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Evaluation of the Moderate Resolution Imaging Spectroradiometer aerosol products at two Aerosol Robotic Network stations in China

Wen Mi,[1] Zhanqing Li,[1,2,3] Xiangao Xia,[3] Brent Holben,[4] Robert Levy,[1,4] Fengsheng Zhao,[1,5] Hongbin Chen,[3] and Maureen Cribb[1]

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[1] Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol products have been used to address aerosol climatic issues in many parts of the world, but their quality has yet to be determined over China. This paper presents a thorough evaluation of aerosol optical depth (AOD) data retrieved from MODIS collections 4 (C004) and 5 (C005) at two AERONET sites in northern and southeastern China. Established under the aegis of the East Asian Study of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE) project, the two sites, Xianghe and Taihu, have distinct ecosystems and climate regimes, resulting in differences in retrieval performance. At the rural northeastern site (Xianghe), MODIS C004 retrievals generally overestimate AOD at 550 nm during clean days, with the largest errors occurring during winter. In the warm and humid regions of southeastern China (Taihu), MODIS C004 retrievals overestimate AOD throughout the year. The systematic error at Xianghe is primarily due to the fixed surface reflectance ratio, while as the error at Taihu is mainly caused by the choice of the single scattering albedo (SSA) for the fine model aerosols. Both problems are alleviated considerably in the C005. The comparisons between C005 retrievals and AERONET data show much higher correlation coefficient, lower offset and a slope closer to unity. Also, the variability of AOD retrieval among neighboring pixels is reduced by several factors. The strong overestimation problem at small AOD values was fixed by using dynamic reflectance ratios that vary with the vegetation index and scattering angle. However, significant uncertainties remain because of the use of highly simplified aerosol models.

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1. Introduction

[2] Fast economic growth in China over the past two decades has resulted in rapid increases in energy consumption and atmospheric emissions [*Streets and Waldhoff*, 2000]. Ground observations [*Hu et al.*, 2003; *Liang and Xia*, 2005; *Qian et al.*, 2006] revealed decreases in visibility and surface solar radiation. Abrupt changes in the atmospheric environment may have contributed toward a tendency of increasing summer flooding in southern China and drought in northern China [*Qian and Giorgi*, 2000; *Xu*, 2001; *Menon et al.*, 2002], because of the heating effect of absorbing aerosols that can alter the atmospheric circulation [*Ramanathan et al.*, 2001, 2005; *Feichter et al.*, 2004]. A positive feedback between the reduction in precipitation and the increase in aerosols over eastern China was proposed [*Zhao et al.*, 2006] from analysis of precipitation data on the ground and the fine-mode aerosol optical depth (AOD) retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor.

[3] Daily global aerosol products have been generated from the MODIS onboard the Terra platform since 2000 and the Aqua platform since 2002 [*Kaufman et al.*, 1997; *Remer et al.*, 2005]. Publications on the use of MODIS aerosol products have grown nearly exponentially. A handful of MODIS aerosol validation studies [e.g., *Chu et al.*, 2002; *Xia et al.*, 2004; *Levy et al.*, 2005; *Ichoku et al.*, 2002; *Remer et al.*, 2005] have been carried out using ground Sun photometer measurements, especially those from the international Aerosol Robotic Network (AERONET) [*Holben et al.*, 1998]. Although AOD retrievals from the MODIS agree with AERONET AOD measurements within the expected error range, AOD is generally overestimated on clean days

[1]Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA.
[2]School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, China.
[3]Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.
[4]Laboratory for Atmosphere, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[5]National Satellite Meteorology Center, China Meteorological Administration, Beijing, China.

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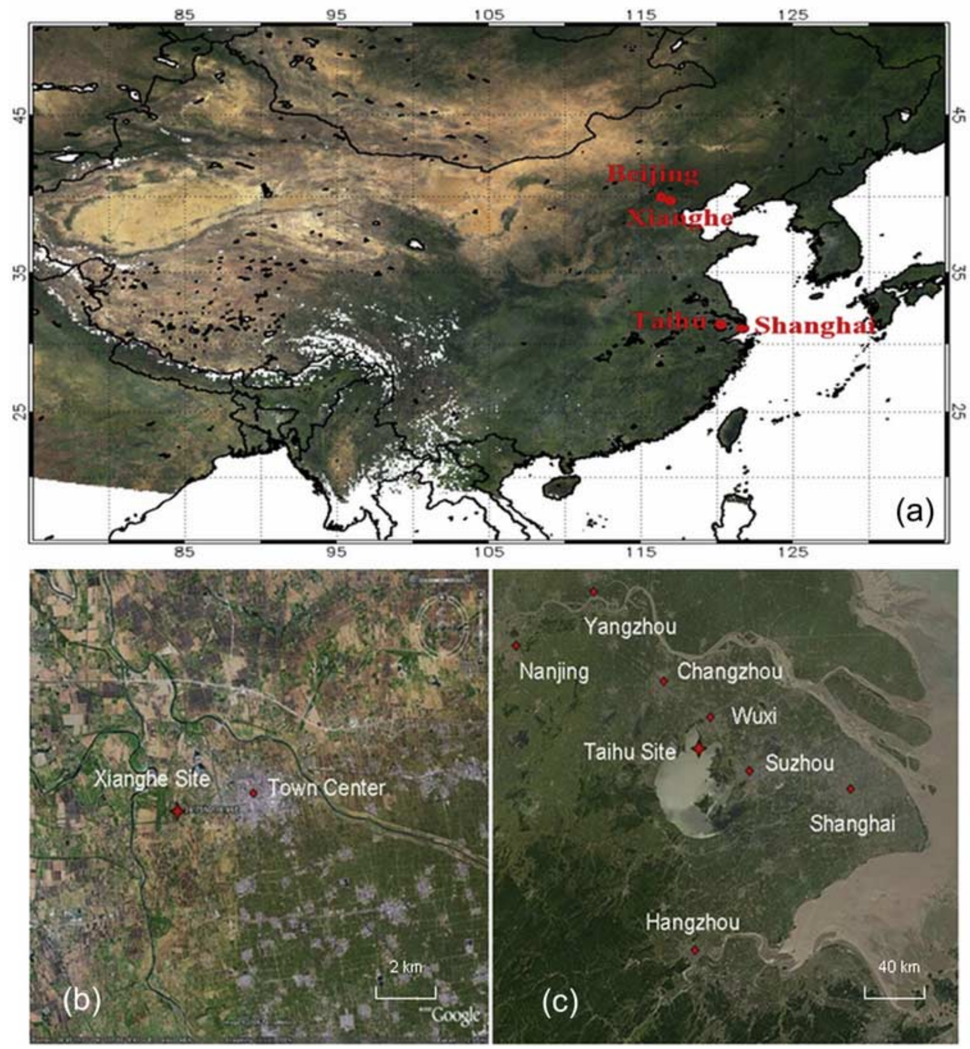

Figure 1. (a) Geographic locations of Xianghe and Taihu site and satellite images for (b) Xianghe and (c) Taihu site.

and underestimated for high aerosol loading events. To remedy the problem, *Levy et al.* [2007a, 2007b] recently proposed a substantially revised algorithm (collection 5) that attempts to reduce the systematic errors incurred by improper treatments of surface reflectance and aerosol models. The revisions were based on analyses of global AERONET data, which included very few data from China. The AOD is generally too high over China so that no data is used for deriving surface reflectance parameterization, and only data from Beijing site was included in aerosol model derivation. Given the distinct surface conditions and aerosol properties in China [*Xia et al.*, 2006; Z. Li et al., An overview of the East Asian Study of Tropospheric Aerosols: An International Regional Experiment (EAST-AIRE), submitted to *Journal of Geophysical Research*, 2007, hereinafter referred to as Li et al., submitted manuscript, 2007], the quality of the MODIS aerosol products in this region need to be thoroughly evaluated.

[4] A large number of published studies employed the collection 4 (C004) aerosol products whose quality deserves further evaluation, especially over understudied regions like China. Taking advantage of data collected from two AERONET sites recently established in northeastern and southeastern China, this study is devoted to the validation of MODIS aerosol AOD products and comparison between collection 4 (C004) and collection 5 (C005) algorithm. In addition to analyses of matched satellite and ground data, some modeling work was done to investigate the sources of retrieval errors and to sort them in terms of contributions due to assumptions of surface reflectance and aerosol models.

[5] The data sets and algorithms used in the study are described in the next section. The newly derived surface reflectance ratios are presented in section 3. The seasonal change in surface reflectance and the relationship with MODIS retrievals are also discussed in this section. Section 4 presents the results from validation and sensitivity tests. Conclusions are given in section 5.

2. Data Sets and Retrieval Algorithms

[6] The Xianghe site (39.75 N, 116.96 E) is located on the outskirts of a small county town, 70–80 km east of Beijing (Figure 1). The site is surrounded by agricultural

land and scattered deciduous trees with distinct seasonal changes. Summer is the main rainy season with green vegetation, while winter and early spring are cold and dry with barren ground. The Taihu site is situated in southeastern China about 100 km northwest of Shanghai on the northern edge of Tai Lake (or "Taihu" in Chinese), the third largest freshwater lake ($\sim$50 km across) in China. It represents roughly the geometric center of a cluster of big cities in the Yangtze delta, e.g., Wuxi, Suzhou, Shanghai, Hangzhou and Nanjing. The AERONET site (31.42 N, 120.21 E) is surrounded by parkland with little local aerosol emission.

[7] The Cimel Sun photometer at Xianghe began operation on 21 September 2004 and since then, has continuously collected aerosol measurements. Collection of Sun photometer measurements at the Taihu site started one year later, and fewer measurements are available because of more frequent cloudy-sky conditions. The annual mean AOD is about 0.6 at Xianghe and 0.72 at Taihu, with extreme values exceeding 4.0 and 3.0, respectively.

[8] Following the colocation method of *Ichoku et al.* [2002], the version 2 AERONET AOD data (level 2) within ±30 min of MODIS/Terra overpass times were matched with MODIS/Terra retrieved AOD over a 50×50 km^2 area centered on the AERONET sites. In addition to AOD, aerosol spectral complex refractive indices and volume distributions in 22 radius size bins were also retrieved [*Dubovik and King*, 2000; *Dubovik et al.*, 2002] from AERONET "sky" measurement. These data are used to perform the atmospheric correction in this study. The top of atmosphere (TOA) radiance data are provided by the MODIS Aerosol and Associated Parameters Subset Statistics (MAPSS) database, which can be access through the MODIS website (http://modis-atmos.gsfc.nasa.gov/validation_corrdata.html). These data are the average of all selected gas corrected (for H_2O, O_3 and CO_2) dark pixels used by the aerosol retrieval over a 50×50 km^2 box. In other words, for the land retrievals, these are the pixels that remain after screening out clouds, snow, water, bright surfaces and the 20% darkest and 50% brightest pixels [*Remer et al.*, 2005].

[9] The stand-alone codes (C4 and C5) of land retrievals developed by MODIS science team are used in this study. They are the essential part of the physics in operational retrieval procedure. The required inputs include geolocation (i.e., latitude and longitude), viewing geometry (i.e., solar/sensor zenith angle and solar/sensor azimuth angle), and TOA reflectance after gas correction, which come from a qualified dark pixel (i.e., cloud/snow/water free dark surface).

[10] To help understand the performance of the two generations of MODIS aerosol retrieval algorithms, their main features and differences are highlighted here. The fundamental assumptions made in the C004 algorithm over land are that (1) aerosols are transparent at 2.12 μm and (2) that the surface reflectance at 0.47 and 0.66 μm over that at 2.12 μm are constant ratios (0.25 and 0.50, respectively) of that in 2.12 μm [*Remer et al.*, 2005]. The difference between the MODIS-measured reflectance and the surface reflectance in the two visible channels is assumed to result from the interaction of radiation within the atmosphere (known as the path reflectance) and includes the effect of aerosols. From the derived path reflectance, the algorithm initially retrieves AOD in two channels (0.47 and 0.66 μm) independently, by assuming a fixed "continental" aerosol model. From the spectral dependence of this initial AOD, the algorithm estimates the relative optical weighting of fine aerosols to the total AOD (i.e., the fine weighting). This relative fine weighting is applied in order to combine one fine-dominated aerosol type (dependent on season and location) with one coarse-dominated aerosol type (properties of dust fixed globally). Note that each of the aerosol models has two or more lognormal modes, but are either fine or coarse mode dominated. The algorithm then retrieves a final AOD based on matching the assumed models and the derived fine weighting to MODIS measurements. To simplify the radiative transfer calculations, the retrieval makes use of a set of previously calculated scenarios, known as a lookup table (LUT). The LUT is a simulation of radiative properties of the atmosphere calculated for expected aerosol types at particular wavelengths, angles and aerosol loading. For C004, most of East Asia was assigned to a strong absorbing aerosol model all year with a low single scattering albedo (SSA) value (equal to 0.85).

[11] For the C005 algorithm, many of the fundamental assumptions were reevaluated and corrected. The surface reflectance ratios are known to vary with vegetation conditions [*Kaufman et al.*, 2002]. An error of 0.01 in surface reflectance can lead to an error on the order of 0.1 in retrieved AOD [*Kaufman et al.*, 1997]. In the C005 algorithm, the surface reflectance relationships are parameterized functions of both viewing geometry (scattering angle) and surface type (midinfrared NDVI) [*Levy et al.*, 2007a]. Aerosols are no longer assumed to be transparent in the 2.12 μm channel, and the surface reflectance at this channel is retrieved simultaneously with AOD and the fine aerosol weighting (FW). The Rayleigh optical depth for elevated surfaces is included in the new algorithm by adjusting the wavelength in the lookup tables. The new aerosol models categorize global fine-dominated aerosols into three types: nonabsorbing (SSA $\sim$ 0.95), moderately absorbing (SSA $\sim$ 0.9) and absorbing (SSA $\sim$ 0.85). Most of China, except for a small section in the southeast, falls into the moderately absorbing category, which assumes larger SSA than those of the C004 algorithm.

3. Surface Reflectance

[12] In order to minimize errors arising from multiple scattering by aerosols, the atmospheric correction was performed only on clean days. Because of generally high aerosol loading over China, we choose the threshold of the clean-day as the AOD less than 0.3 for Xianghe and less than 0.4 for Taihu in order to get enough data sample. These thresholds are larger than the value used in some global studies [e.g., *Levy et al.*, 2007a]. There are much fewer data available at the Taihu station because of the persistent cloudy sky conditions so the threshold is set a little higher than that at Xianghe. MODIS TOA reflectance after cloud/water/snow mask and dark-pixel selection, together with AERONET retrieved aerosol properties, were substituted into the Second Simulation of the Satellite Signal in the Solar Spectrum (6s) radiative transfer model [*Vermote et al.*,

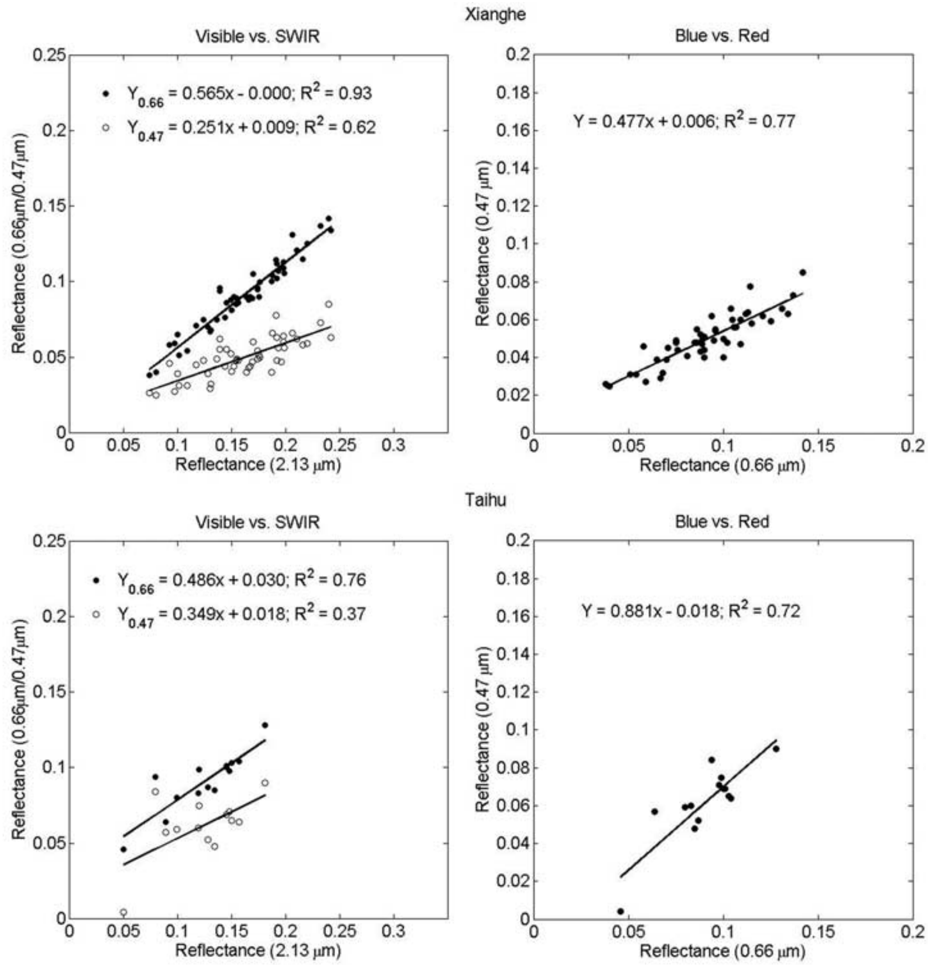

Figure 2. (left) Atmospherically corrected surface reflectance of 0.66 μm (solid circles) and 0.47 μm (open circles) compared with that of 2.12 μm channel and (right) reflectance of 0.66 μm compared with that of 0.47 μm for (top) Xianghe and (bottom) Taihu site.

1997] to estimate surface reflectance at red (0.66 μm), blue (0.47 μm) and SWIR (2.12 μm) channels.

[13] The results for Xianghe are shown in Figure 2 (top). The correlation value is 0.93 between the red and SWIR channels, but only 0.62 between the blue and SWIR channels. Compared to SWIR reflectance, blue reflectance are better correlated with red reflectance (Figure 2, top right), which is consistent with the result of *Levy et al.* [2007a]. Thus a better estimation of spectral surface reflectance can be achieved by calculating 0.66 μm surface reflectance from those at 2.12 μm and calculating 0.47 μm surface reflectance from those at 0.66 μm, as follows:

$$\begin{aligned} \rho_{0.66} &= 0.565\rho_{2.12} \\ \rho_{0.47} &= 0.477\rho_{0.66} + 0.006 \end{aligned} \tag{1}$$

[14] The results for Taihu are displayed in Figure 2 (bottom). The corrected surface reflectance ratios are more scattered than that of Xianghe, but still, the correlation between blue and red channels is much better than that between blue and SWIR channels. More accurate estimation of spectral surface reflectance at this site can be achieved using the following relationships:

$$\begin{aligned} \rho_{0.66} &= 0.486\rho_{2.12} + 0.03 \\ \rho_{0.47} &= 0.881\rho_{0.66} - 0.018 \end{aligned} \tag{2}$$

[15] AOD retrievals are influenced by individual reflectance ratios and the selection of aerosol type, both having a seasonal dependence. The time series of corrected surface reflectance in visible channels and the absolute error of MODIS-retrieved AOD (i.e., MODIS−AERONET) are shown in Figure 3.

[16] Compared to Xianghe, Taihu has a much warmer and humid climate throughout the year. Therefore the variation in surface reflectance at Taihu (Figure 3b) is less evident than that at Xianghe (Figure 3a). The surface reflectance at Xianghe has peaks in winter and early spring (November–March), when there is sparse green vegetation, only dry and barren soil. The C004 retrievals also have largest errors during these times, and its variability is positively correlated with that of surface reflectance. The retrievals are more accurate during summer and early fall (June–October), and

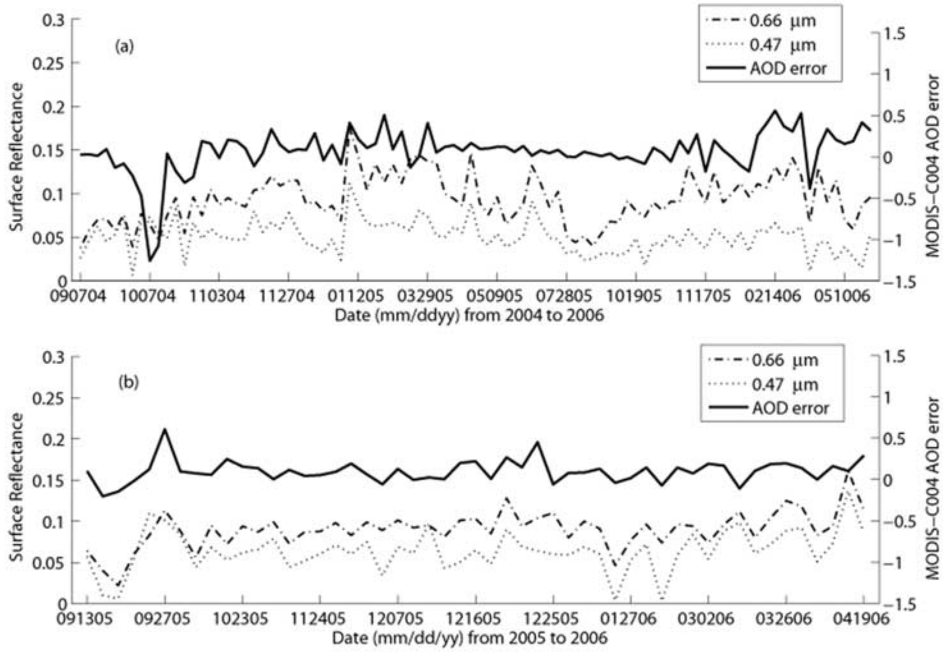

Figure 3. Time series of atmospherically corrected visible surface reflectance (dash-dotted line for red and dotted line for blue band) and the absolute error of MODIS (C004) AOD retrievals (bold solid line) with *y* axis on the right for (a) Xianghe and (b) Taihu.

less correlated with the surface reflectance, which have lower values compared to other seasons. At Taihu, the C004 retrieval is more stable, and errors are smaller than that at Xianghe. In addition, the denser surface vegetation and more humid soil make the surface reflectance less seasonally variable and only weakly correlated with the quality of aerosol retrievals.

4. Validation and Sensitivity Tests

[17] The above analyses suggest that the inaccurate estimation of surface reflectance is a major source of error in C004 retrievals at Xianghe, whereas the aerosol model assumption is the main cause of errors at Taihu throughout the year. To verify and quantify these errors, several experiments were conducted employing data from the two distinct regions of China. The analyses also help to understand the improvements made in the C005 algorithm.

4.1. Validation of MODIS Collection 4 Retrievals

[18] Figure 4 (top left) shows plots of the regression of MODIS-derived AOD (C004) with AERONET Sun photometer data from Xianghe. The results are similar to other comparisons for retrievals over land [*Chu et al.*, 2002; *Remer et al.*, 2005], i.e., overestimation for small AOD and underestimation for high AOD. However, the slope (0.7) of the regression is much smaller and the offset (0.208) is much larger than that from the global consensus, which is 0.9 and 0.1, respectively [*Levy et al.*, 2007a]. The larger offset here implies that potential errors likely stem from the assumed surface reflectance ratios.

[19] Assuming that the atmospherically corrected surface reflectance is an alternative independent estimation, we modified the MODIS stand-alone retrieval code (C004) such that these precalculated daily surface reflectance values were used, instead of the fixed reflectance ratios (i.e., 0.5 for the red channel and 0.25 for the blue channel). We name this modified retrieval as DAC-C004 AOD (i.e., retrieval using Daily Atmospherically Corrected surface reflectance). The results of 89 matched data points from Xianghe station are compared with AERONET measurements in Figure 4 (top right). The accuracy of the DAC-C004 retrieval is significantly better than the original MODIS-C004 retrieval at 550 nm (Figure 4, top left). Not only does the correlation coefficient increase from 0.8 to 0.89, but the slope increases and the offset decreases. The retrievals are much less scattered, especially on days of low AOD. However, little improvement is seen when the AOD is large, because the uncertainty of aerosol model assumed by the MODIS retrieval algorithm dominates on hazy days, and the surface effect diminishes.

[20] As mentioned in the previous section, the surface condition around Taihu is more uniform with little annual variation. As a result, the outcome of the test performed on data from Taihu (50 matched data points) is different from that at Xianghe, as shown in Figure 4 (bottom). Overall, the DAC-C004 AOD retrievals are overestimated, opposite to the original C004 retrievals that are underestimated. Since the DAC-C004 product was based on more accurate surface reflectance, the opposite bias must originate from the use of too low single scattering albedo. To verify if this is the case, we examined the four outlier cases of DAC-C004 AOD retrievals (data points near the top of the plot in Figure 4 (bottom right)) that contribute most to the large slope of the regression. According to the measurement of AERONET, these outliers represent the days with very high value of

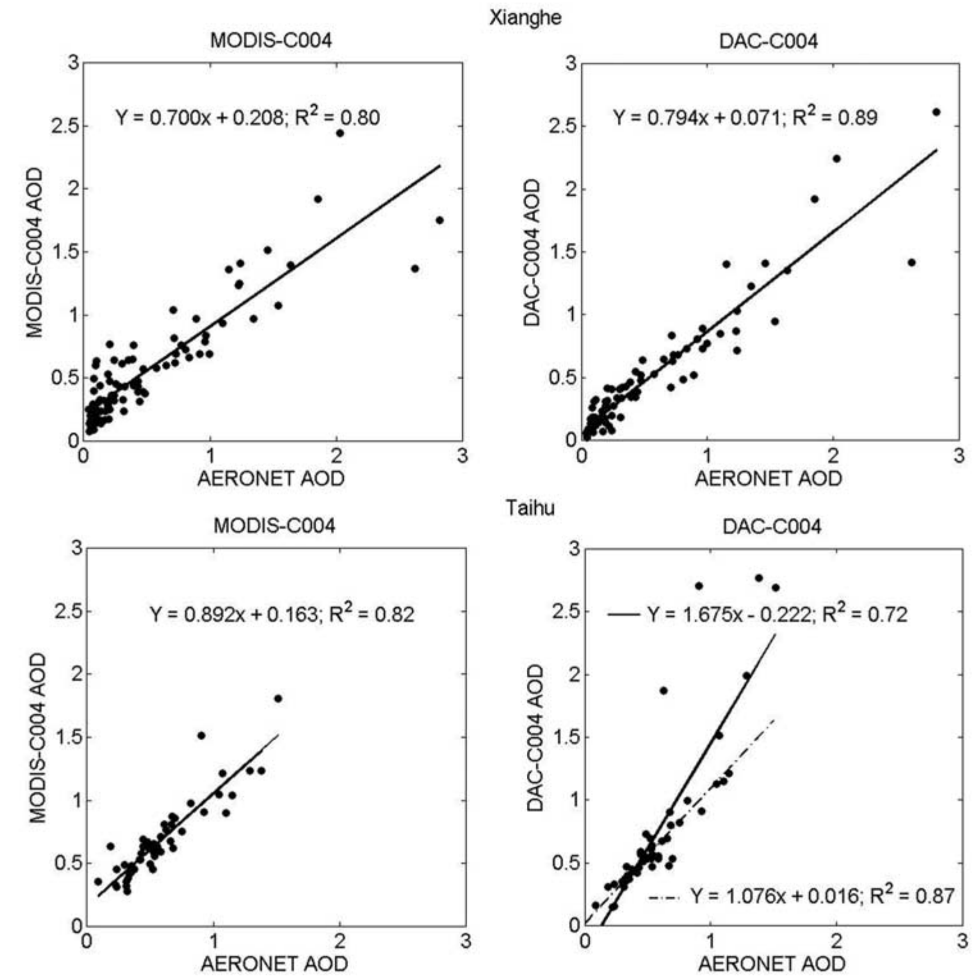

Figure 4. (left) MODIS-C004 and (right) DAC-C004 retrieved AOD compared with AERONET measurements at 550 nm for (top) Xianghe and (bottom) Taihu. The dash-dotted line in Figure 4 (bottom right) is the regression without the four outlier data points near the top.

single scattering albedo (SSA). The maximum SSA value is 0.995 and the mean value is 0.965 for these four outliers, but C004 algorithm assumes SSA of fine-dominated aerosols to be 0.85 constantly. When the error of surface reflectance is negligible as we employed the atmospherically corrected value, the retrieved AOD must be significantly overestimated because of the severely underestimated SSA. Excluding these few outliers would drastically improve the correlation between the DAC-C004 retrievals and AERONET measurements, as shown in the dash-dotted line in Figure 4 (bottom right).

[21] Given that the expected AOD retrieval error over land is $\Delta\tau = \pm 0.05 \pm 0.15\tau$, we may define the fraction of expected error (FOE) in the following manner:

$$FOE = \frac{\tau_{MODIS} - \tau_{AERONET}}{0.05 + 0.15\tau_{AERONET}} \qquad (3)$$

Relative error values falling within the range of -1 to 1 indicate MODIS retrievals within the expected error.

[22] The solid line with circles in Figure 5a shows the seasonal variability of the FOE from the original MODIS-C004 AOD retrievals at Xianghe from September 2004 to June 2006. AOD retrieval errors generally peak around February and are smallest during summer. However, the aerosol loading is highest during summer and lowest during winter (not shown) [*Li et al.*, 2007]. This mismatched variability suggests that the surface reflectance issue is more important on days with low aerosol loading. On the other hand, with the atmospherically corrected surface reflectance, the quality of the DAC-C004 AOD retrievals is improved at Xianghe, as shown by the dotted line with stars in Figure 5a. The magnitude of the error is generally smaller than that of the original MODIS-C004 retrievals and most of the retrievals are within the expected error range. The differences between these two lines thus shed light on the errors in AOD due to the surface reflectance assumption alone. With more vegetation coverage during the summer, errors due to surface assumptions tend to be smaller than during the winter, when land surfaces are less vegetated and inhomogeneous.

[23] The same test performed on data from Taihu leads to different results, as shown in Figure 5b. Compared to the original MODIS-C004 retrievals, the DAC-C004 retrievals are generally within the expected error range during winter season when AOD is smaller. However, some overestima-

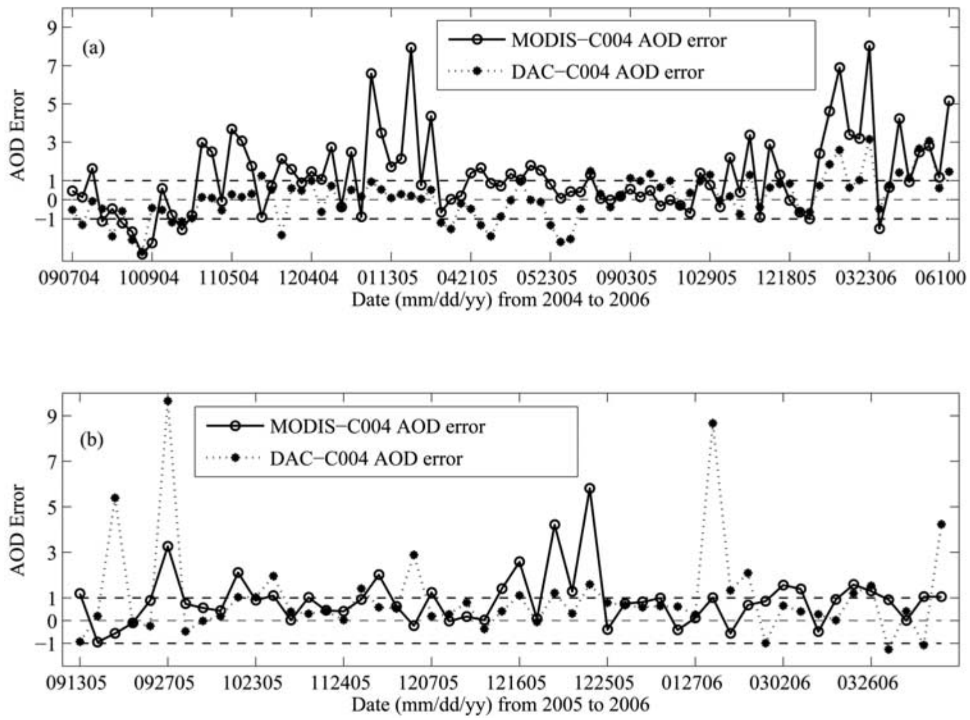

Figure 5. Seasonal variation of the relative error in the fraction of error in AOD retrievals for (a) Xianghe and (b) Taihu. The error of MODIS-C004 retrieval is denoted as the solid line with circles and that of DAC-C004, which uses daily atmospherically corrected surface reflectance, is shown by the dotted line with stars.

tions are significant in September 2005 and February 2006, which are caused by inaccurate aerosol model, as demonstrated above. This suggests that there is compensation between the errors caused by inaccurate surface albedo and incorrect aerosol model assumption in the C004.

4.2. Validation of MODIS Collection 5 Retrievals

[24] The new algorithm, C005, has been revamped to include an improved surface assumption, more realistic aerosol optical models and a new inversion approach. AODs at individual wavelengths are no longer derived independently and are now linked through the choice of aerosol model.

[25] The C005 visible surface reflectance is assumed to depend on scattering angle and surface type. The C005 algorithm no longer assumes that the reflectance at 2.1 μm measured by satellite is the same as the surface reflectance at that channel. One of the aerosol models, the coarse model, is substantially different from the old version because of an updated phase function based on the spheroid model. Global fine-dominated aerosols are categorized into three types: nonabsorbing (SSA $\sim$ 0.95), moderately absorbing (SSA $\sim$ 0.9) and absorbing (SSA $\sim$ 0.85). They are also assigned on the basis of location and season [*Levy et al.*, 2007b].

[26] In order to investigate the performance of the updated surface assumptions in the C005 algorithm, we performed similar tests as we did for the C004. Since the surface reflectance at the 2.1 μm channel is retrieved simultaneously with AOD at blue and red channels, it is difficult to directly use atmospherically retrieved reflectance in the C005 stand-alone code. We thus applied the derived ratios of atmospherically corrected surface reflectance (equations (1) and (2)) in the stand-alone code and the retrieval, namely RAC-C005 (i.e., retrieval using the Ratios of Atmospherically Corrected surface reflectance) is compared with that of the original MODIS-C005 algorithm (Figure 6). Note that as of this writing, the latest version of the MODIS/Terra product is only available back to January 2005. There are 190 matched data available for Xianghe and 55 for Taihu in this test.

[27] Figure 6 (left) shows that the MODIS C005 algorithm produces more accurate AOD retrievals at both AERONET sites than does the C004 algorithm. The strong overestimation of AOD under conditions of low aerosol loading by the C004 algorithm disappears for data at Xianghe (Figure 6, top left). For both Xianghe and Taihu, there is no significant difference between the retrievals from the original (MODIS-C005) and the modified one (RAC-C005). This implies that the surface assumption is improved in the C005 algorithm, which no longer leads to systematic overestimation of AOD on clean days.

[28] However, matched data points of RAC-C005 AOD versus AREONET AOD appear to be more scattered (in Figure 6 (right)) than that of original MODIS-C005 (in Figure 6 (left)) when AOD is larger than 0.5. There are two possible explanations. First, the surface reflectance ratios (equations (1) and (2)) are derived when AOD is smaller than the clean-day threshold, i.e., 0.3 for Xianghe and 0.4 for Taihu. These ratios may not be suitable for larger AODs, which tend to occur during the summer when the high humidity leads to the hygroscopic growth of aerosols [*Li et al.*, 2007]. Second, errors from other assumptions, such as

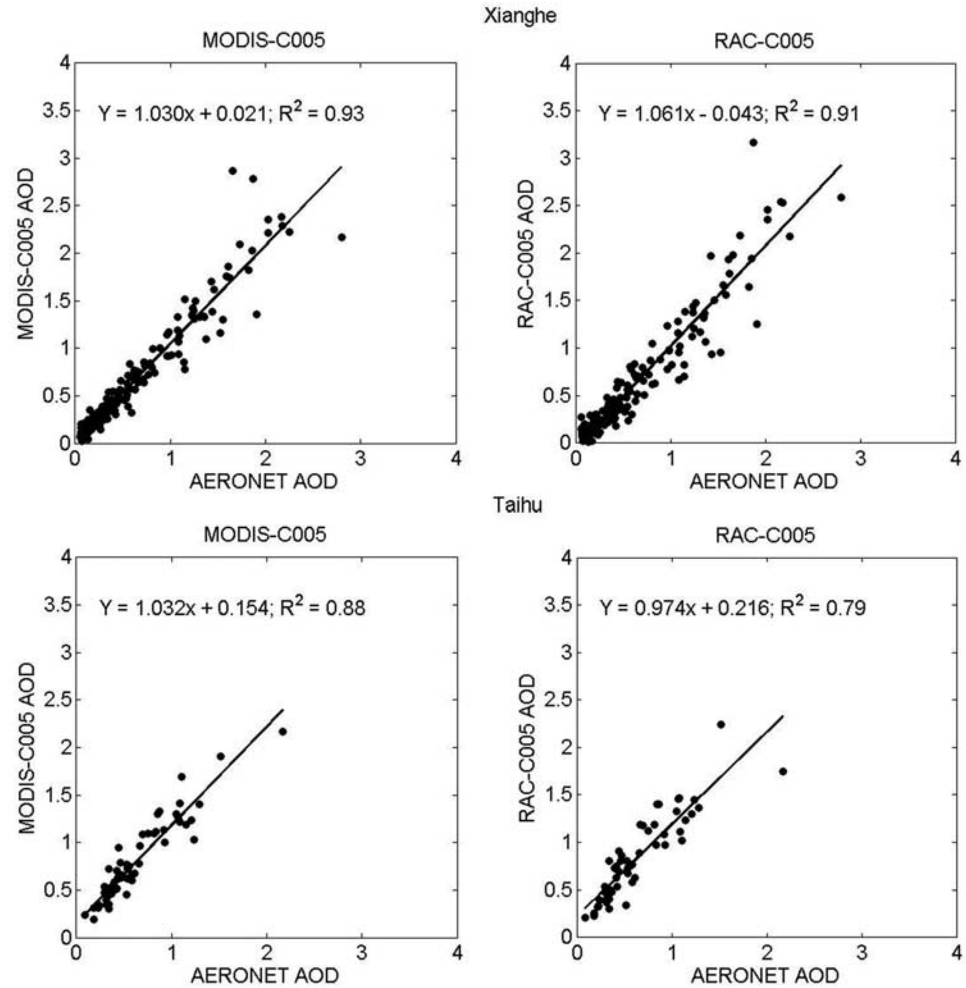

Figure 6. (left) MODIS-C005 and (right) RAC-C005 retrieved AOD compared with AERONET measurements at 550 nm for (top) Xianghe and (bottom) Taihu.

aerosol properties (i.e., single scattering albedo, size distribution, etc.), might have opposite signs to those errors from surface reflectance ratios. So even if no error is induced by the surface assumptions, the retrieved AOD at 550 nm does not necessarily become more accurate.

[29] The time series for the absolute error of retrieved AOD from MODIS-C005, MODIS-C004 and AERONET measurements are shown in Figure 7. Compared to the older version, the retrievals at Xianghe are significantly improved, especially during the winter and spring season. The C005 retrievals over Taihu (Figure 7b) are also improved during low aerosol loading days (e.g., December and January 2006), but not as significant as at Xianghe. Since the surface uncertainty has been substantially reduced in C005, aerosol model is the dominant factor for the systematic overestimation of the C005.

4.3. Performance of Updated Aerosol Models of MODIS Collection 5 Algorithm

[30] In addition to new surface reflectance assumptions, the C005 algorithm has updated global aerosol optical models and lookup tables. The full set of aerosol models includes three fine-dominated (spherical) and one coarse-dominated (spheroid) aerosol optical models. The coarse model has a substantially different phase function from that used in the C004 algorithm due to the assumption of spheroids instead of spheres [*Levy et al.*, 2007b]. The fine-dominated aerosol types used for Xianghe and Taihu are now both assigned as "moderately absorbing" aerosols (SSA $\sim$ 0.90) for all seasons, rather than "strong absorbing" aerosols (SSA $\sim$ 0.85).

[31] The following test is aimed to investigate the performance of the refined aerosol models in C005 algorithm.

[32] To single out and evaluate the influence of the updated aerosol model assumption compared to the old one in C004, we need to fix other inputs and assumptions: employ the same TOA radiance and surface reflectance (derived ratios in equations (1) and (2)) in both C004 and C005 stand-alone retrieval codes. The two test runs are named SSFC-C004 (i.e., retrievals using the Same SurFaCe reflectance) and SSFC-C005, respectively.

[33] The results of the two algorithms are plotted in Figure 8, in terms of the FOE. Errors in retrieved AOD from the SSFC-C004 and SSFC-C005 algorithms are shown by the dotted line with stars and solid line with circles, respectively. Most importantly, the differences between these two lines characterize the performance of the updated aerosol models.

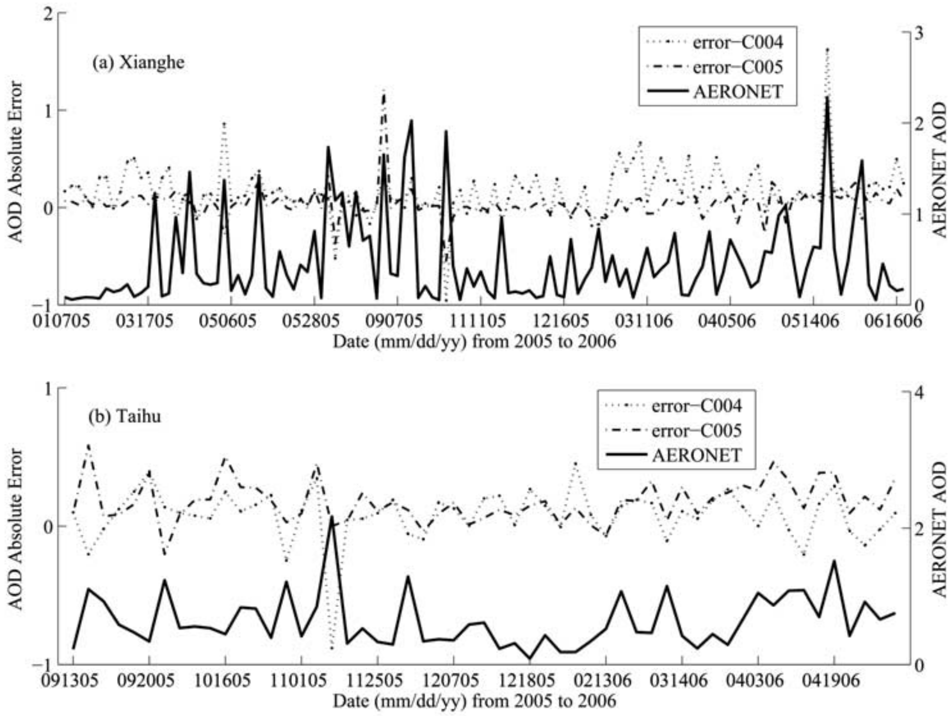

Figure 7. Time series for the absolute error of AOD retrievals of MODIS-C004, MODIS-C005 (with y axis on the left) and AERONET measurement (with y axis on the right) over (a) Xianghe and (b) Taihu.

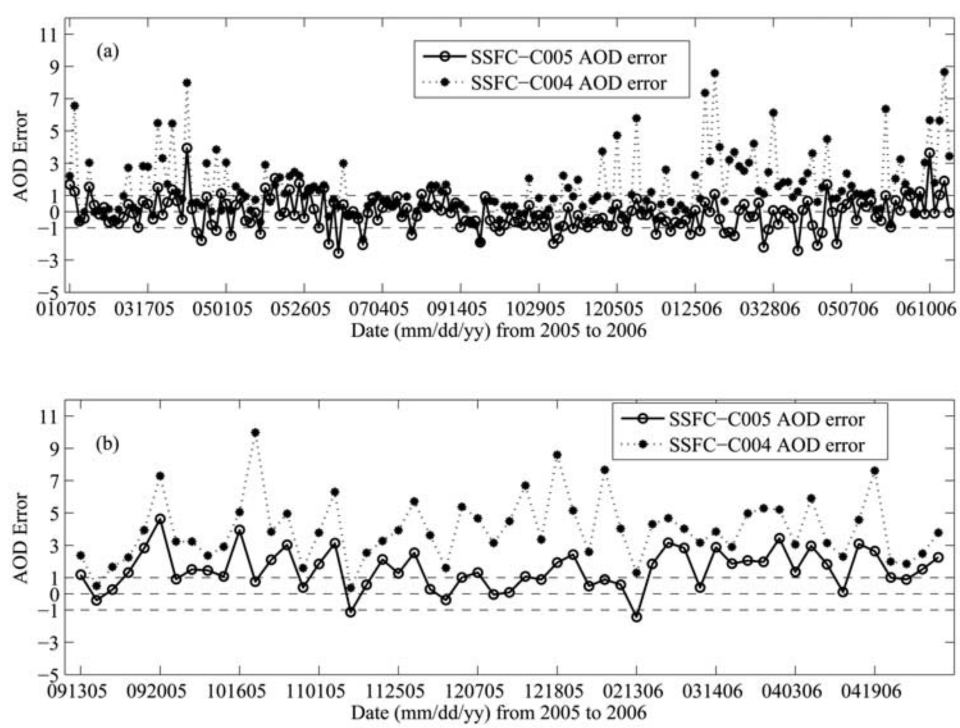

Figure 8. Relative error in FOE of AOD retrieved from the SSFC-C004 (dotted line with star) and the SSFC-C005 (solid line with circle) over (a) Xianghe and (b) Taihu. With the same surface information as input, the difference between the AOD retrievals from these two algorithms is contributed by the assumed aerosol model alone.

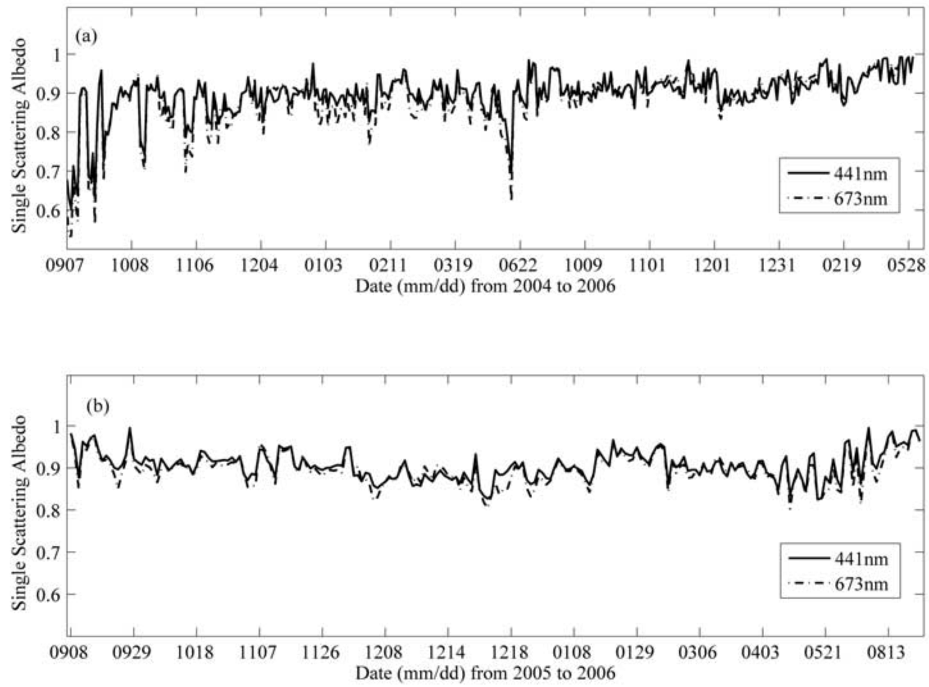

Figure 9. AERONET measured single scattering albedo over (a) Xianghe and (b) Taihu.

[34] At Xianghe (Figure 8a), the difference between the two lines is relatively small and also seasonally dependent. Although the results from both algorithms agree during summertime, the differences between them are large during spring when dust storms appear frequently. The C004 model tends to overestimate AOD, while the C005 model tends to underestimate it during this time. This large discrepancy only happens during spring time at Xianghe, but not for Taihu, a region with almost no dust influence. A more detailed analysis during dust events is addressed in the next section.

[35] The AOD retrievals at Taihu from the SSFC-C004 are consistently higher than those from the SSFC-C005 year-round (Figure 8b). Unlike northern China, spring dust is not transported to the Taihu region, so anthropogenic fine aerosols dominate here. This site is located in the center of the Yangtze Delta region, where the pollution is mainly caused by sulfate aerosols from industrial emissions [*Chin et al.*, 2004]. The MODIS C004 algorithm assumes the fine model aerosols in eastern China with SSA about 0.85. However, the AERONET-retrieved SSA is much higher than this value (Figure 9b). Thus it appears that the underestimation of the SSA of fine model aerosols in the C004 algorithm is the major error source for the systematically overestimated AOD at Taihu. As mentioned in the previous section, retrievals from the C005 algorithm are more accurate during wintertime at Taihu. The AERONET-inferred SSA values happened to be closer to 0.9 at this time of the year (from November to February) with mean values of about 0.90 at 441 nm and 0.89 at 673 nm.

[36] The AERONET-derived SSA at Xianghe is lower (Figure 9a) than at Taihu (Figure 9b). Thus errors concerning the MODIS-C004 assumed SSA are less significant at this site. Compared to the surface uncertainty, the contribution of the SSA error to the MODIS C004 retrievals is relatively small. The assumed size distribution and refraction index might also have large uncertainties, especially in the presence of dust-dominated aerosols. To verify this, more detailed investigation of the assumed aerosol models is needed, especially for the northern China region.

4.4. Effects of Spheroid Dust on Aerosol Retrievals

[37] The large discrepancy between the result from SSFC-C005 and SSFC-C004 is found during spring time when dust events happen frequently. The assumption of spheroids in lieu of spheres for the coarse mode in the C005 model is an likely reason. To further investigate the influence of the new dust mode, dust events are identified first.

[38] UV Aerosol Index (AI) retrieved from Ozone Monitoring Instrument (OMI) on the EOS-AURA is sensitive to the absorbing aerosols. It is a measure of the departure of the spectral dependence of the near UV upwelling radiation at the top of the actual surface-atmosphere system from that of a pure molecular atmosphere bounded at the bottom by a wavelength-independent Lambertian surface. To avoid possible cloud contamination due to the large footprint of OMI observation (about 13 $\times$ 24 km2 at nadir), only data with the highest quality flag is used. The time series of AI over Xianghe is shown as solid line in Figure 10 and the high values are associated with strong absorbing aerosols.

[39] The AERONET measured Angstrom Exponent (AE) for the 440 nm/670 nm wavelength pair at Xianghe is also shown as a dotted line in Figure 10. The mean value of AE from March through May 2006 is about 0.7, which indicates large particles from dust events. The open circles indicates the days when the Fine aerosol Weighting (FW) retrieved by MODIS-C005 is 0, which means the pure dust model is used in the retrieval. Following *Jeong and Li* [2005],

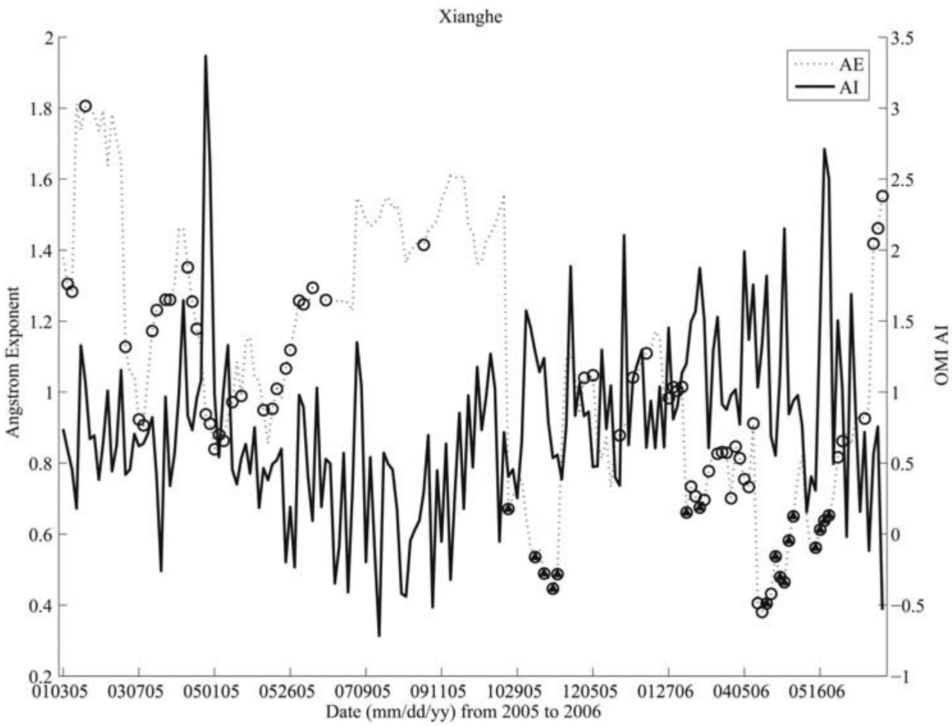

Figure 10. Time series of AERONET measured Angstrom exponent (470 nm/660 nm) and OMI retrieved Aerosol Index (AI) for Xianghe. The open circles are days when pure dust model was used in the retrieval (i.e., Fine aerosol Weighting (FW) = 0). The solid triangles denote pure dust cases meeting the criteria: AE <= 0.7, AI >= 0.3, AOD >= 0.3 and FW = 0.

detection of dust is based on AE <= 0.7, AI >= 0.3, AOD >= 0.3 and FW = 0. The dust events identified are marked as triangles in Figure 10.

[40] For these dust cases, the influence of spheroid rather than spherical dust in the retrievals can be singled out by comparing SSFC-C004, SSFC-C005 with AERONET AOD, respectively (Figure 11). The differences in the comparisons between Figure 11 (left) and Figure 11 (right) are directly caused by the nonspherical assumption, since the surface is the same for both tests and only the pure dust model is used in the retrieval (i.e., FW = 0). Therefore it is evident that the nonspherical dust assumption in C005 leads to a great improvement of MODIS AOD retrievals.

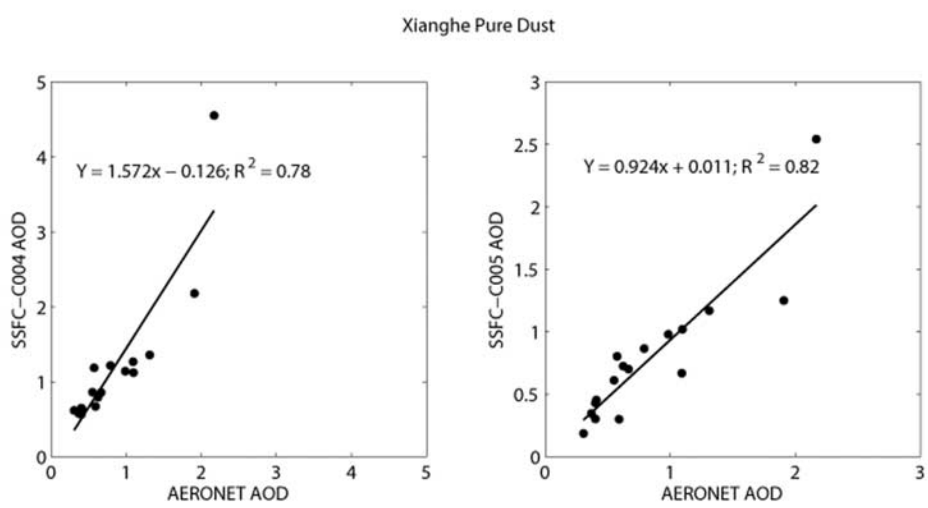

Figure 11. AOD retrieved by (left) SSFC-C004 and (right) SSFC-C005 are compared with AERONET measurement for the pure dust cases indicated by triangles in Figure 10.

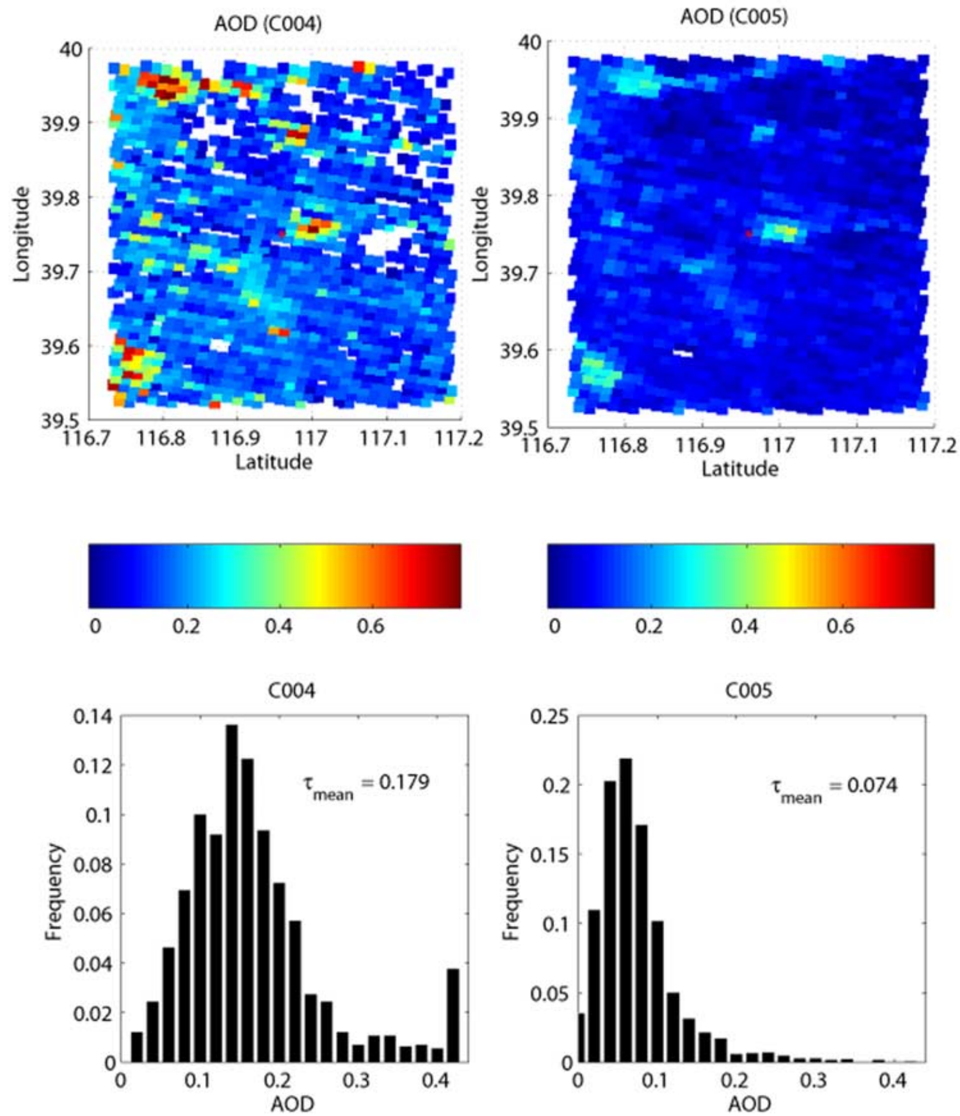

Figure 12. Distribution map and histograms of retrieved AOD using (left) C004 and (right) C005 algorithm over 50 $\times$ 50 km^2 box centered on Xianghe site (marked as a red star in the center of the top plots).

4.5. Spatial Variability of MODIS AOD Retrievals

[41] The MODIS level 2 aerosol product is generated at a spatial resolution of 10 km. Over a 10-km grid, AOD is expected to have little variation in general, but the surface condition may change dramatically, especially for suburban areas where villages, small towns and agricultural land are interspersed.

[42] As a demonstration, we picked a clear and clean day on 3 October 2005 at Xianghe. The AERONET-measured AOD is equal to 0.078, averaged over a 1-hour time interval centered on the MODIS satellite overpass time. Over a 50 $\times$ 50 km^2 area around the ground site, 1-km AOD data were generated by substituting 1-km TOA reflectance data (MOD021KM) of cloud-screened dark-pixels (0.01 $\leq \rho_{2.12} \leq$ 0.25), into the C004 and C005 stand-alone algorithm. The gross spatial distribution patterns of the retrieved AOD from the two algorithms are similar, but AOD from the C004 algorithm has a significantly larger range of retrieval values than those from the C005 algorithm, as seen from both the distribution maps and the histograms shown in Figure 12. Worth noting are several differences between the C004 and C005 AOD maps. First, the C005 retrieval is much more complete than the C004 retrieval, which shows more gaps without retrievals. Second, there are more extreme values generated by the C004 algorithm than the C005 algorithm, which usually occurs over town centers. While anthropogenic emissions from towns are expected to be higher than rural regions, the contrast seems to be excessive, given the size of the towns and the short distance to neighboring pixels of much lower AOD. We argue that much of the enhanced AOD is an artifact resulting from the influence of the surface. This can be more clearly inferred from the histograms of AOD. The AOD from the C005 algorithm shows a single-mode narrow distribution with a mean value of 0.074, which is very close to the ground-based measurement of 0.078. In stark con-

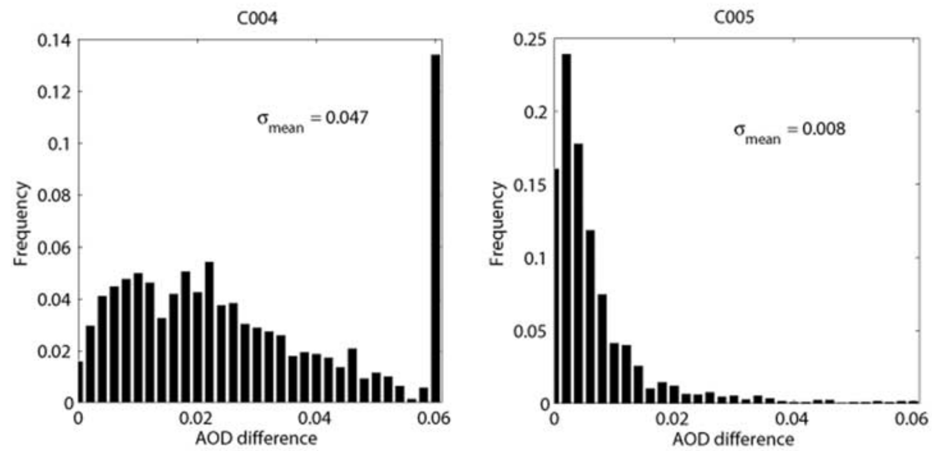

Figure 13. Mean square of AOD differences between a pixel and its eight surrounding pixels using (left) C004 and (right) C005 algorithm.

trast, the AOD from the C004 algorithm exhibits a much wider distribution with a mean value of 0.179, more than twice the magnitude of the ground measurement. There are also many retrievals larger than 0.5.

[43] Since the differences in the scattering angle between neighboring pixels are negligible, the spatial variation of AOD over the small region stems chiefly from inaccurate estimation of the surface reflectance. To better quantify this, the mean square of AOD differences between a pixel and its 8 surrounding pixels were calculated and its histogram of frequency of occurrence is shown in Figure 13. For the C005 retrievals, the distribution has a very narrow range with the majority (79%) of differences smaller than 0.01 and the mean difference equal to 0.008. On the contrary, the C004 retrievals have a much wider distribution and a larger mean (0.047), with more than half of the values greater than 0.02. It thus reinforces the finding that the new MODIS algorithm can substantially reduce the artificial variation of AOD retrievals from pixel to pixel and offers the potential to retrieve AOD at higher resolutions.

5. Summary

[44] Satellite retrievals of aerosol properties are a major challenge over land, due primarily to high surface reflectance and variable aerosol type. As a result, development of satellite retrieval algorithms requires ground-truth information. Thanks to the extensive global aerosol measurements made by AERONET, the MODIS retrieval algorithm can be easily validated, and has undergone a series of revisions, resulting in the widely used C004 aerosol product and the newest C005 aerosol product. The performance of the algorithm hinges upon prior knowledge gained through in situ or ground-based observations. There exist a large number (192) of AERONET stations around the world, but very few sites over China (4), a vast territory where there is generally heavy aerosol loading and complex aerosol properties.

[45] In this study, we take advantage of the AERONET data acquired in China to evaluate the two most recent MODIS aerosol products, C004 and C005. The AERONET data have been acquired continuously since 2004 and 2005 in northeastern (Xianghe) and southeastern (Taihu) China under the aegis of the EAST-AIRE project (Li et al., submitted manuscript, 2007). While both sites are heavily loaded with anthropogenic aerosols, Xianghe is much more susceptible to mineral dust transport than Taihu. In addition the two sites display very different climate regimes and ecosystems. After performing atmospheric corrections using AERONET data, observed relationships were established between surface reflectance in the visible and SWIR channels. Together with these newly derived relationships, aerosol optical properties retrieved from AERONET are employed to evaluate the MODIS products and quantify various uncertainties.

[46] In northeastern China, MODIS C004 retrievals have the largest error around February and the smallest error during the summer. The overestimation of AOD under low aerosol loading conditions is primarily due to the use of biased surface reflectance ratios in winter and early spring. The fixed reflectance ratio assumed in the C004 algorithm cannot properly account for strong seasonal changes in the surface condition, namely barren soil with little vegetation in the dry and cold winter season and green vegetation in the humid summer season. The quality of MODIS C005 retrievals has been significantly improved, as indicated by the high correlation coefficient (0.93), low offset (0.02) and a slope close to unity (1.03). As compared to AERONET, the strong overestimation problem at small AOD values was fixed by using dynamic reflectance relationships that vary with the vegetation index and scattering angle. The improvement also benefits from a change in coarse aerosol particle shape from spheres to spheroids.

[47] On the other hand, the inferior retrieval quality of the C004 algorithm over southeastern China is mostly caused by the inaccurate assumption in aerosol models rather than the surface reflectance. The seasonal variation of the surface reflectance at the Taihu site is much weaker because of its consistently warmer and more humid climate. Both C004 and C005 algorithms systematically overestimate AOD year-round. Most of the aerosols come from industrial pollution, which are highly scattering sulfate aerosols with

small particle size. Compared with AERONET-measured SSA, the assumed SSA in the C004 algorithm (equal to 0.85) is too low. The MODIS C005 algorithm corrected this oversight by assuming a more realistic "moderately absorbing" aerosol with a SSA equal to 0.9.

[48] The new C005 algorithm can also reduce the possibility of artificial variation of AOD retrievals in pixel scale due to the improved strategy in surface reflectance estimation. However, more accurate observations of the surface condition in China are needed to further optimize the algorithm and make it possible to retrieve AOD with higher resolution.

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H. Chen and X. Xia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China.

M. Cribb, R. Levy, Z. Li, W. Mi, and F. Zhao, Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742, USA. (zli@atmos.umd.edu)

B. Holben, Laboratory for Atmosphere, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.