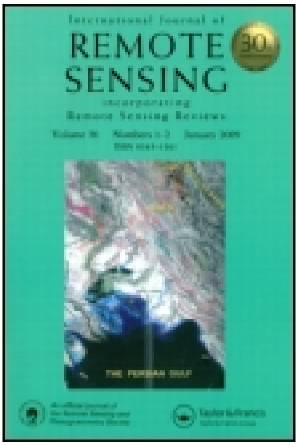

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Monitoring 2.5 μm particulate matter within urbanized regions using satellite-derived aerosol optical thickness, a study in Hong Kong

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This study investigates the relationship between aerosol optical thickness (AOT) derived from MODerate resolution Imaging Spectroradiometer (MODIS) satellite and *in situ* particulate matter ($PM_{2.5}$) from Hong Kong air-quality monitoring stations. The relationship was analysed for three different AOT products, namely, MODIS collection 5 AOT data, MODIS collection 5 fine-mode fraction AOT data, both at 10 km resolution, and MODIS AOT data at 500 m resolution. In view of the predicted low accuracies obtainable for MODIS AOT products for the south China region, these AOT products were first validated against AOT measurements from an AErosol RObotic NETwork (AERONET) station near the centre of Hong Kong. Strong relationships of $R^2 = 0.78$ and $R^2 = 0.77$ for the 10 km and 500 m AOT data, respectively, were obtained, thus providing a robust AOT image database at both coarse and fine spatial resolution for comparison with $PM_{2.5}$ concentrations. When a whole year (2007) of AOT images was compared with $PM_{2.5}$ concentrations recorded at five ground stations, correlations of $R^2 = 0.31$, $R^2 = 0.10$ and $R^2 = 0.67$ were obtained for collection 5, fine-mode fraction of collection 5 (both at 10 km resolution) and 500 m AOT, respectively. Strong correlations between MODIS 500 m AOT and $PM_{2.5}$ concentration were also observed for individual stations ($R^2 = 0.66$, 0.74, 0.76, 0.56 and 0.62, for Central, Tung Chung, Tseun Wan, Yuen Long and Tap Mun stations, respectively). The study suggests that fine particle distributions at a high level of detail over whole cities may be obtained from satellite images. Since the model has potential for further refinement, monitoring of detailed $PM_{2.5}$ concentrations on a routine basis from satellite images will provide a highly useful tool for urban environmental authorities.

1. Introduction

Fine particles in the atmosphere have recently been recognized as the most serious pollutant for damage to the circulatory and respiratory systems (Dominici *et al*. 2006, Chan *et al*. 2007). However, most air-quality stations measure only common gaseous pollutants, as well as total particulate matter in the form of respiratory suspended

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particulates (RSP) or those smaller than 10 μm (PM_{10}). The finer $PM_{2.5}$ (particulate matter with a diameter less than or equal to 2.5 μm) is usually measured at only a few ground stations, for example, five out of 14 air-quality stations in Hong Kong. Furthermore, such ground-based measurements do not provide spatially continuous data over a region, nor do they offer predictive capabilities. In Hong Kong, spatial air-quality modelling by the Environmental Protection Department (EPD) suffers from distant location and uncertainty of emission sources outside Hong Kong, making the model output at resolutions higher than 1.5 km meaningless. Even at this coarse resolution, very little variation in air quality over the 1060 km^2 of Hong Kong's territory is evident, although data from the 14 ground stations (EPD 2008) suggest substantial spatial variation.

These deficiencies have resulted in great interest being paid to the relationship between point-source air-quality data and satellite-derived remote sensing data. Previous studies which analyse the relationships between satellite-derived aerosol optical thickness (AOT) and $PM_{2.5}$ have been conducted in many countries including the USA (Wang and Christopher 2003, Engel-Cox *et al*. 2004, Hutchison *et al*. 2005, Liu *et al*. 2005), Canada (Tian and Chen 2006), India (Kumar *et al*. 2007) and Australia (Gupta *et al*. 2007). Generally only low to moderately significant correlations were obtained between satellite-derived AOT and $PM_{2.5}$ concentrations for data pairs covering all locations and time periods (e.g. $R^2 = 0.36$ for New York, 0.02 for Switzerland and 0.12 for Sydney). However, significant improvements were observed when controls for different $PM_{2.5}$ concentrations (Wang and Christopher 2003, Hutchison *et al*. 2005, Liu *et al*. 2005), humidity (Kumar *et al*. 2007) and atmospheric pressure (Kumar *et al*. 2007, 2008) were applied. For example, Hutchison *et al*. (2005) achieved correlations of 0.4–0.5 between the MODerate resolution Imaging Spectroradiometer (MODIS) 10 km AOT and all concentrations of $PM_{2.5}$ for all 51 ground stations across Texas. However, when the data pairs for different concentrations of $PM_{2.5}$ were averaged, correlations above 0.9 were obtained. Liu *et al*. (2005) also noted higher correlations for lower aerosol levels than for the whole range. Engel-Cox *et al*. (2004) observed great variability in the correlations across the whole USA, with some low correlations explained by inaccuracies in the AOT images especially over bright surfaces. Working in Delhi, Kumar *et al*. (2007) observed a moderate correlation ($R^2 = 0.45$), even when the effects of variable humidity were excluded by restricting the analysis to only three non-humid months. However, this was improved to $R^2 = 0.76$ when the spatial resolution of the MODIS-derived AOT was increased from 10 to 5 km. Except for this study, all other comparisons between image AOT and $PM_{2.5}$ have been at coarse 10 km resolution or more from MODIS or the Multiangle Imaging SpectroRadiometer (MISR) AOT products. Thus only regional-scale observations and comparisons have been possible and there has been no attempt to establish a relationship between $PM_{2.5}$ and satellite AOT derived at finer resolution, which would allow estimates of $PM_{2.5}$ distributions at district level within a city.

A significant improvement in AOT retrieval algorithms using MODIS has been introduced for aerosol retrieval over vegetation. Levy *et al*. (2007) modified Kaufman and Tanré's (1998) algorithm using (i) band correlation based on the normalized difference vegetation index at shortwave infrared band ($NDVI_{SWIR}$) and (ii) scattering angle since Gatebe *et al*. (2001) and Remer *et al*. (2001) suggested the ratio of visible band/shortwave infrared band (VIS/SWIR) was angle dependent. Thus the new (AOT collection 5) data have been shown to have significant improvements in both accuracy and their applicability over a wider range of surfaces (Li *et al*. 2007, Mi *et al*. 2007) over the previous collection 4 algorithm. For retrieving higher-resolution AOT images over urbanized regions such as Hong Kong and the Pearl River delta region, a new high-resolution algorithm has been developed using MODIS 500 m images combined with local aerosol optical properties to construct a look-up table (LUT). High accuracies (Wong *et al*. 2008, 2009, 2010) were obtained when validated with AErosol RObotic NETwork (AERONET) and MicrotopsII sunphotometer measurements.

MODIS collection 5 fine-mode fraction AOT is a rough estimation of the percentage of fine particles using the ratio of MODIS path radiances at 660 and 470 nm (Remer *et al*. 2005). Anthropogenic sources from industrial and vehicle emissions are the main contributors to the fine-mode fraction, while desert dust and sea salt aerosols with larger particles are predominant in the coarse-mode fraction (Kaufman *et al*. 2005a,b). Although fine-mode fraction AOT represents light scattering over the whole atmospheric column in a fine particulate radius (effective radius <1 μm), when the $PM_{2.5}$ concentration is large and significant, the sensitivity to fine-mode fraction AOT should be strong, and the correlation between $PM_{2.5}$ and fine-mode AOT should be significant. Since only one previous study (Liu *et al*. 2007) has examined the relationship between MODIS fine-mode fraction AOT and $PM_{2.5}$, the value of using fine-mode fraction AOT will be evaluated in this study.

In order to develop a robust method for utilizing satellite-derived AOT as a surrogate for $PM_{2.5}$ at city scale, the correlations between $PM_{2.5}$ concentrations and (i) MODIS collection 5 AOT data, (ii) MODIS collection 5 fine-mode fraction AOT and (iii) MODIS 500 m AOT data are evaluated here.

2. Study area and data used

Hong Kong has 14 air-quality stations measuring hourly pollutant gases and particulates, but only five of them are equipped to monitor $PM_{2.5}$ (figure 1). The annual average $PM_{2.5}$ concentrations for the years 2005, 2006 and 2007 are high, at 60, 56 and 53 $\mu g\ m^{-3}$, respectively, and exceed the World Health Organization (WHO 2006) annual air-quality standards (i.e. WHO stated 35 $\mu g\ m^{-3}$ as the interim target (IT–1) and 10 $\mu g\ m^{-3}$ as the ultimate target in the annual fine particle standards). However, considerable spatial variation is usually present. For example, over the last 3 years, Central station had the highest frequency of $PM_{2.5}$ concentrations above 70 $\mu g\ m^{-3}$, which occurred 4130 times. This compares with 4000 times at Yuen Long, 3618 times in Tung Chung, 3304 times at Tseun Wan and 2747 times at Tap Mun.

Long-term air-quality data from Hong Kong suggest a highly constant ratio between PM_{10} and $PM_{2.5}$, that is, $PM_{2.5}/PM_{10} = 0.7$ (Arup 2006); then the relationship between $PM_{2.5}$ and AOT is also expected to be linearly related which is highly constant over time.

The MODIS is a sensor aboard National Aeronautics and Space Administration (NASA)'s TERRA and AQUA satellites. This project uses the 500 m resolution AOT images, derived from the 470, 550 and 660 nm bands of MODIS images using a minimum reflectance technique. The rationale of the minimum reflectance technique is to obtain the surface reflectance by extracting the minimum reflectance values of land surfaces from Rayleigh corrected images over a time period. The aerosol reflectances then can be derived by decomposing the top-of-atmosphere reflectances from surface reflectance and Rayleigh path reflectances. For conversion of aerosol reflectance to AOT, comprehensive LUTs are constructed which consider the properties of local (Hong Kong) aerosol types from AERONET inversion data, as well as relative humidity and sun-viewing geometry, in the radiative transfer calculations (Wong *et al*. 2008, 2009, 2010). The validation of MODIS 500 m AOT data is described in §4.1.

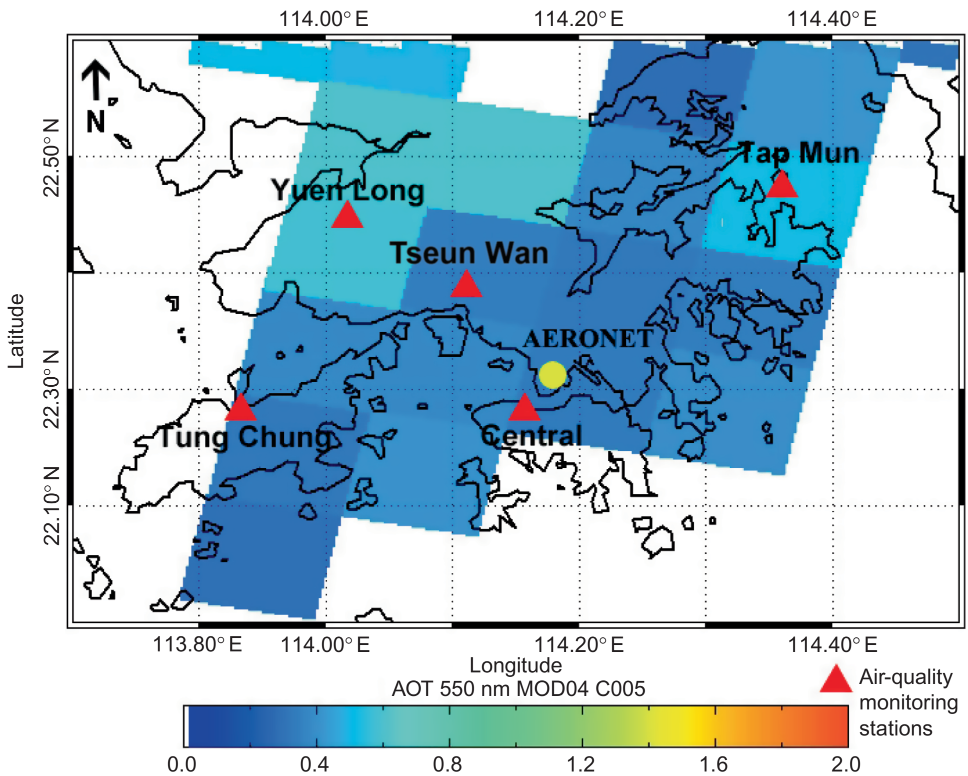

Figure 1. Monitoring stations in Hong Kong overlaid with MODIS collection 5 AOT image on 28 January 2007.

For comparison purposes, the TERRA/MODIS level 2 collection 5 aerosol products which derive both AOT and fine-mode fraction at a spatial resolution of 10 km were also obtained. These data for 2007 were acquired from the NASA's Goddard Space Flight Center archive.

3. Methodology

3.1 *Comparison between MODIS AOT and AERONET measurements*

Validation of MODIS AOT retrieval in Hong Kong was undertaken by comparison with AERONET level 2.0 data, since the MODIS aerosol product MOD04 which is based on using a standard look-up table based on particle type and size has been identified as having a large error for the southern China region (Kaufman and Tanré 1998). For this, the MODIS collection 4, collection 5 and 500 m AOT retrievals for the whole year 2007 were compared with AERONET observations (temporally matching with the criterion of overpass time ± 30 min). The columnar AOT and fine-mode fraction AOT were extracted for pixels corresponding to the five $PM_{2.5}$ stations. A limited amount of MODIS AOT collection 4 data was acquired, because collection 4 was replaced with collection 5 data during the period.

3.2 *Comparison between AERONET AOT and $PM_{2.5}$*

Central station in the Central Business District is the nearest $PM_{2.5}$ station, at 5 km distance from the AERONET site. Hourly collected $PM_{2.5}$ data were selected to be within 15 min of the AERONET observation time. Correlation analysis was performed between Central station's $PM_{2.5}$ measurements and AERONET AOT data.

3.3 *Comparison between MODIS AOT and $PM_{2.5}$*

The hourly collected $PM_{2.5}$ data at the five ground stations were selected to be within 30 min of the MODIS overpass time. Correlation analysis was performed between the *in situ* $PM_{2.5}$ measurements and AOT from the MOD04 product at 10 km resolution, as well as from the 500 m AOT derived from minimum reflectance technique.

4. Results

4.1 *AERONET AOT versus MODIS AOT*

Although Kaufman and Tanré (1998) predicted AOT retrieval problems for the south China region, due to high humidity combined with a diversity of aerosol types, surprisingly strong correlation was observed between MODIS collection 5 AOT and AERONET data (figure 2(*a*)). A similar correlation ($R^2 = 0.77$) was obtained for the 500 m AOT data (figure 2(*b*)), compared with $R^2 = 0.78$ for the MODIS collection 5. However, more importantly, the 500 m AOT data not only retrieve AOT images at a much higher spatial resolution, but also retrieve AOT over bright urban surfaces as well as dark vegetated areas. Both of these improvements are significant for a topographically complex area with heterogeneous land cover like Hong Kong.

Although the signal-to-noise ratio of 10 km resolution data is 20 times higher than the 500 m resolution data (Kaufman and Tanré 1998), Hendreson and Chylek (2005) show that there are only small changes in the accuracy of aerosol retrieval with increasing pixel sizes from 40×80 m to 2040×4080 m, and the AOT variations are negligible. Therefore, any loss of accuracy from a decreased signal-to-noise ratio of 500 m AOT data is thought to be small enough to be compensated by increased accuracy from higher spatial resolution.

4.2 *AERONET AOT versus $PM_{2.5}$*

Since AERONET provides high precision and quality-assured AOT data as well as aerosol-related microphysical data of the whole atmospheric column, the viability of using satellite-derived AOT (which is also whole column) can be evaluated by an initial comparison of AOT from the quality-assured AERONET with $PM_{2.5}$ concentrations. However, it is rare to have both instruments in the same site, and in Hong Kong, the closest $PM_{2.5}$ station to the AERONET in the Kowloon Peninsula is situated ~ 5 km away across the harbour on the Hong Kong Island. Although only a moderate correlation (figure 3) is obtained between the ground AERONET measurements and ground $PM_{2.5}$ data at Central ($R^2 = 0.50$), the result is still significant at 0.01 level. The differences may be due to the variability of atmospheres between Kowloon Peninsula and Hong Kong Island (the two stations are separated by the Victoria Harbour). Thus there would be a better chance to obtain more meaningful results and higher correlations using 500 m resolution AOT data, as described in §4.4.

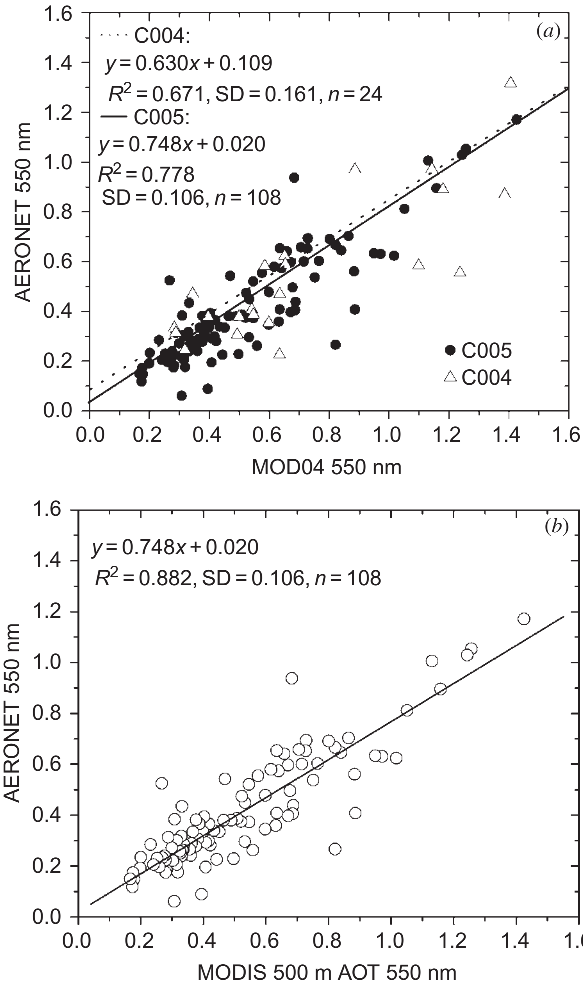

Figure 2. Scatter plots of (*a*) MODIS collection 4 and 5 AOT data versus AERONET level 2.0 AOT measurements for the year 2007 and (*b*) MODIS 500 m AOT data versus AERONET level 2.0 AOT measurements for the year 2007.

4.3 *MODIS collection 5 AOT and fine-mode AOT at 10 km resolution versus* $PM_{2.5}$

Only fair to moderate correlations were obtained for MODIS AOT at 10 km resolution against $PM_{2.5}$. These were $R^2 = 0.31$ for collection 5 AOT and $R^2 = 0.10$ for fine-mode fraction AOT (figure 4(*a*)). These moderate to low correlations are similar to those of previous studies which also used the MODIS AOT product at 10 km resolution, although as previously mentioned, higher correlations have often been demonstrated when the data are controlled for more specific regional and temporal factors.

It is surprising that collection 5 AOT (whole column) obtained a higher correlation with $PM_{2.5}$ than fine-mode fraction AOT, since the latter represents smaller particles. The weaker correlation may be due to the uncertainty during the selection of aerosol models which can play a significant role in $PM_{2.5}$/AOT correlations (Engel-Cox *et al.*

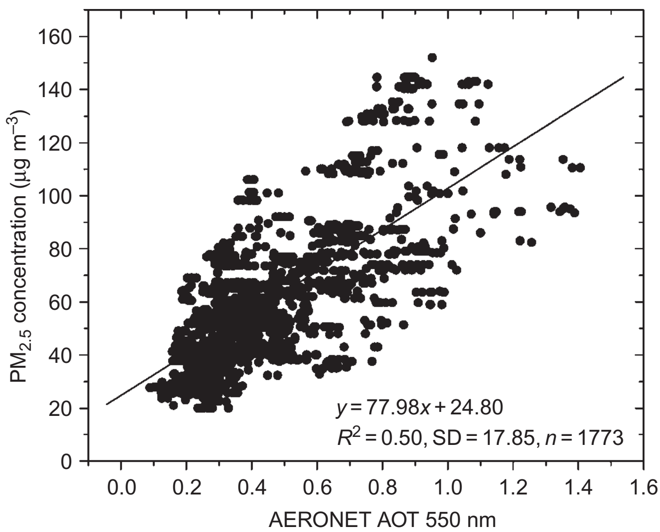

Figure 3. Scatter plot of AERONET level 2.0 AOT data versus $PM_{2.5}$ measurements for the year 2007 ($\mu g\ m^{-3}$).

2004). There are only three fine-mode aerosol models, compared with a total of six in the MOD04 AOT algorithm, and this is due to only three bands (470, 550, 660 nm) being available for selecting the fine-mode model in aerosol retrieval. Additionally, since the particle size of MODIS fine-mode fraction is less than 1 μm, a closer relationship with $PM_{2.5}$ than for whole column AOT may not be assumed, and may depend on the dominant aerosol types in any location. Similar results were observed by Liu *et al*. (2007) when comparing whole column, and fine-mode AOT respectively, with $PM_{2.5}$ data in St Louis, MO, USA.

Using the whole column AOT, the yearly average AOT distribution for 2007 over Hong Kong is shown in figure 4(*b*). These are high, ranging from ∼0.5 in rural areas to ∼0.9 in urban areas. Figure 4(*c*) shows the modelled $PM_{2.5}$ concentrations for the year 2007, based on the regression in equation (1), which is derived from the MOD04 10 km AOT and ground station $PM_{2.5}$ data,

$$PM_{2.5} = (54.16 \times AOT) + 30.66, \quad (1)$$

where $R^2 = 0.31$, standard deviation (SD) = 23.15, number of samples (n) = 183, $p < 0.0001$ (significant at the 0.01 level).

As expected, $PM_{2.5}$ concentrations are higher in urban areas (Kowloon Peninsula and Hong Kong Island) and in the north along the China border. Although not heavily urbanized, northern Hong Kong suffers from cross-boundary pollutants which are emitted from industries in the Pearl River delta region, where very high annual average $PM_{2.5}$ concentrations of over 100 $\mu g\ m^{-3}$ are observed covering large areas (figure 4(*c*)). Such levels far exceed air-quality standards (i.e. WHO (2006) stated the annual fine particle standards: 35 $\mu g\ m^{-3}$ as the interim target (IT–1) and 10 $\mu g\ m^{-3}$ as the ultimate target).

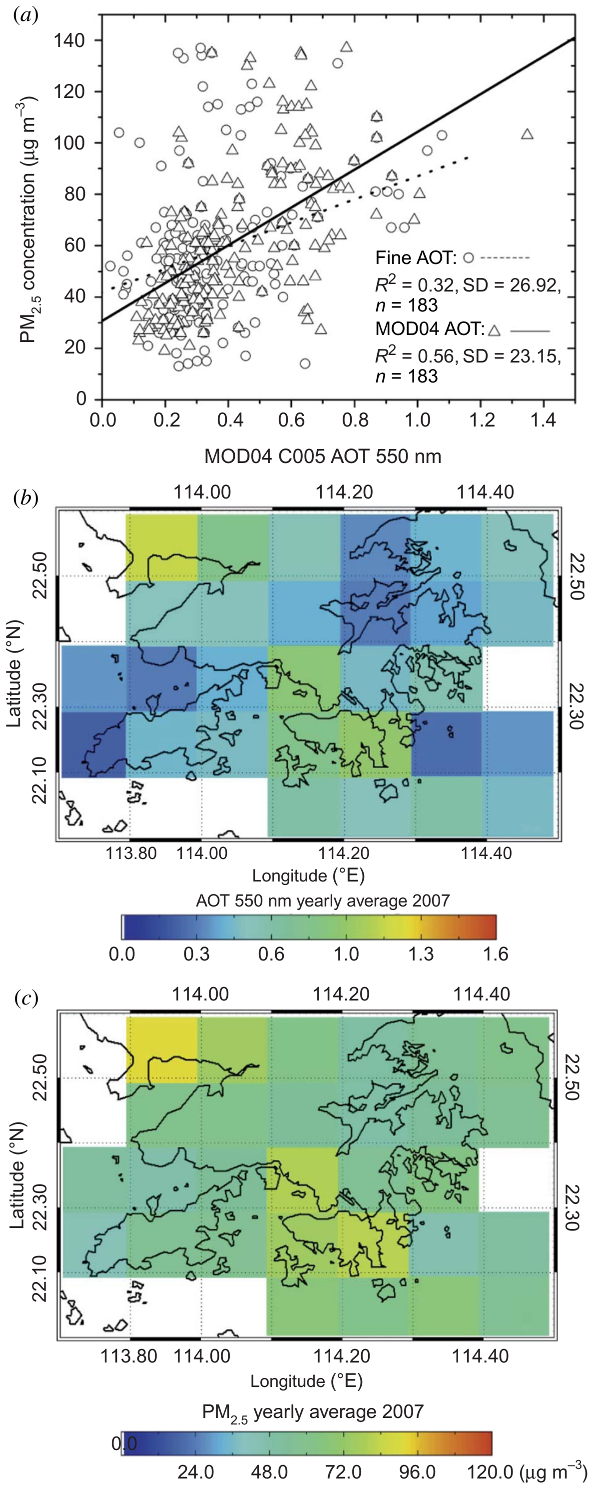

Figure 4. (*a*) Scatter plot of MODIS collection 5 AOT data and fine-mode AOT data versus $PM_{2.5}$ measurements ($\mu g\ m^{-3}$) for the year 2007, (*b*) yearly average AOT in 2007 and (*c*) modelled $PM_{2.5}$ concentrations ($\mu g\ m^{-3}$) in 2007.

4.4 *MODIS 500 m AOT versus $PM_{2.5}$*

Figure 5(*a*) shows the relationship between MODIS 500 m AOT and $PM_{2.5}$ concentrations. Compared with the MODIS collection 5 AOT at 10 km ($R^2 = 0.31$), a much higher correlation ($R^2 = 0.67$) and much lower standard deviation are obtained. The derived equation is

$$PM_{2.5} = (63.66 \times AOT) + 26.56, \tag{2}$$

where $R^2 = 0.67$, SD = 13.13, $n = 203$, $p < 0.0001$ (significant at the 0.01 level).

The 500 m AOT image and modelled $PM_{2.5}$ image for 28 January 2007 (figure 5(*b*) and (*c*)) give values for areas which are masked out with no AOT data values on the MODIS collection 5 images (figure 1) due to their surface reflectances not meeting the surface reflectance criteria in the collection 5 AOT algorithm. Since the new aerosol retrieval algorithm works well over both bright and dark surfaces at 500 m resolution, more AOT data can be retrieved (figure 5(*b*)) permitting $PM_{2.5}$ estimates over the whole region. Furthermore, the greater spatial detail of the AOT retrieval at 500 m (figure 5(*b*)) permits local areas with very high $PM_{2.5}$ concentrations to be detected, namely the Hong Kong International Airport, the Kowloon Peninsula and areas bordering the mainland city of Shenzhen. Indeed on the image date, approximately two-thirds of the area of Hong Kong appears to suffer from $PM_{2.5}$ levels in excess of the WHO annual limit of 35 $\mu g\ m^{-3}$. The fairly high correlation of $R^2 = 0.67$ for the 500 m AOT and $PM_{2.5}$ data is obtained across all data for 2007, with no attempt to control for other physical parameters as in other studies (Engel-Cox *et al*. 2004, Liu *et al*. 2005, Tian and Chen 2006, Kumar *et al*. 2007, 2008).

Data from $PM_{2.5}$ ground stations representing different degrees of urbanization in Hong Kong including city downtown (Central station), urban areas (Tung Chung and Tseun Wan), suburban area (Yuen Long) and rural area (Tap Mun) were evaluated for their relationships between 500 m AOT data and $PM_{2.5}$ concentrations. The correlations (R^2) for Central, Tung Chung, Tseun Wan, Yuen Long and Tap Mun stations were 0.66, 0.74, 0.76, 0.56 and 0.62, respectively (all data are significant at the 0.01 level) (figure 6). The stronger correlations shown for the urban stations Tung Chung and Tseun Wan indicate the strong influence of microscale patterns of air pollution in urbanized areas, as these areas usually have a well-developed urban boundary layer and low wind speeds, and support the need for higher-resolution monitoring in urbanized regions.

5. Discussion and conclusion

This study examines the relationships between satellite-derived AOT and *in situ* $PM_{2.5}$ concentration for different aerosol products and at different resolutions including local (intra-urban) scale. Higher correlations with $PM_{2.5}$ were observed for 500 m than for 10 km AOT ($R^2 = 0.67$ and $R^2 = 0.31$, respectively). As observed by Kumar *et al*. (2007) from measurements at 113 ground locations in Delhi, $PM_{2.5}$ concentrations tend to show large variation within a 10 × 10 km pixel. This helps to explain the low to moderate correlations obtained by most previous studies using coarse (10 km or coarser) resolution AOT datasets, which fall short of the approximately 80% reliability required for an operational model, except when the datasets are controlled for

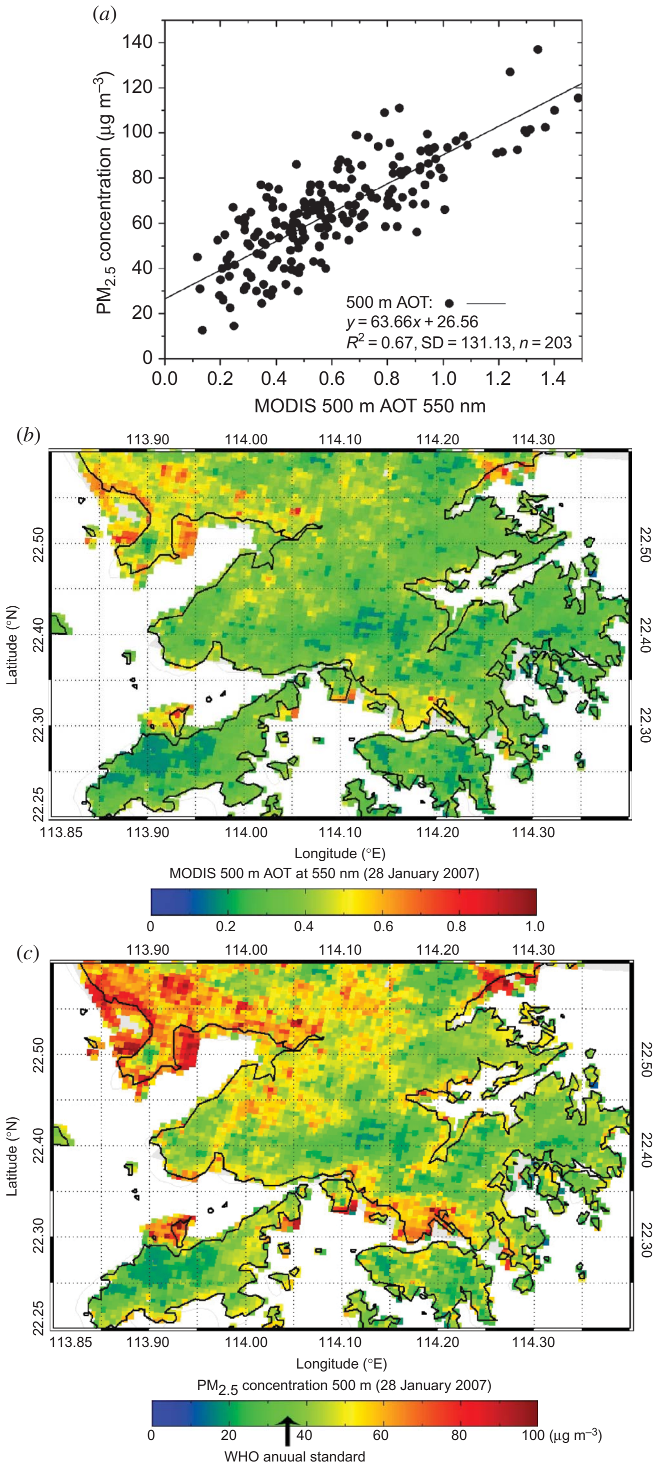

Figure 5. (*a*) Scatter plot of MODIS 500 m AOT data versus $PM_{2.5}$ measurements ($\mu g\ m^{-3}$) for the year 2007, (*b*) 500 m AOT map over Hong Kong on 28 January 2007 and (*c*) modelled $PM_{2.5}$ concentrations ($\mu g\ m^{-3}$) at 500 m resolution over Hong Kong on 28 January 2007.

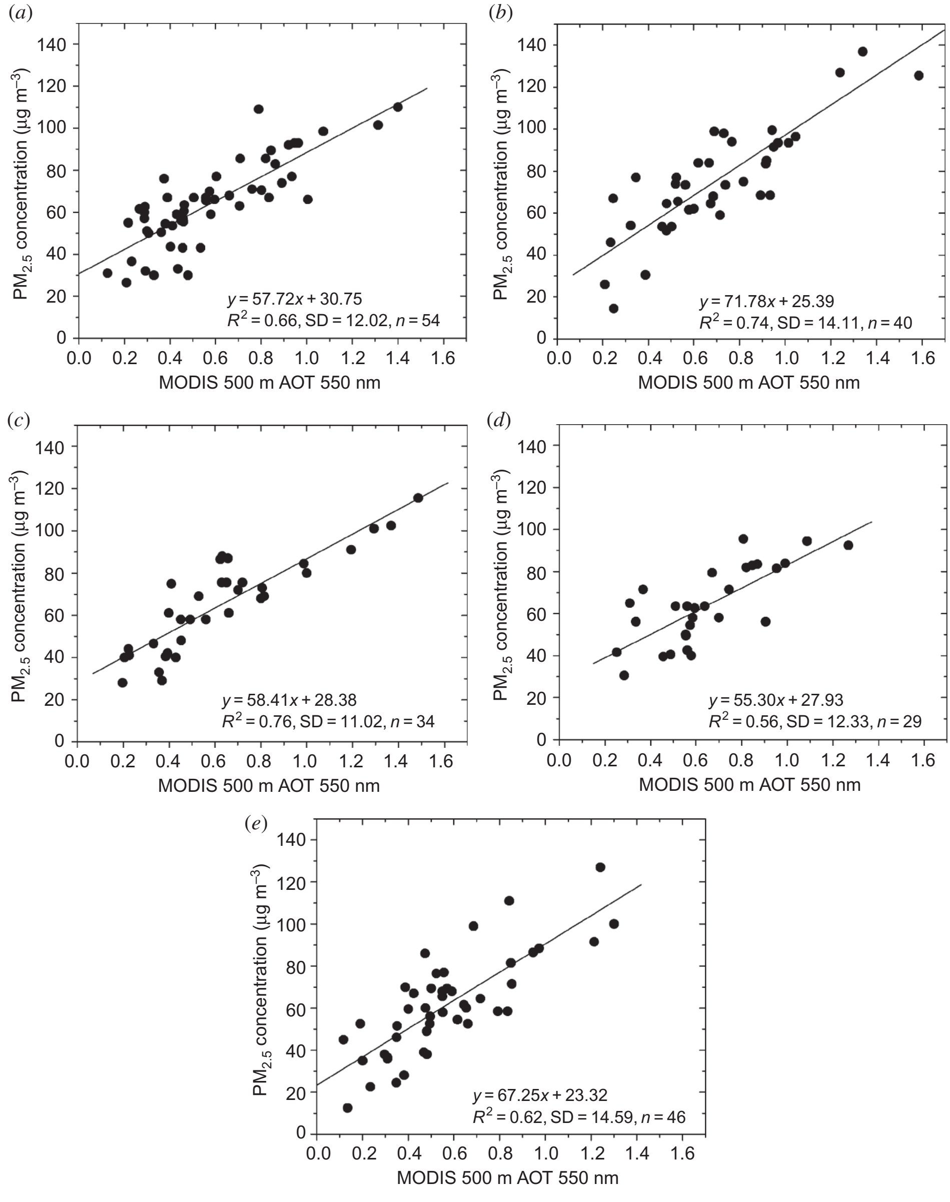

Figure 6. Scatter plots of MODIS 500 m AOT data and $PM_{2.5}$ measurements ($\mu g\ m^{-3}$) in (*a*) Central, (*b*) Tung Chung, (*c*) Tseun Wan, (*d*) Yuen Long and (*e*) Tap Mun.

other parameters. This preliminary study demonstrates great potential for the routine use of satellite-derived AOT as a surrogate for detailed $PM_{2.5}$ distributions at ground level. Furthermore, this is the first study to depict fine aerosols at a high level of spatial detail within city districts, other than by non-empirical air-quality modelling. The AOT images derived at 500 m are able to explain 67% of the variance in $PM_{2.5}$. Assuming accurate AOT retrieval, the remaining 33% of the variance not explained may be due to scale discrepancies between $PM_{2.5}$ distribution and 500 m pixels and variations in the fine-mode fraction as a proportion of the total column AOT (although this proportion is said to be fairly constant at approximately one-third in Hong Kong (EPD, personal communication) and may be one of the reasons for the strong relationship with AOT obtained in this study). Other parameters unrelated to AOT such as atmospheric pressure, stability within the atmospheric boundary layer (ABL) and humidity may also be influential. Indeed, the study assumed a stable planetary boundary layer (PBL) over Hong Kong, with most aerosols concentrated in a well-mixed boundary layer near the ground. For refinement of the model, light detection and ranging (LIDAR) instruments deployed in different areas would be useful to evaluate the influence of aerosol vertical distribution and PBL heights. Further analysis will be conducted using the aerosol fraction column derived from an upward-pointing Lidar which is expected to represent ground concentrations more accurately. As more data become available, different regression models constructed for humid and non-humid seasons and different PBL heights should prove more robust and enable the EPD in Hong Kong and the industrialized Pearl River delta to derive fine particle distributions from daily satellite images, at a high level of detail.

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