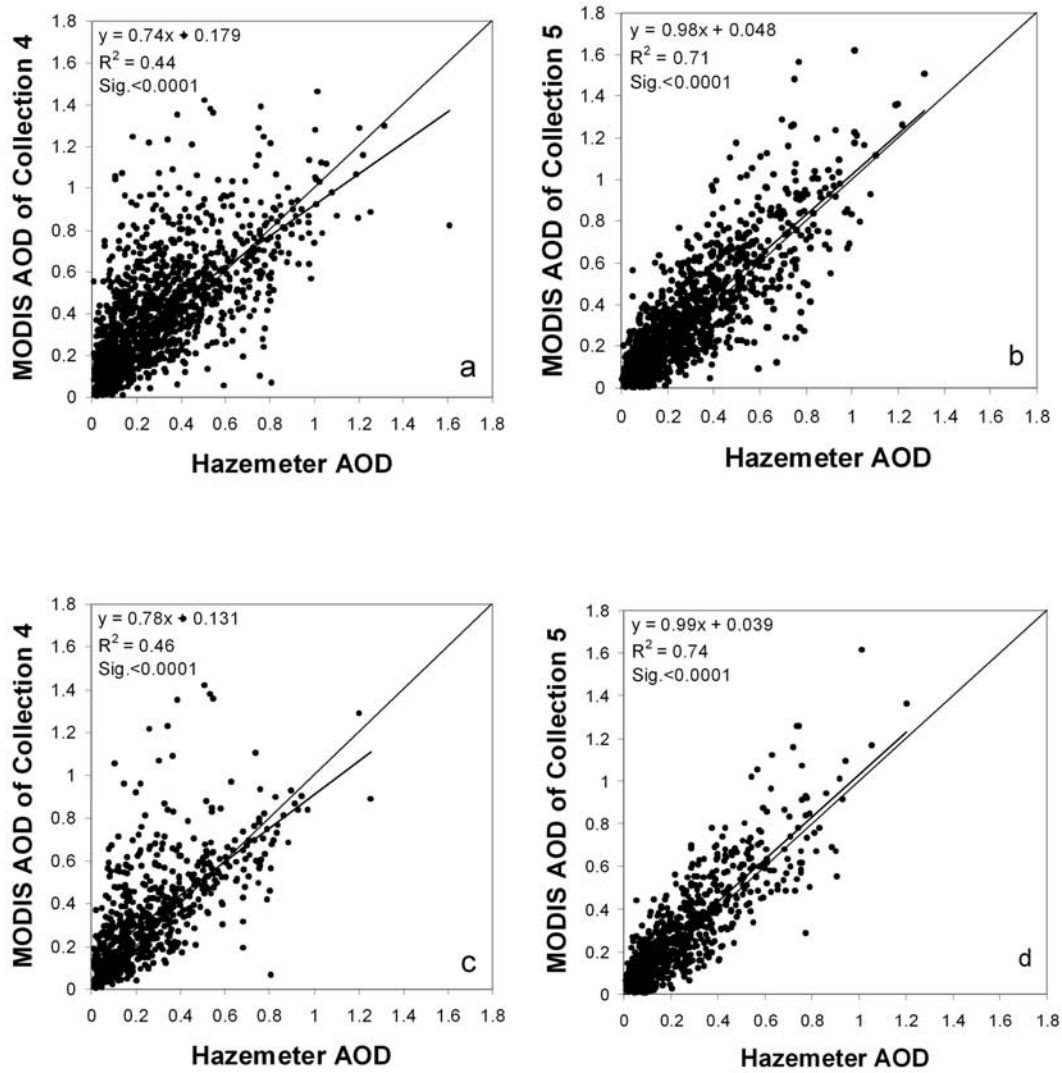


Figure 7. (top) Comparison of MODIS AOT from (left) C4 and (right) C5 with ground-based hazemeter measurements made at all hazemeter stations. (bottom) Same comparisons but for selected data based on standard deviation (see text for details).

However, for some sites, especially the desert sites and sites with complicated land surfaces, the correlation is poor. Significant improvement by the C005 is apparent in terms of the slope and offset as well. Some extremely large or small values for slope, for example Haibei (-0.33) and Eerduosi (2.13), have been improved to reasonable values close to unity. The mean of the slope increases from 0.74 to 0.95 ; the mean of the offset decreases from 0.176 to 0.055 .

[27] We further classified the hazemeter sites into different groups based on ecosystem to see how different land surfaces affect the retrievals. Results for four distinct categories are presented here: desert, forest, urban, and suburban and agricultural. Other small miscellaneous categories such as lakes and the Tibetan plateau were also analyzed but not shown.

[28] The most common land cover type is farmland located in either remote agricultural areas or near urban areas, referred to as suburban regions in this study. Results obtained from six farmland sites are shown in Figure 10.

The Xianghe and Shenyang sites are located near urban areas, while the remaining four sites are in remote areas of central China dominated by farmland. Overall, the comparisons are encouraging for these sites, as attested by the high correlation coefficients, small offsets and slopes close to unity. The best results are found over Xianghe, presumably because of the homogeneous surface reflectance and relatively stable aerosol properties.

[29] Much worse results were obtained over two urban sites located near the centers of Beijing and Lanzhou cities, shown in Figure 11. The Beijing urban site is only 70 km away from Xianghe, but over that distance, the surface conditions change from a rural farmland to a complex urban landscape. As a result, the comparison exacerbates considerably with $S = 0.38$, $O = 0.086$, $R^2 = 0.46$, in comparison to $S = 0.99$, $O = 0.049$, and $r^2 = 0.89$ for Xianghe. At the Lanzhou site, the comparison is even worse than in Beijing, with $O = 0.26$, $S = 0.41$, and $r^2 = 0.09$. Lanzhou is located in a valley basin surrounded by barren mountains in the

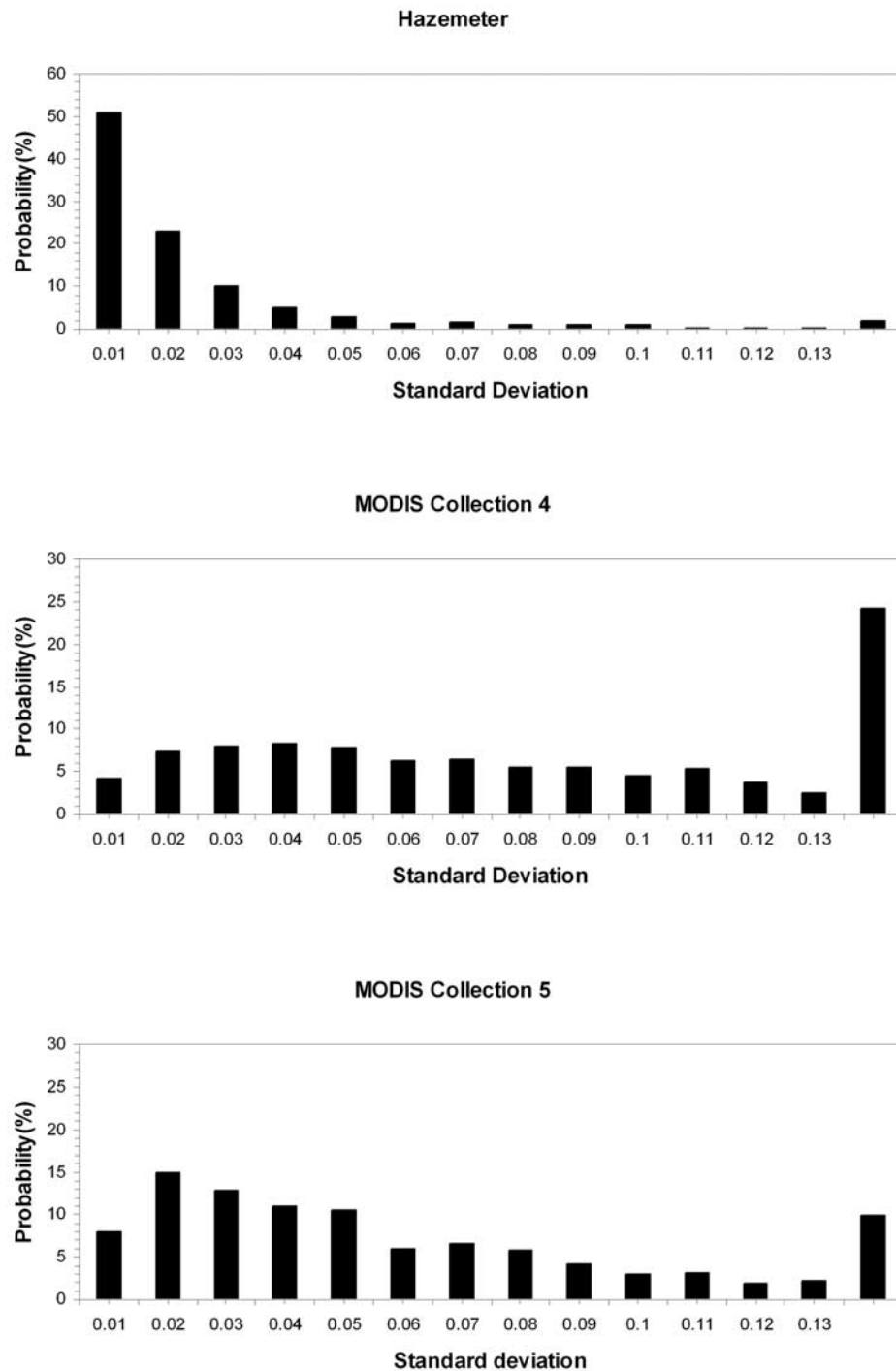


Figure 8. Histograms of the probability of occurrence for the standard deviation of AOD from the hazemeters and the MODIS collection 4 and 5 data.

heartland of the Northwest Plateau. The city has a high concentration of dust particles mixed with heavy industrial pollutants. The complicated landscape and strong local emissions in most cities pose the greatest challenge in any satellite retrieval of aerosol properties.

[30] Figure 12 shows the comparisons at three desert or semidesert sites located in northern China. Although these sites are referred to as desert sites, AOT retrievals can still

be performed because the surfaces are not as bright as typical desert surfaces in other parts of the world. The Shapotou site is situated in an arid part of the Tengger Desert. The Fukang station is located in the transition zone from a glacial environment to a desert environment and the Eerdousi station is situated in a sandy grassland ecosystem. At all sites, AOT was overestimated by the MODIS C005 algorithm by varying degrees, depending on the specific

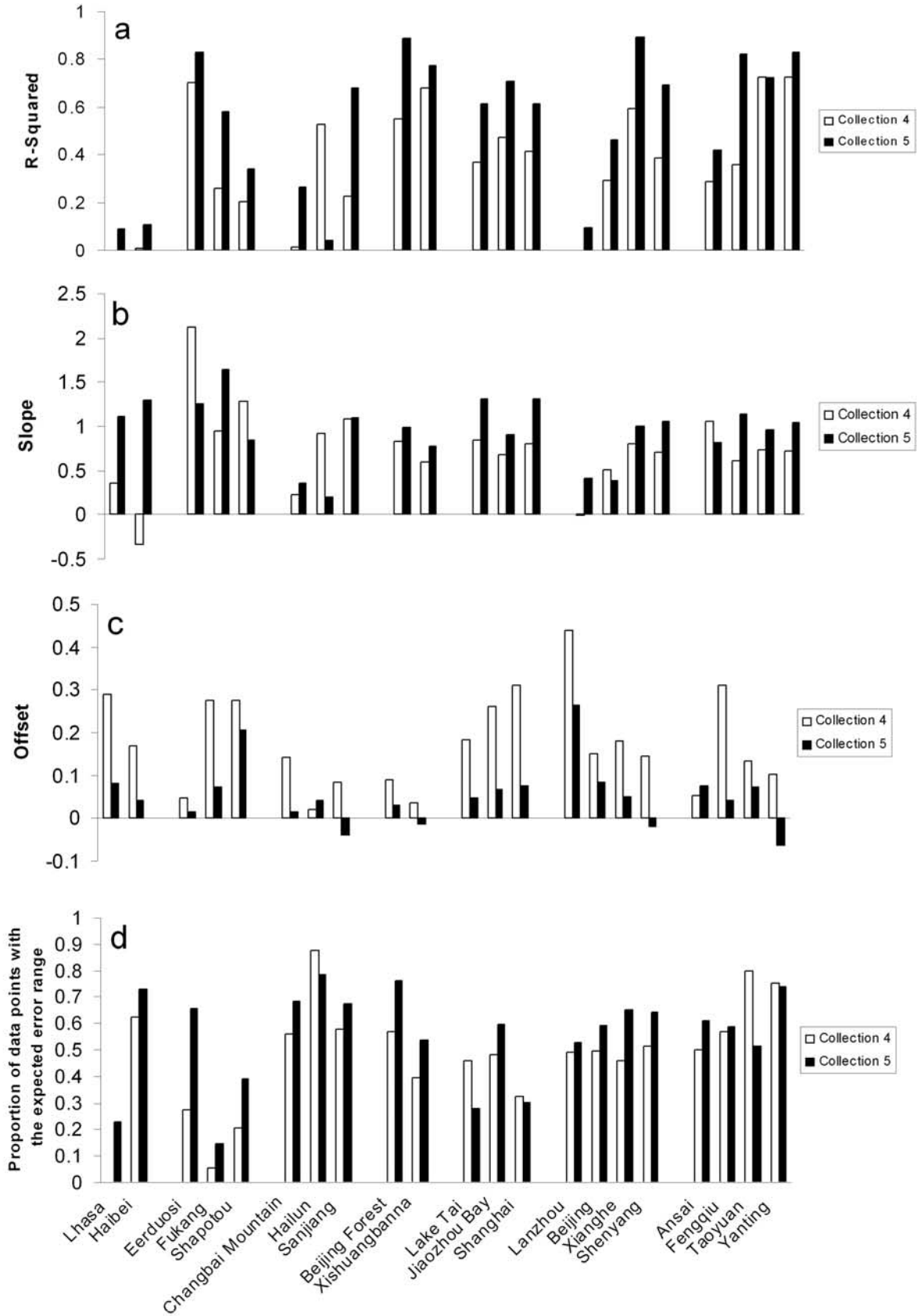


Figure 9. Statistics of linear regressions between MODIS and hazemeter data at individual sites: (a) square of the correlation coefficients, (b) slope, and (c) offset. (d) Probability of data falling within the expected error range.

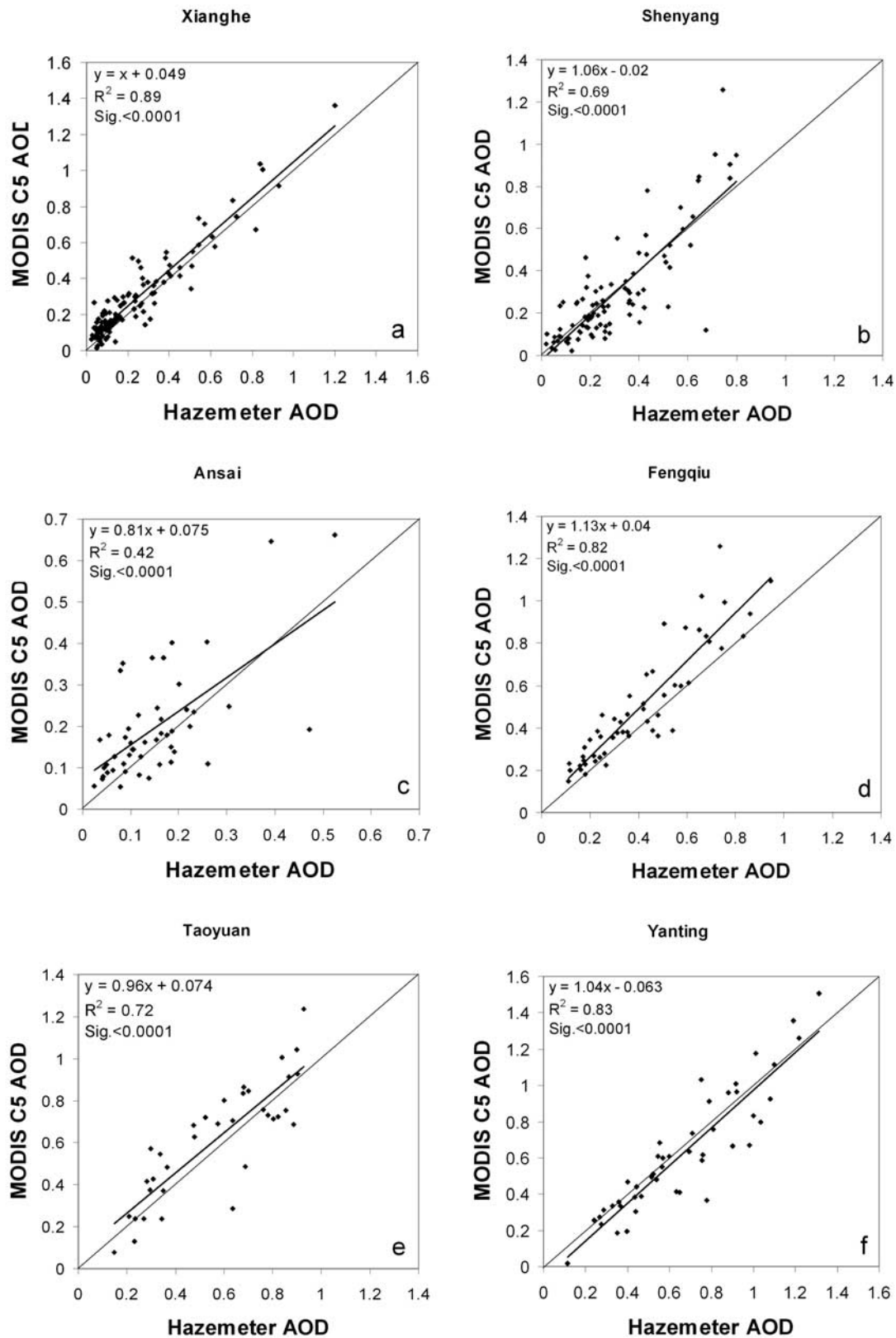


Figure 10. Comparison between MODIS Collection 5 and hazemeter AOTs for six agricultural and suburban sites.

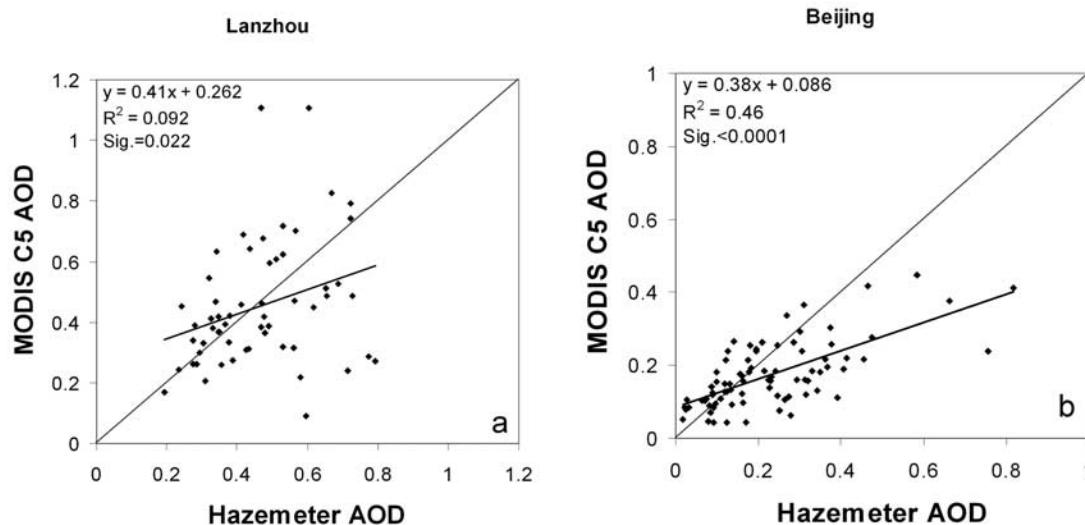


Figure 11. Same as Figure 10 but for two urban sites.

surface condition and aerosol type. Agricultural and pastoral activities take place in the regions surrounding the latter two sites, leading to changes in dominant aerosol types during the year, as inferred from the Angstrom exponent computed from the spectral AOT measured by hazemeters (not shown). Aerosol particles are small during autumn and winter because of biomass burning by the local farmers. The systematic overestimation of AOT indicates biases due to the selection of an incorrect aerosol model in the retrieval. At the Shapotou station, dust aerosols are more persistent given the dominance of dust particles in this more desert-like region.

[31] Figure 13 shows the comparison results at three forest sites, which are located in different parts of China. One is at the southern tip of China (Xishuangbanna) and the other two are in northern China. The results are mixed because of distinct environments. At Xishuangbanna and Changbai Mountain sites, AOT was underestimated, whereas much better agreement was found over the forest in the westerly remote suburb of Beijing which is influenced by regional aerosol emission sources from Beijing and Hebei, and also dust transport from Inner Mongolia and Shanxi provinces. At this site, the three indices are $R^2 = 0.89$, $S = 0.98$ and $O = 0.028$. Substantially smaller values for slope are found at the two mountain sites.

[32] As pointed out earlier, the VIS-SWIR conversion is a major source of error. This is more clearly seen in Figure 14 where comparisons for some representative sites are presented. It shows the AOT comparisons for C004 (Figure 14, left) and C005 (Figure 14, middle), and the corresponding relationships between VIS and SWIR surface reflectances (Figure 14, right) obtained after atmospheric corrections. Note that the representation is good in general, as the same/similar features are found for all or most of the sites in the same category. At all three desert and semidesert sites, surface reflectances are underestimated, causing an overestimation of aerosol optical depth by both C004 and C005 algorithms, although the overestimation is much smaller for C005 than for C004. On the contrary, at the two forest sites

(Xishuangbanna and Changbai Mountain), surface reflectances are overestimated and the AOT is underestimated. At the Beijing forest station, surface reflectance is only slightly overestimated (10%), roughly consistent with the good agreement in the AOT comparison. More overestimation (25%) of surface reflectance is found for the Xianghe site, which would lead to an underestimation of AOT. However, the site showed a very good agreement in AOT with $O = 0.05$ and $S = 1$. It is thus conjectured that other factors must come into play to cancel the error incurred by surface reflectance. This turns out to be the overestimation of the single scattering albedo. The site is fortunately equipped with a Cimel Sun photometer from which the single scattering albedo is retrieved for $AOT > 0.4$ [Dubovik *et al.*, 2002]. The annual mean AOT and ω_0 at the site are 0.82 and 0.92, respectively, at 500 nm [Li *et al.*, 2007b].

[33] The aerosol model used in the C005 algorithm was obtained from a combination of three fine-dominated (spherical) aerosol modes and one coarse-dominated (spheroid) aerosol mode. The coarse-mode phase function is substantially different than that of the C004 coarse-mode because of the assumption of spheroids instead of spheres [Levy *et al.*, 2007b]. The fine-dominated aerosol modes were assigned a “neutral” absorption ($SSA \sim 0.90$) for all seasons across China, except for a narrow strip along the eastern China Sea. This simplification is necessary because of a lack of measurements of ω_0 . In reality, ω_0 varies rather dramatically as indicated by the time series of ω_0 estimated from a Cimel Sun photometer deployed at Xianghe [Li *et al.*, 2007b].

5. Summary

[34] Aerosols have been recognized as the source of the largest uncertainty among all climate forcing agents due largely to a poor knowledge of their loading, optical, physical and chemical properties, and their inhomogeneous distribution. While remote sensing can provide global coverage, retrieval of aerosol variables requires more a

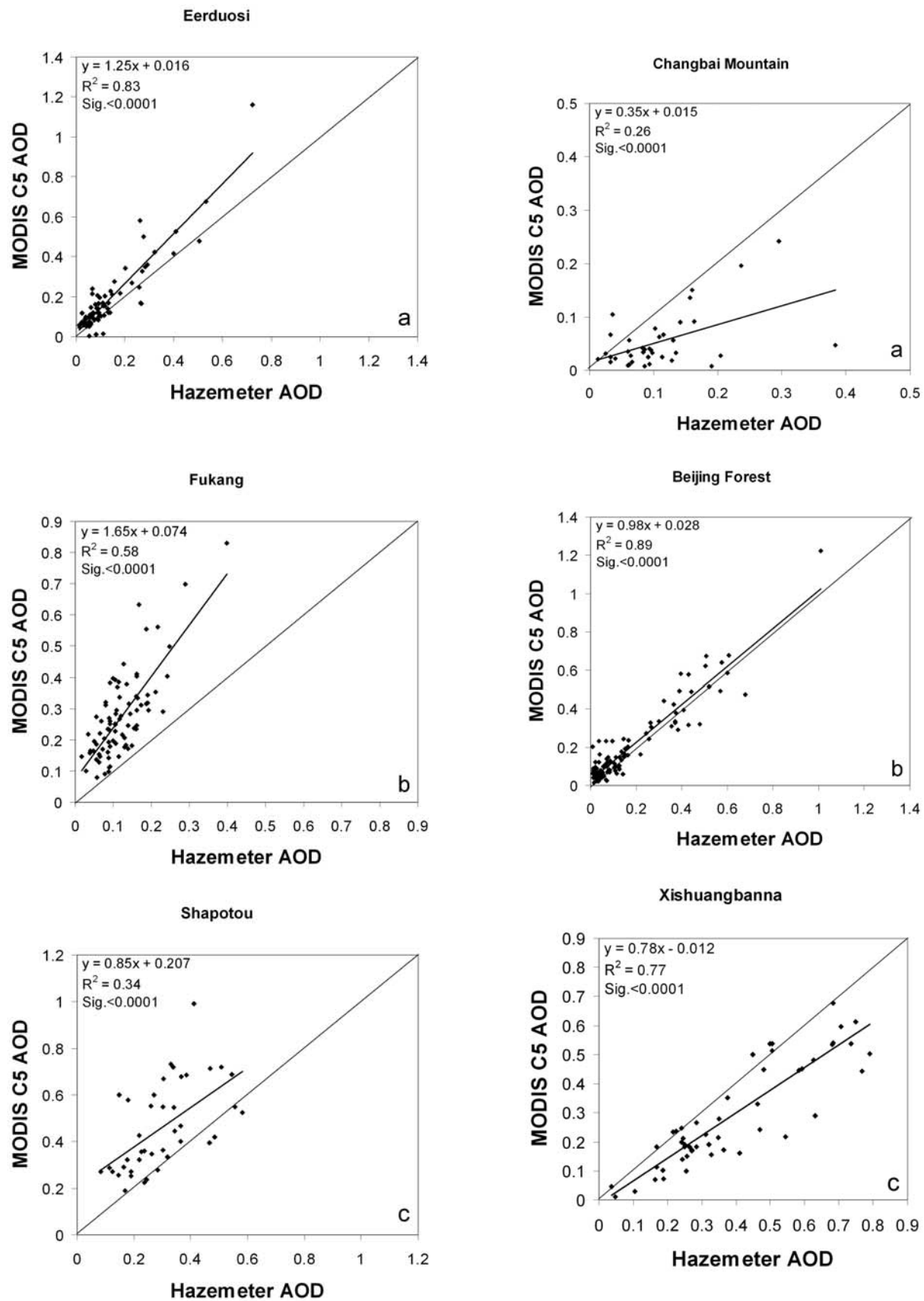


Figure 12. Same as Figure 10 but for three desert and semidesert sites.

Figure 13. Same as Figure 10 but for three forest sites.

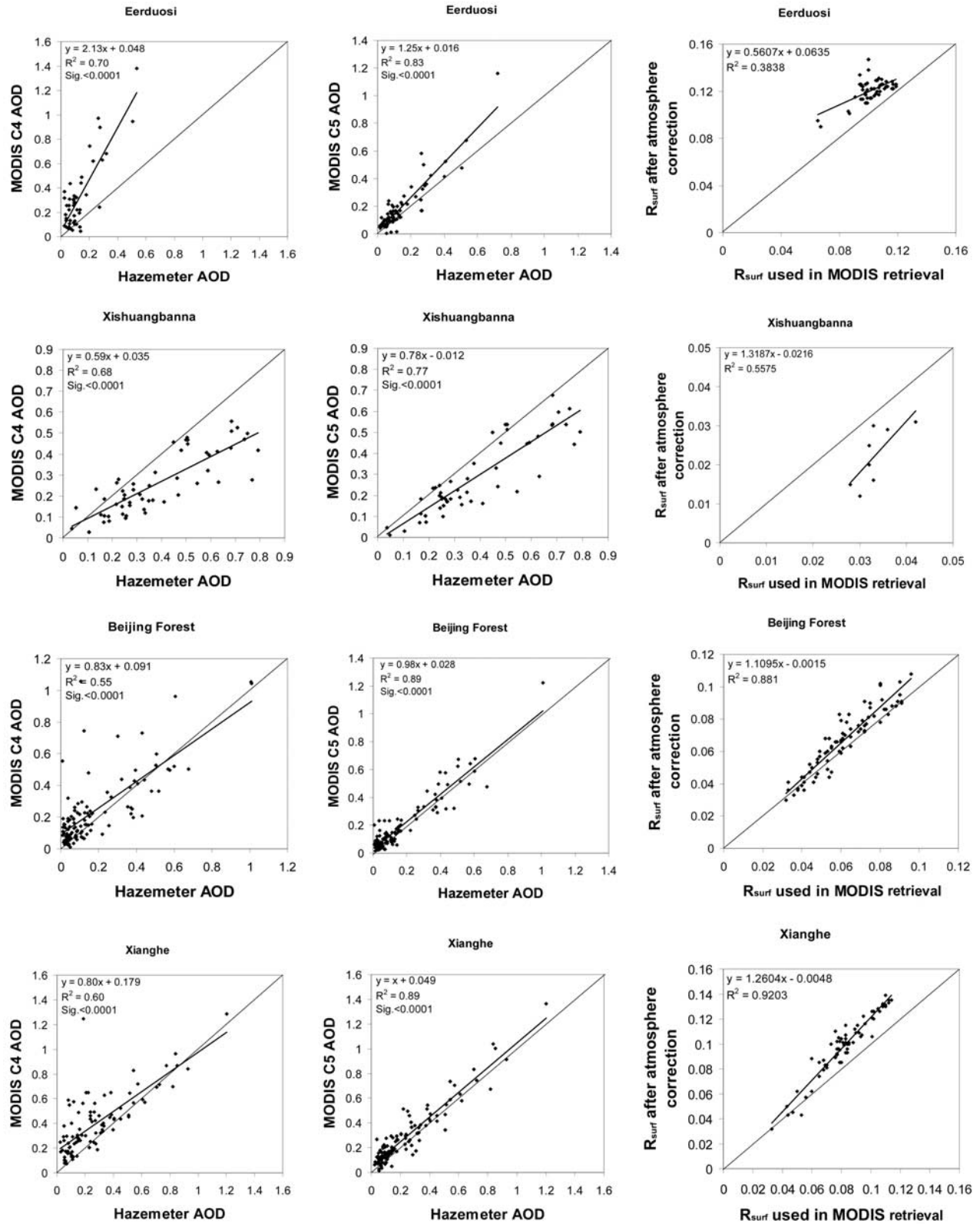


Figure 14. Comparisons between AOT from MODIS (left) C004 and (middle) C005 against hazemeter AOT, with reference to (right) the comparisons of surface reflectances estimated from the MODIS algorithm and after atmospheric corrections.

priori knowledge than what is conveyed in satellite measurements. Unfortunately, there has been a dearth of ground aerosol measurements over the majority of major aerosol source regions around the world, including China.

[35] Recently, the MODIS aerosol retrieval algorithm over land was modified dramatically, from which a new generation of product, denoted as Collection 5, is being generated to replace the widely used Collection 4 product. In the development of the new algorithm, advantage was taken of ground-based aerosol retrievals from the AERONET to develop improved relationships between surface visible and near-IR reflectances and aerosol models. Since AERONET data over China was scarce during the process of improving the retrieval algorithm, its performance is unknown over this vast region of complex surface and atmospheric properties.

[36] Under the aegis of the EAST-AIRE project, a network of handheld Sun photometers was established across China and has been in continuous operation since 2004. The data are used in this study to evaluate the aerosol products in the two most recent collections retrieved from the MODIS. The comparisons attest to the superior quality of the C005 collection over the C004 collection, in terms of all regression indices, i.e., smaller offsets, closer to unity slopes and higher correlation coefficients. Nevertheless, the performance of the C005 algorithm varies with surface and aerosol types. AOT over bright surfaces (deserts, semi-deserts, urban areas) are generally overestimated, whereas underestimation of AOT is found over some forest sites.

[37] To sort out the contribution of various factors, the surface reflectance was derived on clear and clean days with $AOT < 0.2$. The resulting reflectances are compared with those estimated from the MODIS 2.12 μm channel. They are very close to the true values for the majority of cases with good agreement in AOT, and differ for those with large discrepancies in AOT. The direction of the discrepancies in AOT is in accordance with those in reflectance. This attests that surface reflectance is still the major cause of inaccurate retrievals over land, despite the substantial improvement made by the C005 algorithm. In urban and suburban sites, the surface effects are often mixed with aerosol type effects, which may enlarge or suppress the AOT discrepancies depending on the amount of aerosol absorption assumed in the retrieval. Since both surface and aerosol types change with season, the discrepancies in AOT also show a strong seasonal pattern, especially over northern China, with more overestimation during the winter than during the summer.

[38] **Acknowledgments.** The study was supported by the NASA Radiation Science Program (NNG04GE79G), the National Science Foundation (IIS0611892, ATM425069), the National Science Foundation of China (40250120071, 40637035), and the 973 National Basic Research Program of China (2006CB403706).

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