Retrieval of Aerosol Optical Thickness Using MODIS 500 × 500 m^2, a Study in Hong Kong and the Pearl River Delta Region

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***Abstract*—Aerosol detection and monitoring by satellite observations has been substantially developed over the past decades. While several state-of-the-art aerosol retrieval techniques provide aerosol properties at global scale, high spatial detail that is suitable for urbanized regions is unavailable because most of the satellite-based products are at coarse resolution. A refined aerosol retrieval algorithm using the MODerate Resolution Imaging Spectroradiometer (MODIS) to retrieve aerosol properties at 500-m resolution over land is described here. The rationale of our technique is to first estimate the aerosol reflectances by decomposing the top-of-atmosphere reflectance from surface reflectance and Rayleigh path reflectance. For the determination of surface reflectances, a modified minimum reflectance technique (MRT) is used, and MRT images are computed for different seasons. A good agreement is obtained between the surface reflectances of MRT images and MODIS land surface reflectance products (MOD09), with a correlation of 0.9. For conversion of aerosol reflectance to aerosol optical thickness (AOT), comprehensive lookup tables are constructed which consider aerosol properties and sun-viewing geometry in the radiative transfer calculations. The resulting 500-m AOT images are highly correlated ($r = 0.937$) with AErosol RObotic NETwork sunphotometer observations in Hong Kong for most of the year corresponding to the long dry season. This study demonstrates a method for aerosol retrieval at fine resolution over urbanized regions, which can assist the study of aerosol spatial distribution. In addition, the MODIS 500-m AOT images can also be used to pinpoint source areas of cross-boundary aerosols from the Pearl River Delta region.**

***Index Terms*—Aerosols, air pollution, remote sensing.**

I. Introduction

ATMOSPHERIC aerosols are defined as suspended particles in the atmosphere in liquid or solid phase. They have different size distributions, shapes, and residence times and originate from different sources. Aerosol retrieval from satellite remotely sensed images is well developed, and it basically aims to distinguish the attenuated radiation by aerosols from that of reflection from the surface. The procedure is complex because ground surface reflectances are difficult to distinguish from the total satellite received signal. The estimation of surface reflectances is thus the key factor in aerosol retrieval which attempts to differentiate the aerosol signal from that of the surface.

Kaufman and Tanré [1] first proposed the dense dark vegetation (DDV) method using a multiband algorithm from the MODerate Resolution Imaging Spectroradiometer (MODIS) satellite images. The DDV method (known as collection 4 algorithm) works only on vegetation areas with coverage larger than 60% where surface reflectances are very low. It cannot be used on bright surfaces such as deserts and urban areas. Chu *et al.* [2] revealed that the MODIS collection 4 algorithm has a positive bias when compared with the AErosol RObotic NETwork (AERONET [3]) sunphotometer data. Remer *et al.* [4] and Levy *et al.* [5] also reported certain inherent problems in determining surface reflectance using the DDV algorithm. These results imply that inaccurate surface properties can lead to errors in aerosol retrieval. Recently, Levy *et al.* [6] modified the surface reflectance determination in the MODIS aerosol retrieval algorithm (known as collection 5) by considering the normalized difference vegetation index (NDVI) $NDVI_{\mathrm{SWIR}}$ for dark pixel screening, as well as the scattering angle. Although significant improvement in MOD04 collection 5 algorithm was shown in terms of both accuracy and continuity of aerosol retrieval [7], [8], the southern China region, including Hong Kong and the Pearl River Delta (PRD) region, has been identified as having a large error in aerosol optical thickness (AOT) retrieval [1]. Thus, there remain two major limitations of MOD04 data for local/urban scale study, namely bright surfaces such as urban areas and low spatial resolution. To overcome these limitations, new techniques are presented in this study.

Aerosol retrieval over bright surfaces is challenging because the land surface and atmospheric aerosol content are not easy to differentiate due to the fact that both have high reflectance. Hsu *et al.* [9], [10] recently developed a deep blue algorithm for aerosol retrieval over desert, arid, semiarid, and urban areas using MODIS images. This algorithm makes use of the blue wavelengths where the surface reflectances are bright in the red region and darker in the blue region.

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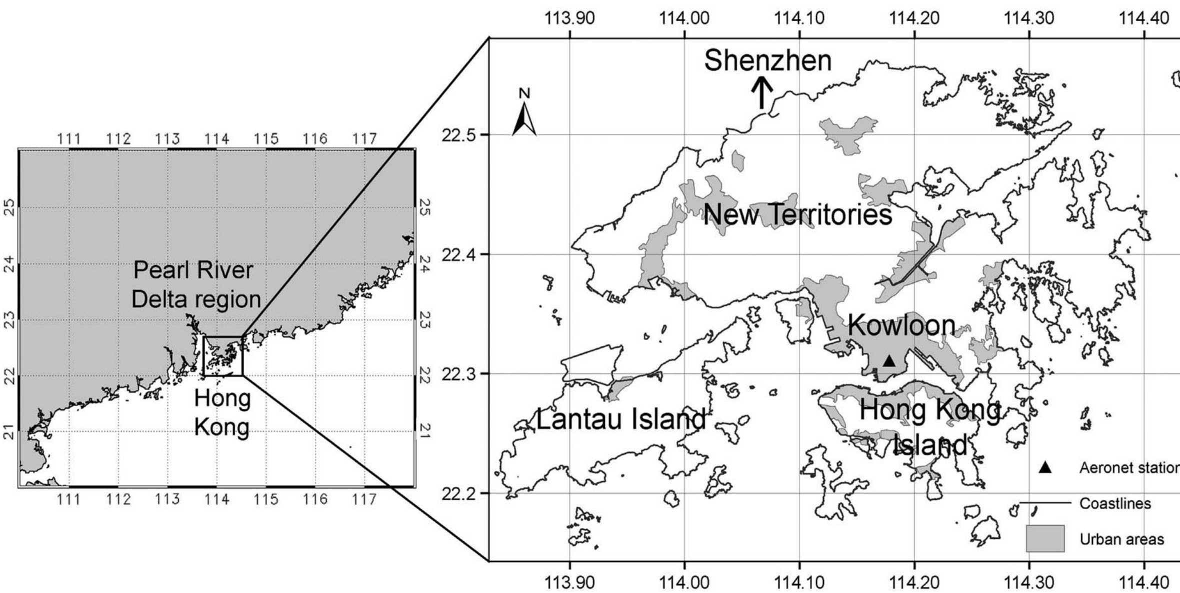

Fig. 1. Map of Hong Kong and AERONET station.

In order to estimate aerosols over variable cover types, including bright and dark surfaces, the minimum reflectance technique (MRT) was developed for TOMS [11] and GOME [12] data at coarse resolution ($> 1^\circ$). In view of the coarse resolution, the accuracy of AOT (within 30% of AERONET ground measurements) could be considered good. The coarse (10-km) spatial resolution of the National Aeronautics and Space Administration (NASA)'s MODIS aerosol products only provides meaningful depictions on a broad regional scale, whereas aerosol monitoring over complex urbanized regions, such as the PRD region and Hong Kong, requires more spatial and spectral details. The only "high"-resolution aerosol study, by Li *et al.* [13], who applied the MODIS collection 4 algorithm at the resolution of 1 km to retrieve AOT over Hong Kong, was limited to dark vegetated areas, and the results were validated only between October and December 2003 using handheld sunphotometers [13]. In order to retrieve and map aerosol loading distributions over urban areas with a high level of detail, a new MODIS 500-m resolution aerosol retrieval algorithm, which modifies the MRT technique, is proposed in this study.

II. Study Area and Data Used

Hong Kong, a city with a mainly service-based economy, has suffered serious air pollution for many years as the nearby PRD region (Fig. 1) has urbanized and industrialized. Previous studies [14]–[16] in the PRD have measured a range of particle concentrations for PM10 of 70–234 $\mu\text{g/m}^3$, with high average PM10 concentrations above 200 $\mu\text{g/m}^3$ in winter and around 100 $\mu\text{g/m}^3$ for PM2.5 in the autumn. These high concentrations of suspended particles create low visibility and greatly affect the regional radiative budget [17]. During the long dry season (ca. eight months), air masses are mainly northeasterly bringing continental pollution into the PRD region and Hong Kong [18].

This study uses the 500-m resolution TERRA/MODIS level 1B calibrated reflectance (MOD02Hkm) and MODIS level 2 aerosol products (MOD04) of the year 2007. Validation of the AOT retrieved from our new methodology was carried out by comparison with the Hong Kong AERONET station. AERONET is a federated network of ground sunphotometers, which consists of a Cimel sunphotometer for measuring the aerosol extinction every 15 min using a multiple wavelength radiometer. In order to validate the surface reflectance estimated from our modified MRT method, the MODIS surface reflectance products (MOD09 eight-day composite surface reflectance images) were also acquired from the NASA Goddard Earth Science Distributed Active Archive Center (DAAC) for year 2007. The MOD09 images were temporally averaged from eight-day composites to seasonal (ca. ten MOD09 images were averaged for each season). The resolution was resampled from 1 km to 500 m using the bilinear interpolation method, for comparison with seasonal MRT images at 500-m resolution. The MOD09 images are corrected for aerosols, gases, and water vapor using MODIS atmospheric data. Their surface reflectances are validated with 150 AERONET stations and are considered acceptable if the data error lies within $\pm 0.005 + 5\%$ [19].

III. Methodology

The rationale of the proposed aerosol retrieval algorithm is to determine the aerosol reflectance by decomposing the top-of-atmosphere (TOA) reflectance from surface reflectance and the Rayleigh path reflectance. The TOA reflectance $\rho_{\text{TOA}}(\theta_0, \theta_s, \phi)$ is expressed as [20]

$$\rho_{\text{TOA}} = \rho_{\text{Aer}} + \rho_{\text{Ray}} + \frac{\Gamma_{\text{Tot}}(\theta_0) \cdot \Gamma_{\text{Tot}}(\theta_s) \cdot \rho_{\text{Surf}}}{1 - \rho_{\text{Surf}} \cdot r_{\text{Hem}}} \qquad (1)$$

where θ_0 and θ_s are the sun and satellite zenith angles. ρ_{Aer}, ρ_{Ray}, and ρ_{Surf} are aerosol, Rayleigh, and surface reflectances. $\Gamma_{\text{Tot}}(\theta_0)$ and $\Gamma_{\text{Tot}}(\theta_s)$ are the total atmospheric transmittances, containing both direct and diffuse transmissions for sun

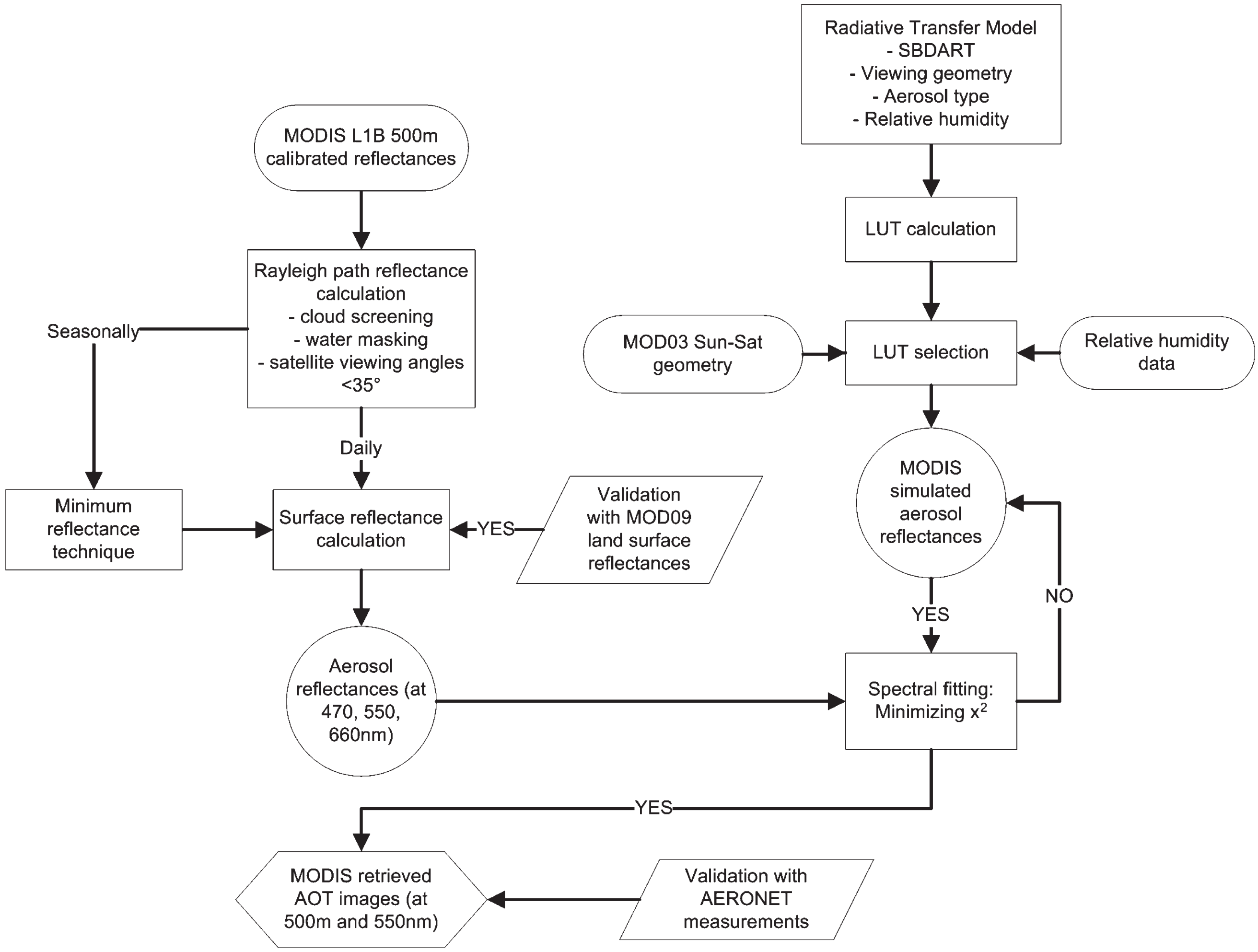

Fig. 2. Schematic diagram for aerosol retrieval in the study.

illumination and satellite viewing geometry. The total transmittances include Rayleigh scattering and aerosol extinction, which can be given as $\Gamma_{\text{Tot}} = \Gamma_{\text{Ray}} \cdot \Gamma_{\text{Aer}}$. r_{Hem} is the hemispheric reflectance. Detail descriptions of the determination of each term in (1) can be found in [21].

Fig. 2 shows the work flow of aerosol retrieval in this study.

A. Rayleigh Path Reflectance

The determination of Rayleigh path reflectance is based on the computation of spectral dependence of the Rayleigh optical depth and phase function. The following equation was adopted for calculating the Rayleigh scattering optical thickness (ROT) [22]:

$$\tau_{\text{Ray}}(\lambda) = A \cdot \lambda^{-(B+C\lambda+D/\lambda)} \cdot \exp\left(\frac{-z}{8.5}\right) \tag{2}$$

where A, B, C, and D are the constants of the total Rayleigh scattering cross section and the total Rayleigh volume scattering coefficient at standard atmosphere. z is the height in kilometers, and 8.5 is the exponential scale height of the atmosphere.

A digital elevation model (DEM) in MOD03 geolocation data was used for estimating the height z and for calculating the pressure for each pixel. By using the ROT, the Rayleigh path reflectance can be obtained in the following equation:

$$\rho_{\text{Ray}}(\lambda) = \pi \cdot \tau_{\text{Ray}} \cdot p_{\text{Ray}} \cdot m(\theta_0) \cdot m(\theta_s) \tag{3}$$

where p_{Ray} is the phase function of Rayleigh scattering which can be given as

$$p_{\text{Ray}} = \frac{4}{3}(1 + \cos\Theta^2)\left(\frac{1-\delta_{\text{Ray}}}{1+2\delta_{\text{Ray}}}\right) \tag{4}$$

where Θ is the scattering angle and δ_{Ray} is the Rayleigh polarization factor (i.e., 0.0279).

The Rayleigh correction was only applied for land pixels. The water was masked based on the land mask data in the MOD03 product. The thresholds of land mask values and the reflectance values were set for masking the water areas

$$\begin{aligned}&\text{If (land mask} > 1 \text{ or} = 0)\\ &\qquad \text{or (reflectance at 660 nm} < 0.08) \text{ then mask.}\end{aligned} \tag{5}$$

Since there is no high-resolution thermal band in MOD02Hkm (500-m) data, a tailor-made cloud-masking algorithm was devised for this study by making use of three visible channels and an NDVI band. This algorithm tests the brightness of reflectance for each pixel, with thresholds set based on a trial-and-error approach

$$\begin{aligned}&\text{If}\,(\text{reflectance at } 470 \text{ nm} > 0.2)\\&\quad\text{or}\,(\text{reflectance at } 550 \text{ nm} > 0.2)\\&\quad\text{or}\,(\text{reflectance at } 660 \text{ nm} > 0.2)\\&\quad\text{or}\,(NDVI < -0.5) \text{ then mask.}\end{aligned} \tag{6}$$

The cloud masking was validated using the Hong Kong Observatory cloud cover data which measure oktas of cloudiness. The accuracy of cloud masking is 78.13% which is comparable to the accuracy stated in the MODIS operational algorithm (ca. 82%). This procedure is likely to be more accurate with higher resolution images [23].

B. Surface Reflectance

The basic scheme of the modified MRT is to extract the minimum reflectance values of land surfaces from Rayleigh-corrected images over a time period. In this study, an entire year (2007) of MOD02Hkm (500-m) images was acquired from NASA DAAC. To minimize the effects from land cover changes, seasonal minimum reflectance images were derived based on at least 30 clear-sky images for each of the four seasons. Then, the second minimum reflectance values (rather than the actual minimum) were retrieved in order to avoid abnormally low reflectance such as noise or shadow. The second minimum reflectance was applied to all surface reflectance levels in the image, but the second minimum reflectance was only higher than the first minimum reflectance at lower reflectance levels below 0.03. This suggests that it is effective only in very dark areas where shadow is present, and can eliminate them.

In addition, only nadir images with satellite viewing angle $< 35^\circ$ were considered in order to minimize the angular effects caused by the bidirectional reflectance distribution function (BRDF) effect in heterogeneous areas. The viewing angles are restricted in determining surface reflectance, but they are all considered during AOT calculation.

C. LUT Construction

In this study, a comprehensive lookup table (LUT) was constructed using the Santa Barbara DISORT Radiative Transfer (SBDART) code [24] for calculating the aerosol reflectance as a function of AOT under various sun-viewing geometries and relative humidity (RH). Inputs to SBDART comprise atmosphere, aerosol, and surface data, and for aerosols, a few aerosol models from the Optical Properties of Aerosols and Clouds (OPAC) [25] database were used. Each aerosol model is characterized by its own microphysical and optical properties, such as particle size distribution, and complex refractive index. Six default classes from the OPAC model were selected, and they are: 1) continental clean; 2) continental average; 3) continental pollutant; 4) desert dust; 5) maritime clean; and 6) marine pollutant models. Fig. 3 shows the size distribution of each aerosol model used in this study.

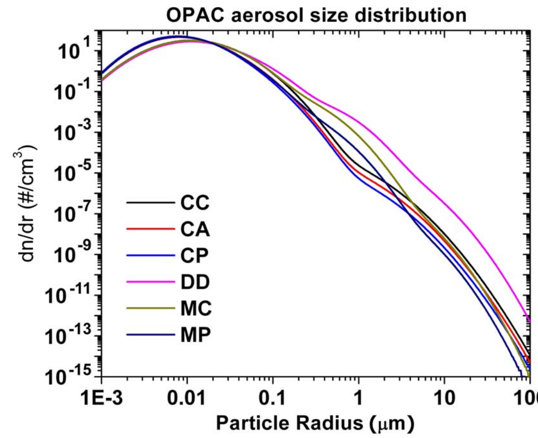

Fig. 3. Aerosol size distributions used in this study.

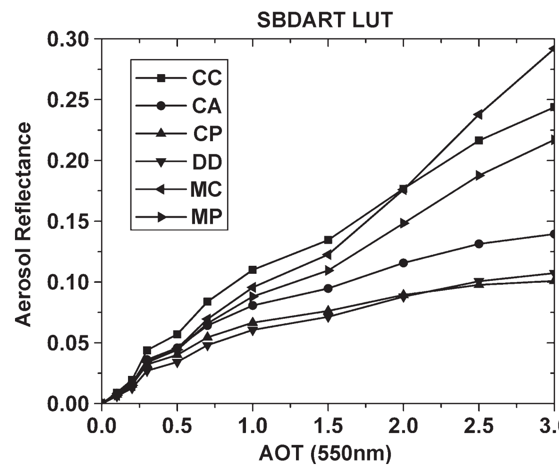

Fig. 4. Aerosol reflectance as a function of AOT. The SBDART calculations were performed with solar zenith angle $= 30^\circ$, satellite zenith angle $= 10^\circ$, azimuth angle $= 150^\circ$, and RH $= 50\%$.

For the LUT construction, the aforementioned six aerosol models with nine solar zenith angles ($0^\circ \sim 80^\circ$, $\Delta = 10^\circ$), 17 view zenith angles ($0^\circ \sim 80^\circ$, $\Delta = 5^\circ$), 18 relative sun/satellite azimuth angles ($0^\circ \sim 170^\circ$, $\Delta = 10^\circ$), and eight RH values (RH $= 0\%$, 50%, 70%, 80%, 90%, 95%, 98%, and 99%) were considered. The SBDART code uses the aerosol properties associated with a given model, plus the combinations of values for the four parameters listed earlier [amounting to 132192 combinations for three bands (470, 550, and 660 nm)], to compute the hypothetical AOT. Fig. 4 shows one of the LUTs from the SBDART results.

D. Aerosol Retrieval

The satellite measured aerosol reflectances decomposed from TOA reflectances, surface reflectances, and Rayleigh path radiance can be fitted to the LUT to derive the AOT from the images. The first step in this retrieval starts from deriving aerosol reflectances from images. The second step is to derive modeled aerosol reflectances from the LUT, and the last step is to compare the image and modeled aerosol reflectances to find the appropriate aerosol model and AOT for each pixel.

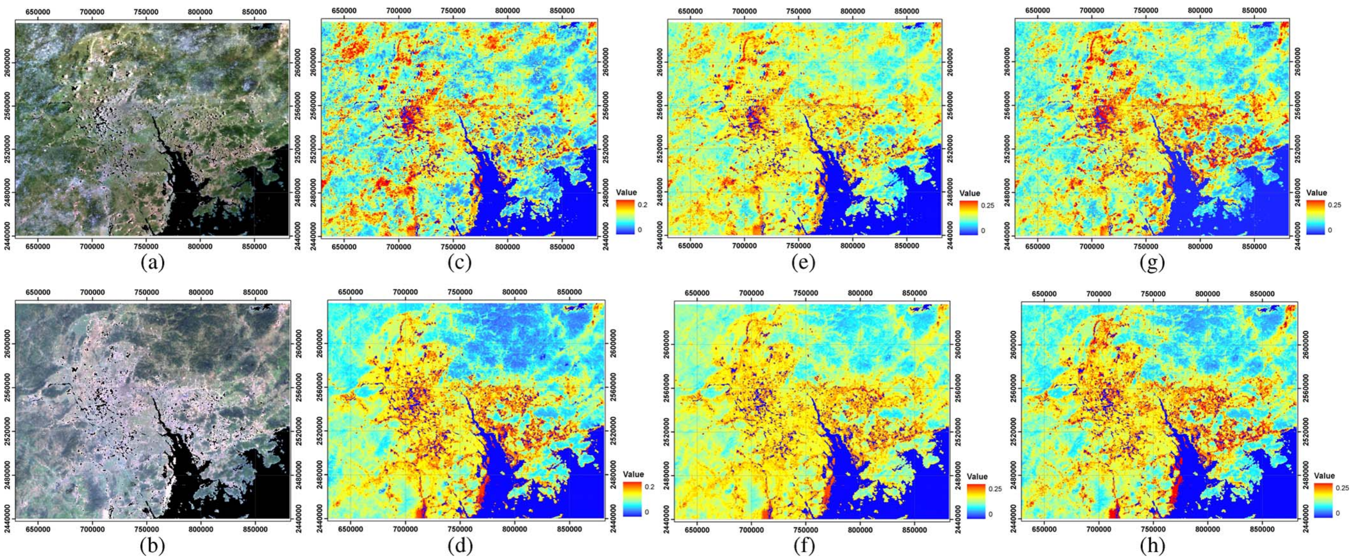

Fig. 5. Surface reflectance maps in autumn (in Universal Transverse Mercator grid coordinate system). (a) RGB composite of MOD09. (b) RGB composite of MRT. (c) MOD09 at 470 nm. (d) MRT at 470 nm. (e) MOD09 at 550 nm. (f) MRT at 550 nm. (g) MOD09 at 660 nm. (h) MRT at 660 nm.

Step 1—Deriving Image Aerosol Reflectances: Before deriving aerosol reflectances from images, the LUTs with a specific RH should be read. The hourly RH values were acquired from the Hong Kong Observatory station at Kowloon. They were co-matched with the MODIS overpass time (within ± 30 min), and the nearest RH values in the LUT were read. The next step is the interpolation of the LUT geometry to the measured (satellite) geometry. The bilinear interpolation method was adopted for interpolating between two nearest data in the LUTs at a given geometry. These two steps can reduce the number of LUT values being read in the computer memory.

Then, aerosol path reflectance in (1) is determined by separation of the Rayleigh reflectances (Section III-A) and surface reflectances (Section III-B) from the MODIS TOA reflectances.

Step 2—Deriving Modeled Aerosol Reflectances: The original LUT contained the AOT values and TOA reflectances at different geometries and relative humidities, while LUTs of aerosol reflectances as a function of AOT values at different geometries and relative humidities were also created by simply

$$\rho_{\mathrm{Aer}} = \rho_{\mathrm{TOA}} - \rho_{\mathrm{TOA\_when\_AOT=0}} \tag{7}$$

where ρ_{Aer} is the aerosol reflectance, ρ_{TOA} is the TOA reflectance, and $\rho_{\mathrm{TOA\_when\_AOT=0}}$ is the TOA reflectance when AOT $= 0$, which is also a Rayleigh reflectance.

Therefore, both image and modeled aerosol reflectances with specific RH and geometry were obtained for each pixel.

Step 3—Deriving AOT: Finally, the satellite-observed aerosol reflectances $(\rho^a_{\lambda_j})$ were compared to the modeled aerosol reflectances $(\rho^m_{\lambda_j})$ for each geometrically corrected LUT. For these comparisons, an optimal spectral shape-fitting technique was executed to select the aerosol model with the smallest systematic errors [1], [26]–[28]

$$x^2 = \frac{1}{n}\sum_{j=1}^{n}\left(\frac{\rho^m_{\lambda_j} - \rho^a_{\lambda_j}}{\rho^m_{\lambda_j}}\right)^2. \tag{8}$$

The error term of x^2 is described as the residual of the measured aerosol reflectances $\rho^m_{\lambda_j}$ from MODIS and modeled aerosol reflectances $\rho^a_{\lambda_j}$ from aerosol models for three different wavelengths (e.g., $j = 470,\ 550,$ and 660 nm). The minimum residual of x^2 is selected from the four aerosol types for each pixel. After allocating the appropriate aerosol model, the AOT values at 550 nm were derived for each pixel. Since the MODIS collection 4 and collection 5 AOT end products are only at 550 nm, only the AOT images at 550 nm wavelength were produced here, and these were compared with AERONET ground measurements.

E. Validation of Surface Reflectance

The minimum reflectance images, which were created for each season, were validated by comparison with the MOD09 surface reflectance images. The comparison between the seasonally averaged MOD09 and MRT images is shown in Fig. 5. The MRT images of the two longer wavelengths, i.e., 550 and 660 nm, are similar to the MOD09 images [Fig. 5(e)–(h)], but the 470 nm image is not [Fig. 5(d)]. The strongest correlations were observed in the autumn and winter seasons $(r > 0.9)$, while moderate correlations were noted in spring $(r > 0.8)$ (Fig. 6). The differences in surface reflectances (y-intercepts of the slopes) were less than or equal to 0.01 for the 550 and 660 nm wavelengths [Fig. 6(b), (c), (e), (f), (h), and (i)], while the differences were greater for the shorter 470 nm wavelength ($\sim$0.02–0.03) [Fig. 6(a), (d), and (g)]. For summer data, correlations were lower because of insufficient clear-sky images due to cloud cover.

F. Validation With AERONET Measurements

To evaluate the performance of our methodology, the MODIS 500-m retrieved AOT was compared with the AERONET measurements for 2007 [Fig. 7(a)]. For further comparison, the MOD04 collection 4 and 5 AOT data at 10-km resolution were

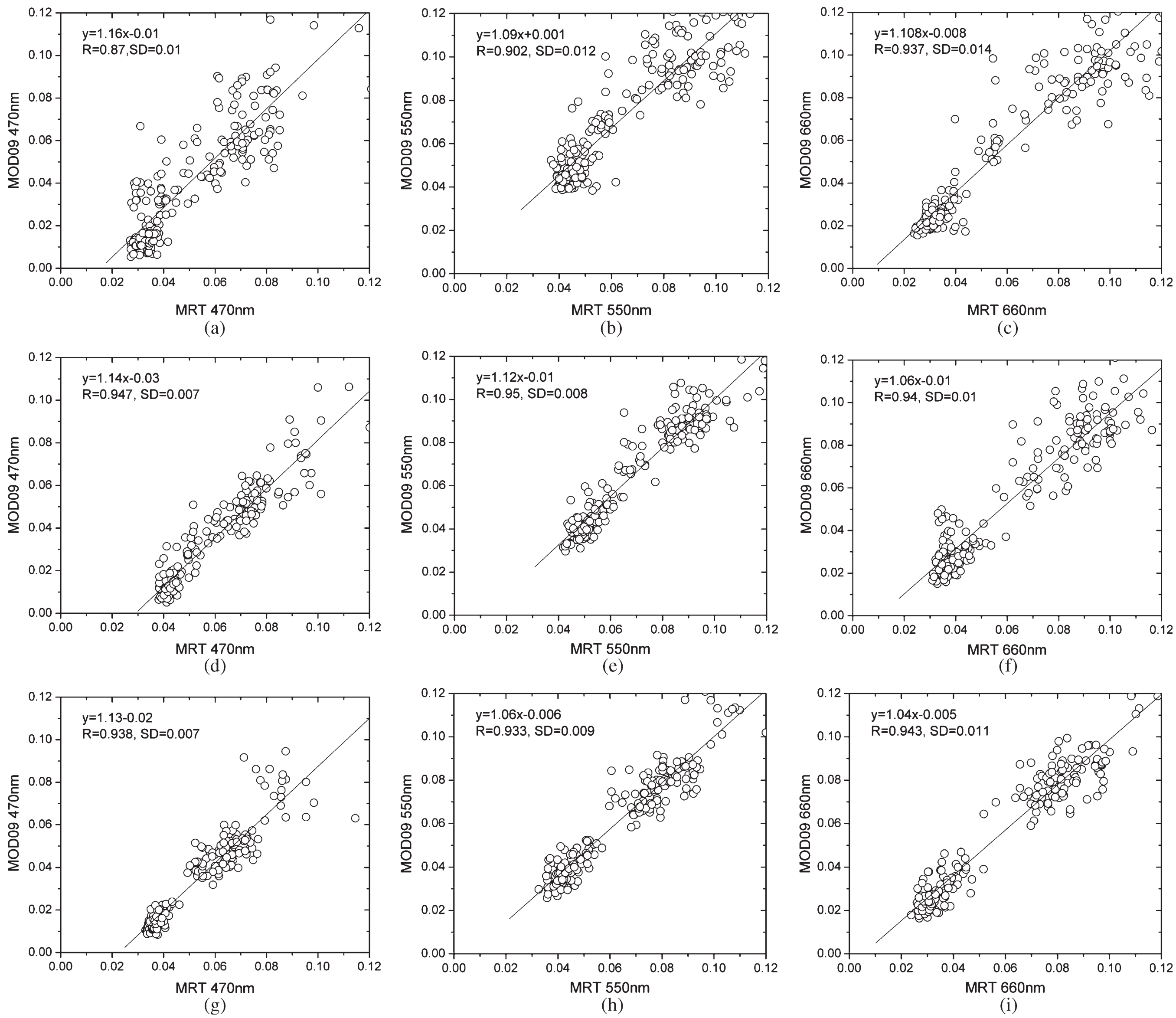

Fig. 6. Scatter plots between surface reflectances derived from MRT and from MOD09 products. (a) At 470 nm in spring, (b) at 550 nm in spring, (c) at 660 nm in spring, (d) at 470 nm in autumn, (e) at 550 nm in autumn, (f) at 660 nm in autumn, (g) at 470 nm in winter, (h) at 550 nm in winter, and (i) at 660 nm in winter. Sample points were randomly taken from vegetated, urban, grassland, and shrubland areas.

also compared with AERONET [Fig. 7(b)]. Good agreements are shown between the MODIS 500-m AOT derived from our methodology and the AERONET, with a linear-fitting correlation coefficient (r) of 0.937, which is higher than AOT from MOD04 collection 5 $(r = 0.913)$ and MOD04 collection 4 $(r = 0.877)$ in dry season. The mean absolute difference (MAD) errors between AERONET and MODIS 500-m AOT, MOD04 collection 5, and MOD04 collection 4 are 0.056, 0.120, and 0.174, respectively. The relative errors are 9.3%, 20%, and 29% for an annual mean AOT of 0.56 in 2007. In addition, the slope of the linear-fitting equation for the MODIS 500-m data [Fig. 7(a)] is closer to unity, which suggests a more direct linear relationship with AOT. Most importantly, this method can retrieve AOT images at a higher spatial resolution than previously and can operate over both bright and dark surfaces. This improvement is significant for the Hong Kong region which is a complex of bright urban and dark rural surfaces.

The AOT distribution over Hong Kong and the PRD region on January 30, 2007, retrieved using MODIS 500-m data is shown in Fig. 8(c). The AOT is relatively high with a range of $\sim$0.6 in rural areas to $\sim$2 in urban areas. Higher AOT values are expected due to anthropogenic pollution sources [see RGB image in Fig. 8(a)]. The northern part of Hong Kong, particularly near the Chinese city of Shenzhen, suffers from cross-boundary pollutants which are emitted from industries in the PRD region, and here, AOT values of 1.0 are observed. Fig. 8(c) shows severe air pollution around the city of Guangzhou due to emissions from the many industries and power plants located there. The pollutants are often trapped in the PRD region due to low wind speeds $(\sim 1 \text{ m} \cdot \text{s}^{-1})$ in the dry season corresponding to the image. The MODIS collection 5 AOT image is not only less accurate as shown in Fig. 7(b) but also visually and spatially inferior [Fig. 8(b)] due to its coarser resolution $(10 \times 10 \text{ km}^2)$. It is also ineffective for aerosol mapping in urban areas, since

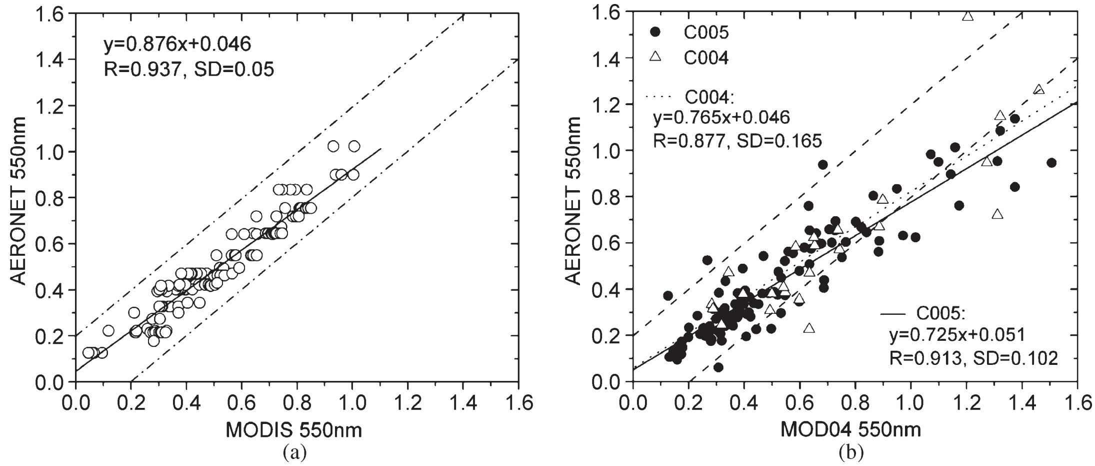

Fig. 7. Scatter plots. (a) Between MODIS 500-m AOT and AERONET measurements, all samples lie within 0.2 AOT threshold (dashed lines). (b) Between MOD04 collection 4 and 5 AOT and AERONET measurements. Note that there is insufficient MOD04 collection 4 data in the NASA Goddard Space Flight Center database since collection 4 data were replaced with collection 5; only 24 measurements were temporally matched with AERONET data.

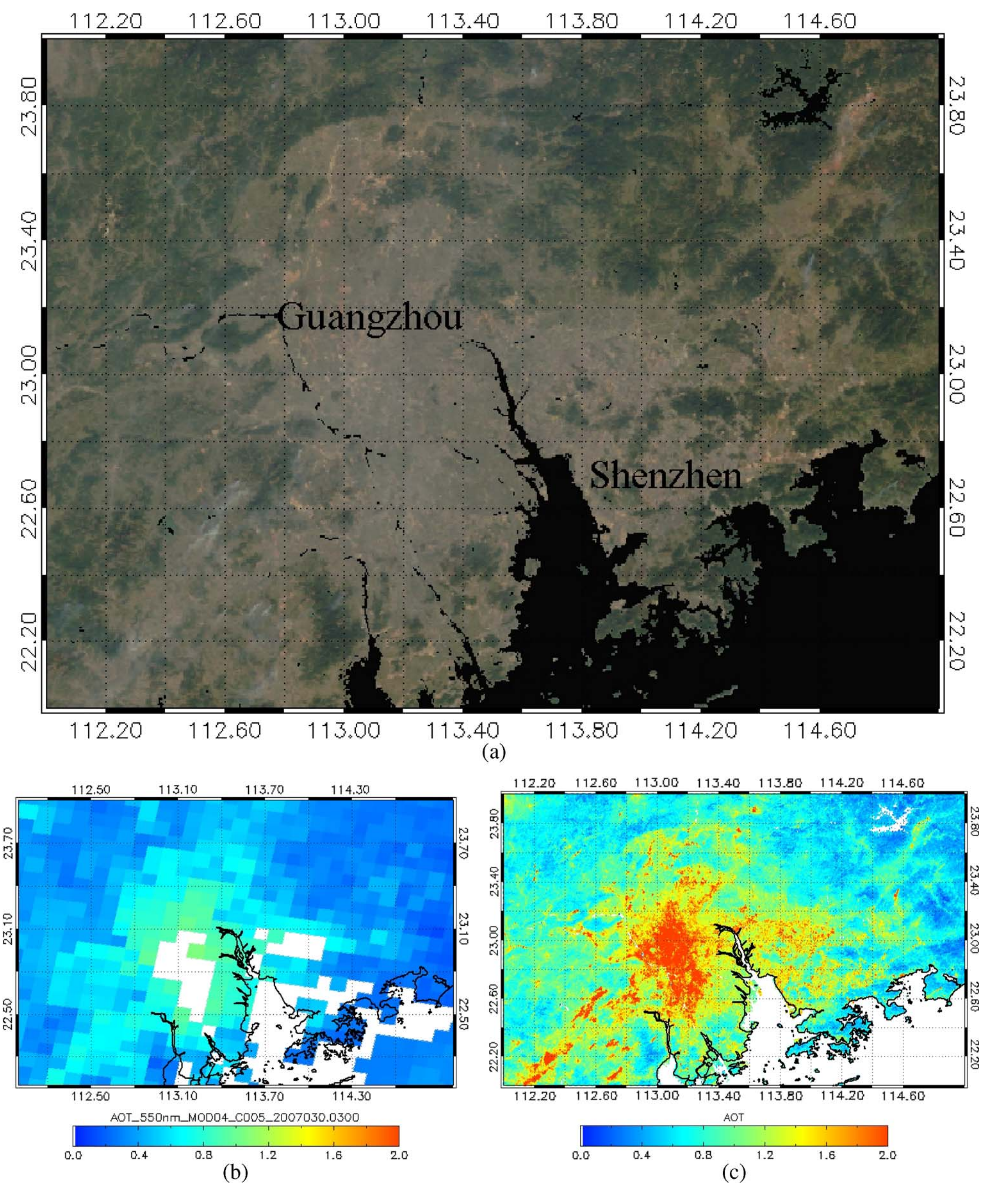

Fig. 8. (a) Color composite RGB image on January 30, 2007. (b) AOT at 550 nm derived from MOD04 collection 5 algorithm. (c) From this study with 500×500 m^2 resolution over Hong Kong and the PRD region.

these areas, with heavy pollutants, are masked out with no AOT data [Fig. 8(b)] due to their high reflectance values not meeting the criteria in the operational algorithm.

IV. Discussion

The aerosol retrieval algorithm from high-resolution 500-m MODIS satellite images shows good results, with strong correlations with AERONET ($r = 0.937$) in the eight-month dry season. This result was similar to that obtained from MODIS operation collection 5 product at 10-km resolution ($r = 0.913$). However, this study only validated the AOT images with AERONET measurements in the dry season, due to the following reasons. First, the wind direction in Hong Kong is northerly in the winter dry season, and anthropogenic pollutants are carried from nearby China during winter, whereas in summer, Hong Kong has onshore monsoon winds from the south. Thus, Hong Kong suffers more from local cross-boundary air pollutants in winter than in summer. Second, cloud cover is usually present in summer, and less than 15 clear-sky images could be acquired. Therefore, it would be expected that the accuracy of AOT over the whole year would be lower.

Although the 500-m AOT shows good agreement with ground measurements, possible error sources include the following.

1) The assumption of surface reflectance using MRT techniques: Although the surface reflectance images derived from the MRT technique were validated with the MOD09 surface reflectance images, the findings suggest errors of 0–0.03 from the uncertainty of surface reflectance. This error would be smaller at longer wavelengths. The AOT uncertainty estimated from the magnitude of error in surface reflectance ranges from 0 to 0.3, whereas the actual errors when the AOT images were validated against AERONET measurements were smaller (MAD of 0.056 and 0.120, respectively, for 500-m AOT and collection 5 images). Thus, the error contribution from surface reflectance is considered to be not significant.
2) The systematic bias from the aerosol model: Chu *et al.* [2] found the systematic bias from the aerosol model in the collection 4 algorithm which uses default global models to be between 0% and 20%. In this study, since six aerosol models specifically for Hong Kong were devised from the OPAC database, the error may be considerably reduced.
3) The assumptions of insignificant adjacency effect: The adjacency effect causes a dark pixel to be affected by atmospheric scattering from the path of adjacent bright pixels between the ground and sensor. This effect is critical at the boundaries between bright and dark surfaces. The effect may be reduced by degrading and averaging the original pixel to coarser resolution, but a level of detail will be lost. For our study, 500-m resolution AOT images are produced which would be expected to have greater adjacency effects than the MOD04 product at 10 km. In fact, there is no research which systematically describes and recommends a best resolution for aerosol retrieval to avoid the adjacency effect, but Justice *et al.* [29] expected that the adjacency effect would be less significant for MODIS 250- and 500-m pixels than for Landsat Thematic Mapper pixels.
4) The assumption of insignificant BRDF effect: The BRDF effect is caused by different viewing angles in heterogeneous areas. MODIS viewing angles are not constant and can vary from 0° to 65°. The error caused from different viewing angles can be reduced by BRDF correction algorithms [30] but is beyond the scope of this study. For reducing the BRDF in determination of surface reflectance, only nadir images with satellite viewing angle $< 35^\circ$ were used in this study. Future work may be necessary to isolate the BRDF effect during aerosol retrieval.
5) An accuracy of 78.13% is achieved for cloud masking in this study, which is comparable to the accuracy from the MODIS operational AOT algorithm which is 82%. Even though collection 4 and 5 algorithms make use of the MODIS 1-km thermal band for detecting and masking the clouds, sometimes, their AOT end products show large patches of very high AOT values over the sea, which is caused by an error in the cloud masking.
6) Although the signal-to-noise ratio of 10-km resolution is 20 times higher than that of 500-m resolution data [1], Henderson and Chylek [23] found that there are only small changes in aerosol retrieval with increasing pixel sizes from $40 \cdot 80$ to $2040 \cdot 4080\ \mathrm{m}^2$, and the AOT variations are even negligible. Therefore, any loss of accuracy due to a decreased signal-to-noise ratio of the 500-m AOT may be small or is small enough to be compensated by increased accuracy due to the higher resolution when validated against AERONET data.

V. Conclusion

An aerosol retrieval algorithm for MODIS 500-m data has been proposed in this study. This method is based on a modified MRT to derive surface reflectance images coupled with comprehensive LUTs which consider many different aerosol models, sun–satellite geometries, and RH conditions in radiative transfer modeling. The MODIS 500-m AOT is able to estimate aerosols over both urban and vegetated areas at a high level of detail. A good correlation was found between land surface reflectance from MOD09 products and the MRT images, and this suggests that the MRT method can accurately represent surface reflectance. The derived MODIS 500-m AOT shows a high level of accuracy ($r = 0.937$) compared with ground-based AERONET measurements in the dry season, and the results are better than those from MODIS collection 4 ($r = 0.877$) and collection 5 ($r = 0.913$) data. The main reasons for the higher accuracy from our algorithm than from the MODIS operational algorithm are thought to be consideration of the viewing angle in surface reflectance retrieval, the higher spatial resolution giving better correlation with AERONET ground measurements, the use of a set of comprehensive LUTs, and consideration of RH. Given the higher accuracy and higher spatial resolution of the derived MODIS 500-m AOT images, they can be used to study transient cross-boundary aerosols and localized intraurban aerosol distributions.

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