Chapter 17
MODIS 500 × 500-m^2 Resolution Aerosol Optical Thickness Retrieval and Its Application for Air Quality Monitoring

Kwon H. Lee[1], Dong H. Lee[1], Young J. Kim[1*], and Jhoon Kim[2]

Abstract Atmospheric aerosol optical thickness (AOT) was retrieved over urban areas using moderate resolution imaging spectroradiometer (MODIS) 500-m resolution calibrated radiance data. A modified Bremen Aerosol Retrieval (BAER) algorithm was used to retrieve AOT over Seoul, Korea. Since the surface reflectance of an urban area is typically brighter than that of vegetation or soil areas in the visible wavelength region, the error associated with aerosol retrieval is higher. Surface reflectance determination using the linear mixing model (LMM) produced values that were smaller (~0.02) than those obtained using the minimum reflectance technique (MRT). This difference would lead to an overestimated AOT when using the LMM approach. Retrieved AOT data using MRT and standard MODIS 10-km aerosol products (MOD04) were compared to Rotating Shadow-band Radiometer (RSR) observations at Yonsei University, Seoul, Korea. Regression analysis showed that the root mean square error (RMSE) of MODIS AOT and MOD04 AOT was 0.05 in both cases. In addition, MODIS AOT data were compared with ground-based particulate matter data (PM10) from air quality monitoring networks of the National Institute of Environmental Research (NIER). MODIS AOT data showed a relatively low correlation (r = 0.41) with surface PM10 mass concentration data due to differences in ground-based and column-averaged data, variability of terrain, and MODIS cloud mask. This result is similar to that of other investigations. The application of fine-resolution satellite data supports the feasibility of local and urban-scale air quality monitoring.

Keywords: AOT, LMM, MODIS, MRT, PM10

[1] *Advanced Environmental Monitoring Research Center (ADEMRC), Gwangju Institute of Science & Technology (GIST), 1 Oryong-dong, Buk-gu, Gwangju 500-712, Republic of Korea*

[2] *Department of Atmospheric Sciences, Yonsei University, Shinchon-dong 134, Seodaemun-gu, Seoul 120-749, Republic of Korea*

**Corresponding author: Tel: + 82-62-970-3401, Fax: + 82-62-970-3404*

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17.1 Introduction

Satellite remote sensing has provided quantitative information on aerosols with an accuracy comparable to that of surface measurements. The large-scale distribution of aerosol concentration and characteristics, aerosol radiative forcing, and property changes of clouds interacting with aerosols are among the important observations that can be provided by satellite remote sensing. Due to the growing recognition of the importance of aerosol properties for studies of climate and global change, it is indeed fortunate that a number of very significant and greatly enhanced satellite systems are being developed for launch in the next few years. These systems will also provide information on the global distribution, including seasonal and interannual variation, of aerosol sources (forest fires, desert dust and aerosol from the oxidation of SO_2 emissions from industrial regions), aerosol loading and optical properties, as well as direct and indirect radiative forcing.

Satellite measurements can also be inverted to yield information on aerosol optical thickness (AOT), angular scattering properties, and size distribution. Satellite measurements clearly have the advantage of being the only set of measurements that provide a wide coverage. The disadvantage of the presently used passive sensors is that they can only be applied under clear-sky conditions, and their application over land is difficult. Furthermore, a number of additional assumptions have to be made regarding atmospheric conditions. In spite of these disadvantages, many researchers have studied global and local-scale aerosol remote sensing using satellites. Techniques associated with satellite observation in the field of atmospheric science are advancing rapidly (Kaufman et al. 1997a; Gordon et al. 1997; King et al. 1999). Total ozone mapping spectrometer (TOMS) measurements are designed to monitor ozone and provide valuable information on aerosol geographical distributions (Herman et al. 1997). Such measurements were used to detect an increase in biomass burning smoke in African savanna regions during the 1990s (Hsu et al. 1999). The Sea-viewing Wide Field-of-view Sensor (SeaWiFS), developed to provide ocean color data products for the study of marine biogeochemical processes, produces an aerosol data product from its atmospheric correction algorithm (Gordon and Wang 1994) through a separate algorithm (von Hoyningen-Huene et al. 2003), and has been used to investigate transport of Asian dust plumes (Lee et al. 2004). The launch of polarization and directionality of the earth's reflectance (POLDER) on ADEOS II adds greater capabilities (Leroy et al. 1997). Extracting the full potential from the satellite data requires correlative suborbital data to not only validate the satellite measurements (Clark et al. 1997; Fraser et al. 1997; Vermote et al. 1997), but to supply information not obtainable from space. The EOS/Terra and EOS/AQUA satellites and their new instruments, such as the moderate resolution imaging spectroradiometer (MODIS) and multi-angle imaging spectroradiometer (MISR), provide improved measurement capabilities and unprecedented volumes of data regarding the atmosphere, land, ocean, and radiative processes (Tanré et al. 1997; Wanner et al. 1997).

AOT is a key property used in the characterization of atmospheric aerosols from satellite data. The radiant energy obtained from an earth-observing satellite sensor is converted into reflectance or apparent reflectance using information about the atmospheric condition along the path between the ground and the satellite, as well as the viewing geometry and solar geometry. Aerosols also block the view for systems observing changes in land use. Basic aerosol retrieval techniques are therefore employed to remove the aerosol signal, and can also be used to highlight or enhance the aerosol-only signal. King et al. (1999) summarized the major retrieval methods well.

Aerosol retrieval from remote sensing data has many important applications, including a role in climate studies and the atmospheric correction of satellite imagery. Remote sensing of atmospheric aerosol using MODIS satellite data has been shown to be very useful in global/regional-scale aerosol monitoring. Recently, satellite-retrieved AOT has also been used to estimate local/regional air quality (Engel-Cox et al. 2004a,b; Hutchison 2003; Hutchison et al. 2004). Due to the large spatial resolution of $10 \times 10\text{-km}^2$ for the MODIS standard aerosol product (MOD04), AOT data have limitations for local/urban-scale air quality monitoring applications. Its large spatial resolution is incapable of reflecting various types of urban-scale (Seoul ~ 600 km^2) pollution with a complicated topography. Therefore, a modified Bremen Aerosol Retrieval (BAER) algorithm (von Hoyningen-Huene et al. 2003) as detailed by Lee et al. (2005) was used in this study to retrieve AOT for fine resolutions of $500 \times 500\,\text{m}^2$ over Seoul, Korea. Figure 17.1 shows the study area.

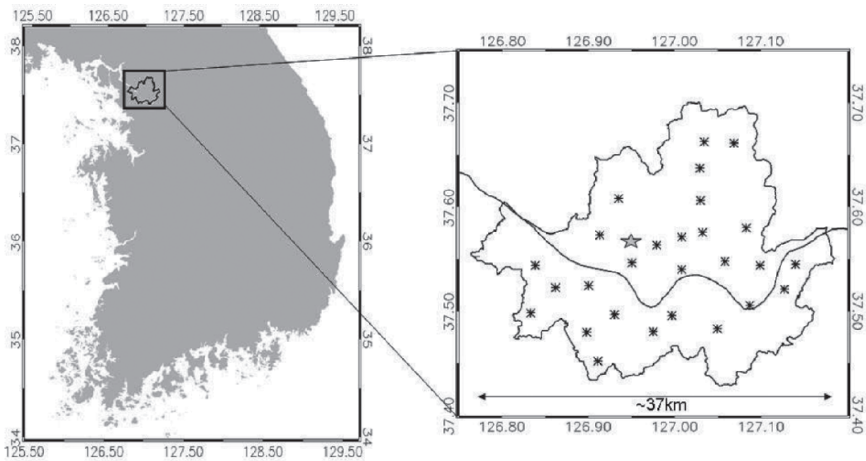


Fig. 17.1 Map of the Korean peninsular and the Seoul metropolitan area. Symbols on the right represent the 27 air quality monitoring stations (asterisks) and the radiometer measurement site (large star)

17.2 Methodology

MODIS is a multispectral (36 bands), multi-resolution (1 km, 500 m, 250 m) sensor dedicated to the observation of the Earth. It is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon. Two bands are imaged at a nominal resolution of 250 m at nadir, with five bands at 500 m and the remaining 29 bands at 1 km. A ±55-degree scanning pattern at the EOS orbit of 705 km achieves a 2,330-km swath and provides global coverage every 1–2 days. Global/regional-scale aerosol distribution information has been provided by MODIS measurements since the launch of the satellites. However, the operational MODIS AOT from the NASA algorithm is not appropriate for local/urban-scale aerosol monitoring as it has a spatial resolution of 10 × 10-km^2. Therefore, we used TERRA/MODIS 500-m resolution data (0.47, 0.55, 0.66 μm) for aerosol retrieval over an urban area for 2004 in this study. Figure 17.2 briefly describes the aerosol retrieval processes using MODIS 500-m resolution data.

The aerosol retrieval algorithm for MODIS 500-m resolution data is a modified version of BAER, which retrieves aerosol properties in greater detail and can be applied to other sensors with relative ease. In order to retrieve AOT, a radiative transfer equation was introduced to determine aerosol reflectance by decomposing the top-of-atmosphere (TOA) reflectance into surface reflectance and Rayleigh path radiance (Kaufman et al. 1997a). The TOA reflectance ρ_{TOA} (θ_0, θ_S, ϕ) is expressed as

$$\rho_{TOA}(\theta_0,\theta_S,\phi) = \rho_{ATM}(\theta_0,\theta_S,\phi,\tau_{Aer},\tau_{Ray},p(\theta),\varpi_0) + \frac{T_{Tot}(\theta_0)\cdot T_{Tot}(\theta_S)\cdot \rho_{Surf}(\theta_0,\theta_S)}{1-\rho_{Surf}(\theta_0,\theta_S)\cdot r_{Hem}(\tau_{Tot},g)} \quad (1)$$

where θ_0 is the solar zenith angle, θ_S the satellite zenith angle, and ϕ the azimuth angle. τ_{Aer}, τ_{Ray} and τ_{Tot} represent aerosol, Rayleigh, and total optical thickness, respectively. $p(\theta)$ is the phase function, ϖ_0 a single-scattering albedo, g the asymmetry parameter, ρ_{ATM} the atmospheric path reflectance, $T_{Tot}(m_0)$ the total transmittance, $\rho_{Surf}(m_0, m_S)$ the surface reflectance, and r_{Hem} (τ_{Tot}, g) the hemispheric reflectance. The atmospheric contribution consists of the Rayleigh and aerosol fractions. The Rayleigh path reflectance can be determined through the use of a relevant wavelength method (Bucholtz 1995). The Rayleigh optical thickness ($\tau_{Ray}(\lambda)$) can then be determined from the surface pressure $p(z)$ in each pixel through the following equation:

$$\tau_{Ray}(\lambda) = A\cdot\lambda^{-\left(B+C\cdot\lambda+\frac{D}{\lambda}\right)}\cdot\frac{p(z)}{p_0} \quad (2)$$

where A, B, C and D are the constants for the total Rayleigh scattering cross-section and total Rayleigh volume scattering coefficient for a standard atmosphere. p_0 is the mean sea level surface pressure.

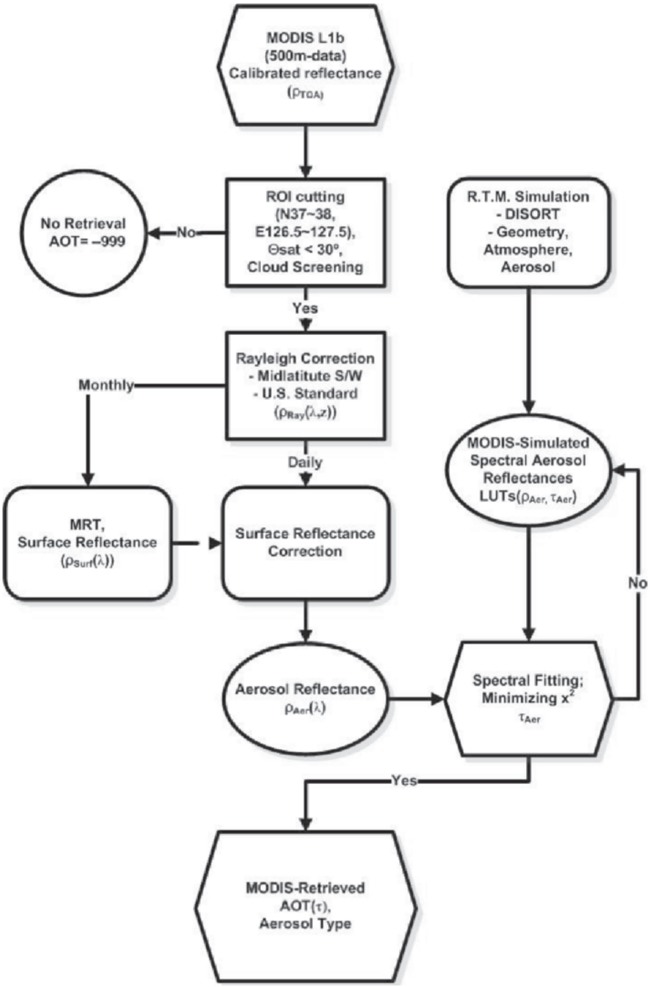


Fig. 17.2 Schematic diagram for aerosol retrieval in this study

There exists an inherent problem in determining surface reflectance for aerosol retrieval, since photons reflected by the surface reach the satellite after they transmit through the atmosphere. However, aerosol retrieval over a bright surface such as an urban area is problematic because of the large uncertainties concerning the contribution of surface reflectance to satellite data. Although Kaufman et al. (1997c) used the 2.1-um channel reflectance for estimation of surface reflectance at visible wavelengths, it is mainly suitable over vegetation or dark soils. The original BAER algorithm used a linear mixing model (LMM) between vegetation and soil spectra for surface reflectance determination in a pixel. Surface reflectance (ρ_{Surf}) can be calculated by portion of vegetation and bare soil spectra in the following manner:

$$\rho_{Surf}(\lambda) = C_{Veg} \cdot \rho_{Veg}(\lambda) + (1 - C_{Veg}) \cdot \rho_{Soil}(\lambda) \tag{3}$$

where λ is wavelength, and $\rho_{Veg}(\lambda)$ and $\rho_{Soil}(\lambda)$ the spectral reflectances of 'green vegetation' and 'bare soil', respectively. C_{Veg} is the vegetation index representative of the vegetation fraction in each pixel. LMM also possesses a problem since it uses only two surface composition parameters. Recently, new techniques like 'Deep Blue' as introduced in Hsu et al. (2004) can retrieve AOT over bright surfaces using the minimum reflectivity technique (MRT). In this study, we used MRT to determine the surface reflectance by finding the clearest scene during each month over an urban area. The MOD35 cloud screening method (Ackerman et al. 1998) was used to determine cloud contamination. Near nadir data (viewing angle < 35°) were only used to minimize angular effects due to bidirectional reflectivity by inhomogeneous surfaces. Since cloud shadows can also lead to lower reflectance in a pixel, the second minimum reflectance was taken.

Physical and optical characteristics of aerosol particles in the atmosphere also greatly affected satellite aerosol retrieval. Since the original BAER method uses one Look-up Table (LUT) for aerosol retrieval to one whole satellite scene, this method should be improved. In this study, a few aerosol models for LUT construction were used to determine the best aerosol model selection method for a pixel. LUTs were constructed from the discrete ordinate radiative transfer (DISORT) code (Stamnes et al. 1988). MODIS-received aerosol reflectances were simulated with the four aerosol models (1, 2, 3 and 4) presented in Table 1 from Lee et al. 2007, comprising four standard aerosol models (rural [RR], urban [UB]) from Shettle and Fenn (1979) and two AERONET-derived aerosol models (Asian dust [AD] and biomass burning [BB] aerosol models). The non-sphericity of dust particles should be considered in scattering calculations, which could cause changes in the phase function signature. Therefore, non-spherical dust phase function data were used to minimize the effects of non-sphericity of aerosol in our retrieval method. For LUT construction, TOA reflectances were computed for various input conditions that included solar and sensor geometries, Rayleigh scattering, the six aerosol models, a dark surface, and an AOT ranging from 0 to 3. An optimum spectral shape-fitting procedure was used for best aerosol model selection by comparing the MODIS-measured spectral aerosol reflectances with corresponding calculated values (Kaufman and Tanré 1998; Costa et al. 1999; Torricella et al. 1999). Minimizing the error term (x^2) that describes the agreement between measurement and simulation involved the use of the following equation:

$$x^2 = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\rho_{Aer}^{m}(\lambda_i) - \rho_{Aer}^{c}(\lambda_i)}{\rho_{Aer}^{m}(\lambda_i)}\right)^2 \tag{4}$$

where n is the number of selected wavelengths (λ_i), and ρ^m_{Aer} and ρ^c_{Aer} are the measured and calculated aerosol reflectances, respectively. Fitting was done at the selected wavelengths of 0.47, 0.55, 0.66 μm.

Retrieval errors under various aerosol loadings were estimated by comparing MODIS AOT data with broadband rotating shadowband radiometer (RSR) observations at Yonsei University (N 37.565°, E 126.935 °), Seoul, Korea. Furthermore, the application of MODIS AOT data for an assessment of urban air quality is also discussed through comparisons with PM10 mass concentrations recorded at a ground air quality monitoring network in Korea.

Daily aerosol product (Tanré et al. 1997; Kaufman et al. 1997a,b) of MODIS level 2 aerosol datasets (MOD04 L2; MODIS aerosol product, Version 4.1.3) were also collected from the National Aeronautics and Space Administration (NASA) Distributed Active Archive Center (DAAC) for comparisons with MODIS 500-m resolution AOT data obtained in this study. The MOD04 data include various aerosol physical and optical parameters with a $10 \times 10\text{-km}^2$ spatial resolution. MODIS AOT has been validated with ground-based sunphotometer AOT using a spatiotemporal approach (Ichoku et al. 2002). MODIS aerosol retrievals over land surfaces, except in coastal zones, possess retrieval errors of $\Delta\tau_a = \pm 0.05 \pm 0.2\ \tau_a$ (Chu et al. 2002).

17.3 Result

17.3.1 Surface Reflectance Assessment

In order to retrieve AOT using MODIS 500-m resolution data, surface reflectance should first be determined and then the temporal and local variability of surface properties within the study area should be estimated. Our surface reflectance determination by MRT was compared with that of LMM in Figure 17.3. The MODIS RGB (red = 0.66 µm, green = 0.55 µm, and blue = 0.47 µm) color composite image shows green vegetation areas and vegetation index values that are relatively higher (>0.6) than the urban area (<0.4), which mainly consists of artificial construction materials. In LMM analysis, a low vegetation index leads to a high soil reflectance portion for mixed reflectance in a pixel. However, this value is less than the real reflectance of an urban area. The difference in surface reflectance between LMM and MRT was about 0.02. This underestimated surface reflectance estimation could lead to a larger AOT (~0.2).

17.3.2 Validation

MODIS-retrieved AOT results were compared with ground-based measured AOT in Figure 17.4. The RSR measurement site is located within Yonsei University (see Figure 17.1). Since MODIS scans the study area at around 02~03 UTC, RSR data closest in time (±30 min) and MODIS data from the nearest pixel to the measurement site were used for the comparison. Although the comparison was done for a limited number of cases, there was good agreement between RSR-measured

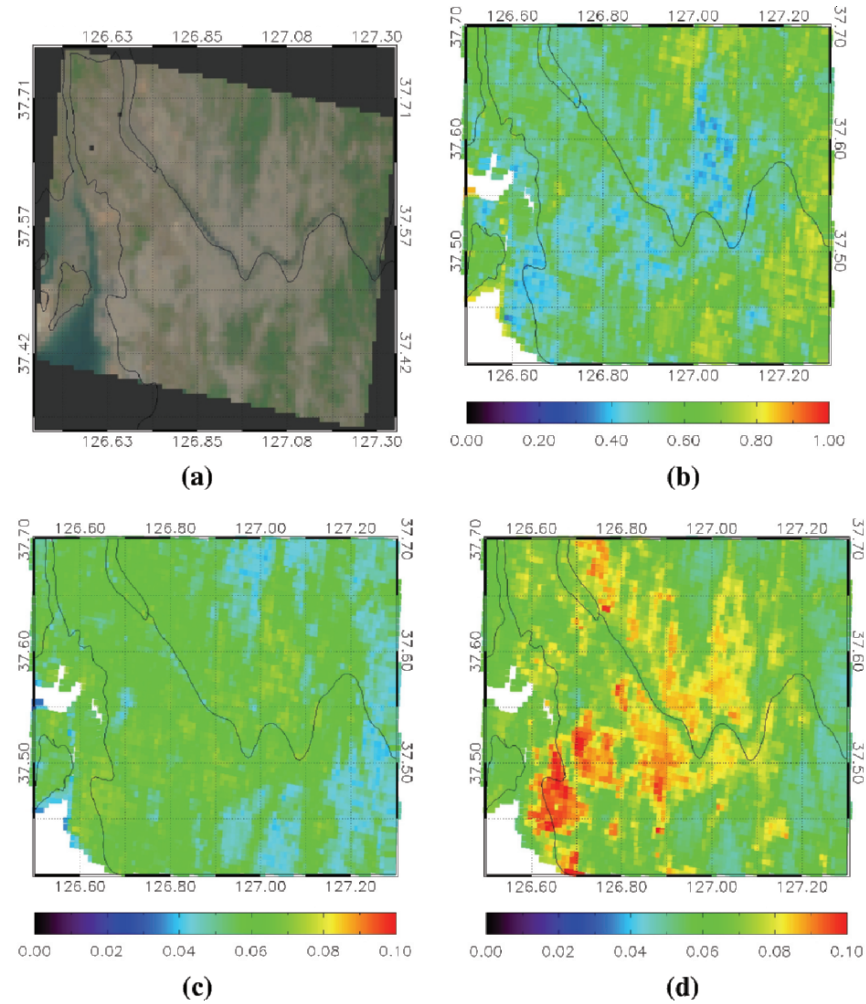
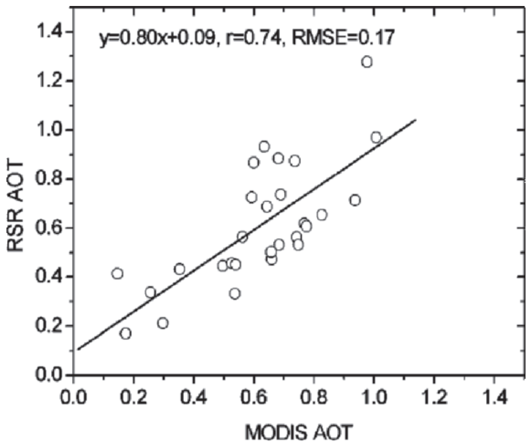


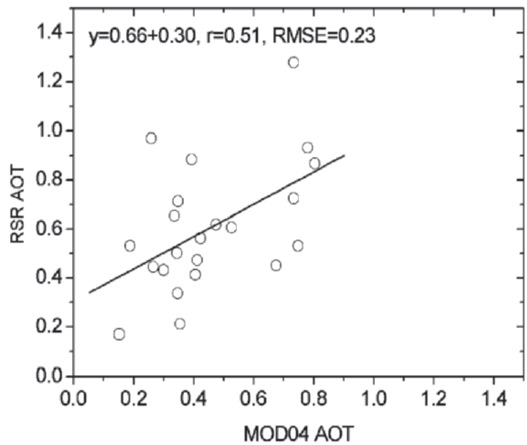
Fig. 17.3 MODIS RGB composite image (**a**) aerosol-free vegetation index (**b**) (AFRI, Karnieli et al. 2001), and surface reflectance ($\lambda = 0.46$) determined by (**c**) LMM and (**d**) MRT

and MODIS-retrieved AOT, with a linear-fitting correlation coefficient (*r*) of 0.80 and 0.74, respectively. Moreover, when compared with MOD04 AOT data, MODIS 500-m resolution AOT data showed a much better correlation with RSR AOT data over Seoul, suggesting a lower level of accuracy for 10-km resolution data because of its coarse spatial resolution.

Figure 17.5 shows the AOT map for different aerosol loading cases on a hazy and clear day, with MODIS RGB images and MODIS AOT showing the different aerosol loading states. On April 24, 2004, the sky was relatively clear and there was



(a)



(b)

Fig. 17.4 Comparison between (**a**) MODIS AOT and (**b**) RSR AOT

a northerly wind blowing from North Korea towards the Seoul metropolitan area. AOT was very low (~0.3) in Seoul. On December 8, 2004, a Chinese haze plume was transported to the Korean peninsular by a westerly wind and an increased AOT value (~2.0) was the result of aerosol mass increases in the local atmosphere. Note that the white areas indicate no-retrieval pixel due to clouds and a high satellite viewing angle.

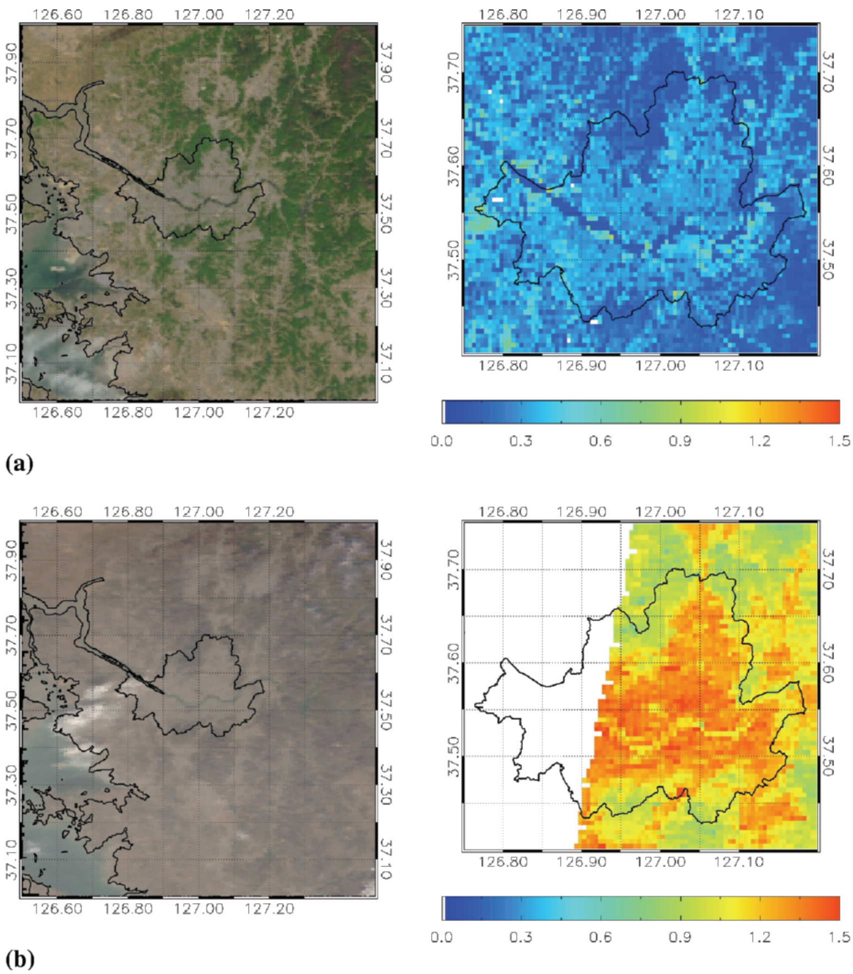


Fig. 17.5 MODIS RGB images and AOT over Seoul, Korea on (**a**) April 24, 2004 (clear day), and (**b**) December 8, 2004 (hazy day)

17.3.3 Application to Air Quality

In this section, MODIS-retrieved AOT data were compared to data pertaining to PM monitoring in Seoul, Korea. Figure 17.6 shows the comparison between PM10 and MODIS AOT for the 27 locations in Seoul, Korea. The linear correlation coefficient (r) is 0.41, suggesting that the PM10 mass concentration is indicative of near surface values that are not as well reflected by the MODIS column AOT data. The correlation between satellite AOT and PM increases with the use of PM2.5 mass concentration data. There was a better correlation between MODIS AOT and surface PM10 concentration when compared to other published values

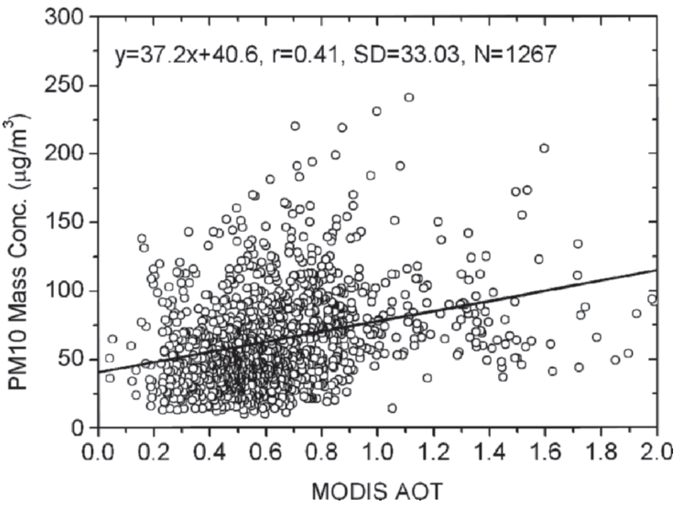


Fig. 17.6 Comparison between MODIS AOT and PM10 mass concentrations measured from 27 air quality monitoring stations in Seoul, Korea

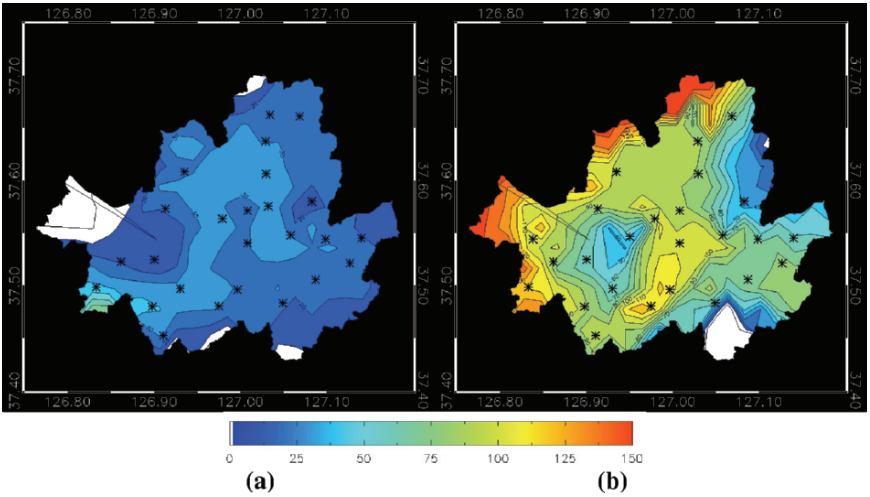


Fig. 17.7 Contoured PM10 mass concentration map on (**a**) April 24, 2004 and (**b**) December 8, 2004 in Seoul, Korea

(Engel-Cox et al. 2004b), which supports the feasibility of using high-resolution MODIS AOT for local and urban-scale air quality monitoring.

For an easier comparison between satellite-retrieved AOT and ground-based PM10 mass concentrations, the contour map of MODIS AOT and PM10 in Seoul for the days detailed in Figure 17.5 are shown in Figure 17.7(a) and 17.7(b). These PM10 distributions clearly depict a high PM10 loading case with large AOT values on December 8, 2004 and a low PM10 loading case with low AOT on other day.

17.4 Conclusion

This study has demonstrated the retrieval of MODIS 500-m resolution AOT products and their potential application to urban air quality monitoring. MRT was used successfully for fine-resolution aerosol retrieval over bright land surfaces. Furthermore, 500-m resolution AOT was estimated with a better accuracy of MODIS standard aerosol products when compared with ground-based radiometer observation data. Fine-resolution aerosol retrieval data can be used to study spatial aerosol loading distribution and the impact of transient pollution on local/urban air quality. The initial application of MODIS AOT for a study of air quality with ground-measured PM10 mass concentration data is encouraging and indicates that fine spatial resolution satellite scenes can provide air quality information. Despite the moderate correlation between MODIS AOT and PM10 mass concentrations, this case study demonstrates the usefulness of satellite-retrieved AOT data for air quality monitoring.

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