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Full Length Research Paper

Influences of the window size of moderate resolution imaging spectroradiometer (MODIS) aerosol optical thickness (AOT) values on particulate matter (PM_{10}) motoring in Klang Valley, Malaysia

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Remote sensing has been shown to be a useful tool in retrieval aerosol optical thickness (AOT) in particulate matter (PM) pollution monitoring. In this study, daily AOT data retrieved from moderate resolution IMAGING spectroradiometer (MODIS) and the amount of PM_{10} measured at eight air quality monitoring ground stations in Klang Valley from 2004 to 2006 were used. The AOT values consisted of three different average window sizes (WS): (3 × 3) pixels, (5 × 5) pixels and (7 × 7) pixels. PM_{10} mass concentration consists of real-time (hourly) and 24 h mean. Linear correlation coefficients (LCC) were used to determine the best validation result. Best validation results were obtained between AOT WS in (5 × 5) pixels and PM_{10} mass in 24 h mean. The LCCs in dry season were acquired higher than those in rainy season. The validation results in rainy season were improved when nonlinear correlation coefficients (NLCC) with polynomial equation were used for analysis. This study reveals that the correlation coefficients are dependent on time and location.

Key words: Particulate matter, aerosol optical thickness, real-time, 24 h mean, Klang Valley-Malaysia.

INTRODUCTION

The Department of Environment (DOE) monitors the Malaysian ambient air quality in both residential and industrial areas through a network of 51 stations. Solid and liquid particles in the air, referred to as particulate matter (PM), are monitored from 21 stations (MMD, 2009). Respirable particles with sizes of less than 10 and 2.5 microns are named PM_{10} and $PM_{2.5}$, respectively (Krewski et al., 2000). PM_{10} and $PM_{2.5}$ are small enough to penetrate the upper and lower parts of the human respiratory system (Liu and Huza, 1995). Hence, they are capable of having harmful effects on human health (Ostro et al., 1999; Adamson et al., 1999; Williams et al., 2003; WHO, 2005). Suspended particulate matter (SPM) is able to reduce atmospheric visibility through absorbing and scattering solar radiation (Seinfeld and Pandis, 1998). It can also affect the global change through interactions with the earth's radiation energy balance (IPCC, 2001; Garland et al, 2008). Therefore, PM is a subject of increasing concern. PM_{10} concentration usually can be measured in ground station sites in cities and rural areas. Ground site measurement can cover only a few meters around the station. High installation and maintenance costs of ground station sites and the need to investigate distribution process of pollution are some of the reasons that urge scientists to find new ways to monitor air pollution. As a possible method, monitoring urban air quality with remote sensing has created a new corridor of

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research concerning the atmospheric pollution processes. Electromagnetic radiation is used for acquiring information in remote sensing (Martin, 2008). For aerosol remote sensing, the reflected solar radiation at the top of the atmosphere is measured (Liu, 2008). Terra and Aqua are satellites equipped with certain sensors to spatially monitor the amount of PM in air. The Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-Angle Imaging Spectroradiometer (MISR), Clouds and the Earth's Radiant Energy System (CERES), Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Measurements of Pollution in the Troposphere (MOPITT) are sensors onboard National Aeronautics and Space Administration (NASA's) Terra satellite (Sohrabinia and Khorshiddoust, 2007). These sensors are able to monitor clouds, climate and air quality. Aerosol Optical Thickness (AOT) is among the important data produced by MODIS sensor. AOT represents columnar aerosol loading from the surface to the top atmosphere (Gupta et al., 2006). In the last decade, several studies validated the relationship between particulate mass concentration measured by ground station sites and satellite-derived AOT (Amanollahi et al., 2011a, b, c). To limit the impact of the spatial variation in AOT measurement, window pixels around the corresponding pixel with the ground site coordinate are required. Ichoku et al. (2002) tested four Window Sizes (WS) consisting of (3 × 3), (5 × 5), (7 × 7) and (9 × 9) AOT pixels which cover (30 × 30), (50 × 50), (70 × 70) and (90 × 90) km areas at nadir to evaluate the effect of WS on parameter statistics. They reported the size of (50 × 50) km as the best option for validation analysis. Xueliang et al. (2008) showed that variation in the WS of MODIS data can influence the validation result. They observed the (3 × 3) pixels (30 × 30 km) WS as the best alternative for the China Sea. For comparing the AOT with 24-hourly mean $PM_{2.5}$ mass in Alabama, Wang and Christopher (2003) used (3 × 3) pixels to limit the potential cloud contamination. Some previous studies in different parts of the world for AOT with 24-hourly mean and $PM_{2.5}$ mass have used a resolution of (5 × 5) pixels, for the global study (Gupta et al., 2006), in Sydney (Gupta et al., 2007), and in south eastern United States (Gupta and Christopher, 2008). In order to study the air quality using MODIS Aerosol optical depth (AOD), Engel-Cox et al. (2004) employed satellite AOD pixels lower than 40 to 50 km far from the ground stations. Hutchison et al. (2004) used hourly $PM_{2.5}$ and AOT to support operational air quality forecast. Hutchison et al. (2005) acquired better correlation coefficients using (5 × 5) AOT pixels and 24-hourly mean $PM_{2.5}$ than hourly $PM_{2.5}$. Furthermore, they tested both (3 × 3) and (5 × 5) AOT pixels in validation analysis and did not acquire significant differences between the two groups in the results of validation.

The two main objectives of this paper are: (1) to determine the best WS of MODIS AOT pixels to acquire good correlation coefficient between AOT and PM_{10} mass concentration in Klang Valley, and (2) to determine the correlation coefficient in dry and rainy season using the results of the first objective.

MATERIALS AND METHODS

Air quality in the study area

The climate characteristics of Malaysia are indicated by high humidity, uniform temperature, copious rainfall and generally light winds (MMD, 2009). Klang Valley is a part of Selangor and covers an area of about 2826 km^2. The number of stationary pollution sources in Selangor is the highest in Malaysia (Afroz et al., 2003). In Klang Valley, only 23% of air quality was reported as good, 70% as moderate and 7% as unhealthy levels in 2006. Geographical position as well as large-scale industrial and commercial activities is among the reasons for the increase in air pollution in Klang Valley (EQR, 2006).

PM_{10} monitoring stations were first installed during the 1996 by Alam Sekitar Malaysia Sdn Bhd (ASMA). The hourly PM_{10} mass concentrations are measured using the β-ray attenuation mass monitor. The highest annual average value of PM_{10} concentration in Malaysia was measured for industrial area. Emission load of total PM measured from various sources include 25% by industries, 8% by motor vehicles, 44% by power stations and 23% by others (EQR, 2006). Currently, eight Air Quality Monitoring Stations (AQMS) measure the PM_{10} in Klang Valley (Figure 1). Stations are located principally near industrial and residential areas.

Figure 2 shows the monthly mean of PM_{10} in 2004. The amount of PM_{10} for April, May, June and August was observed to be more than that of the other months. This may be due to forest fires in Indonesia. In dry season, burning the scrub and forest to clear land by Indonesian farmers creates haze. This was the main reason behind the events in 1997 (Koe et al., 2001), 1999 and 2000 (Keywood et al., 2003), slight haze in 2004 and 2006 (EQR, 2004, 2006) and intense haze in 2005 (EQR 2005) in Malaysia.

Data collection

MODIS collects data from land; atmosphere and ocean in 36 spectral bands ranging from 0.4 to 14.5 µm. Seven (7) of these bands ranging from 0.47 to 2.13 µm are able to retrieve aerosol characteristics over ocean and land. Only two wavelengths, 0.47 and 0.67 µm, are used to provide AOT over land (Remer et al., 2005).

For retrieval of MODIS data at 0.55 µm, interpolation from the 0.47 and 0.66 µm was used. In this study, daily AOT at 0.55 µm wavelengths for 2004 to 2006 from the MODIS onboard Terra satellite and PM_{10} mass concentration were utilized. The MODIS level 2 (MYD04_L2) daily AOT products from Terra were downloaded (http://ladsweb.nascom.nasa.gov/data/search.html). The validation between MODIS AOT and PM_{10} mass concentration in the atmosphere was analyzed using simple linear regression. Three different WSs of MODIS AOT consisting of (3 × 3, 5 × 5 and 7 × 7 pixels) and two ranges of PM_{10} mass concentrations consisting of real-time and 24-hourly mean were analyzed (Figure 3). The hierarchical data format (HDF) of MODIS AOT files can include text files, charts and tables (NASA, 2009). There is a table for each item and there are thousands of pixels in each table. Each pixel of level 2 AOT item has a 10 × 10 km^2 resolution.

To arrange the AOT data and corresponding stations coordinate in a row, Visual Basic program was written to run the model in MS Excel macro. In this way, the table of longitude, latitude and table of

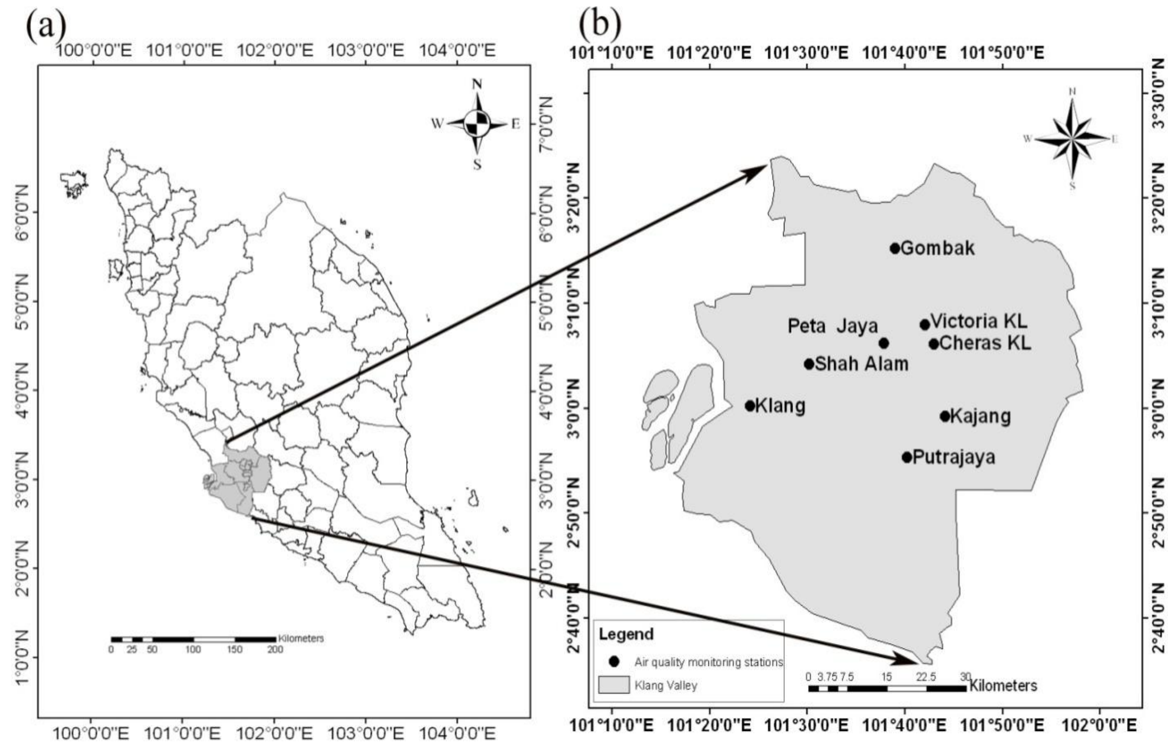

Figure 1. Geographical characteristics of eight AQMS in Klang Valley.

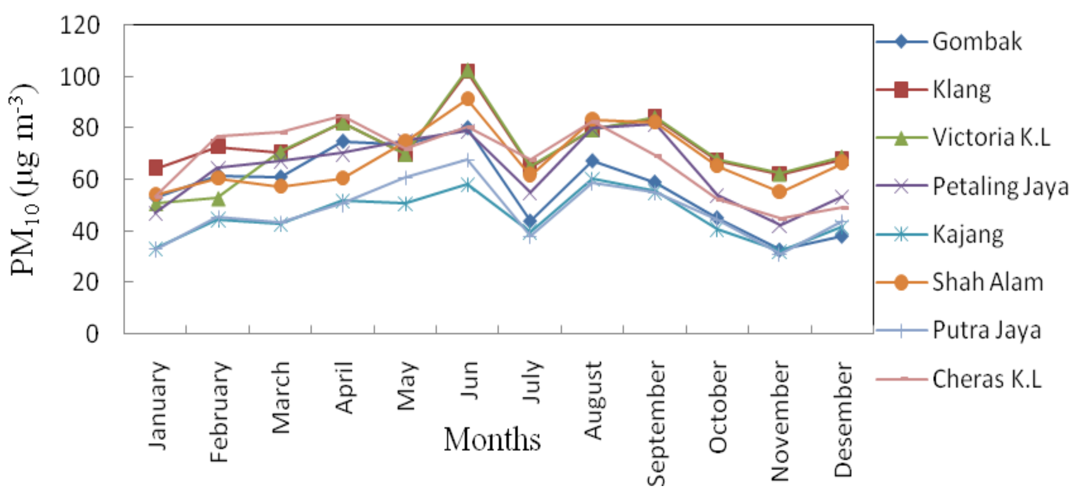

Figure 2. Monthly mean of PM_{10} mass concentration over eight AQMS in Klang Valley in 2004.

AOT data were listed in different columns. In addition, the corresponding data in the cells of all tables were arranged in a row (Sohrabinia and Khorshiddoust, 2007). Another Visual Basic program was written to identify the 49 AOT cells for (7 × 7) WS, 25 AOT cells for (5 × 5) WS and 9 AOT cells for (3 × 3) WS over the eight stations in Klang Valley area. For averaging of window size which over PM_{10} monitoring stations at least three cells were needed, so the data cells below three were ignored (Gupta et al., 2007).

RESULT

Relationship between two ranges of PM_{10} mass and different WSs of MODIS AOT

The linear correlation coefficients (LCC) were used to test the correlation between different WSs of MODIS AOT and two ranges of PM_{10} mass (Table 1). The lowest LCC

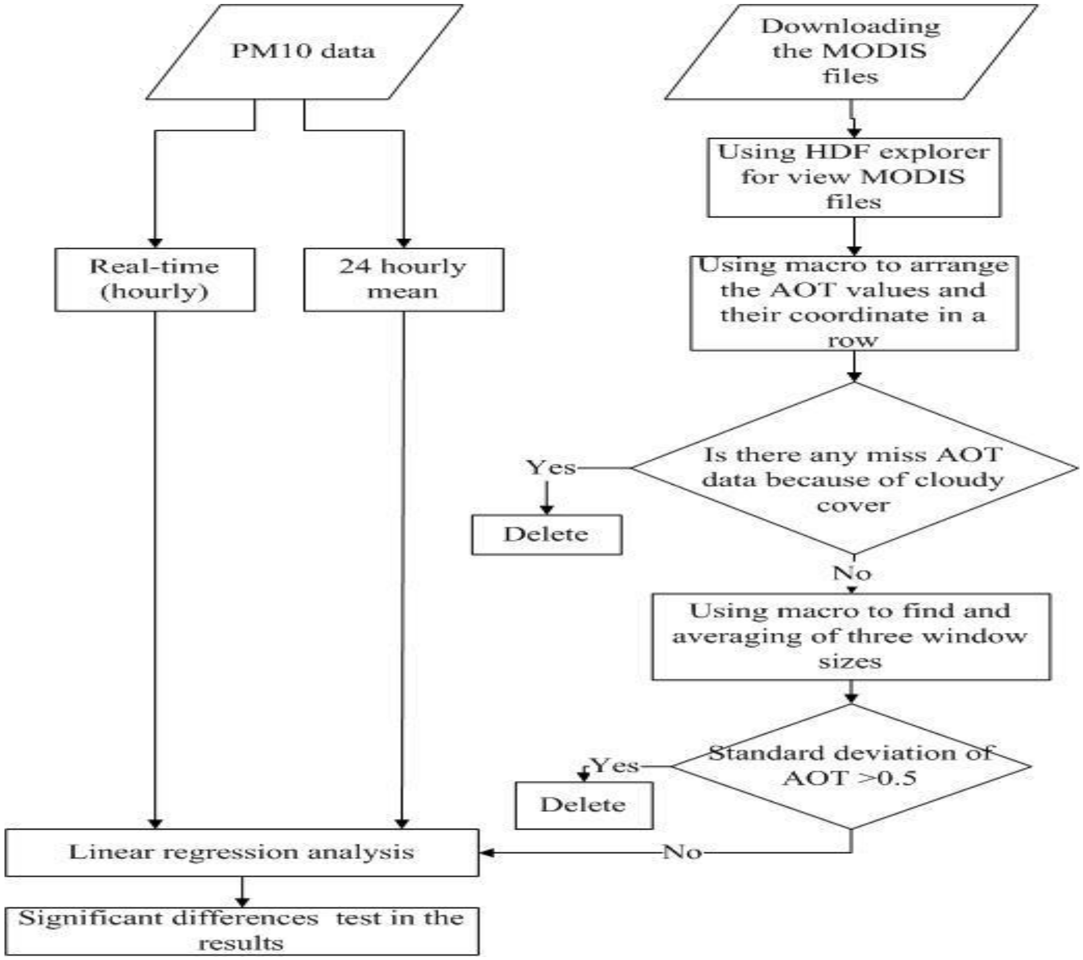

Figure 3. Validation process between different WSs and two ranges of PM_{10}.

Table 1. Correlation statistics between different WSs of MODIS AOT and two ranges of PM_{10} (μgm^{-3}) mass in eight AQMS in Klang Valley from 2004 to 2006.

Station name	3 × 3			5 × 5			7 × 7		
	No. of points	Correlation coefficient		No. of points	Correlation coefficient		No. of points	Correlation coefficient	
		Hourly PM_{10}	24 h mean PM_{10}		Hourly PM_{10}	24 h mean PM_{10}		Hourly PM_{10}	24 h mean PM_{10}
Gombak	80	0.25	0.14	86	0.23	0.14	204	0.24	0.31
Klang	25	0.13	0.33	32	> 0.10	0.42	106	0.17	0.39
Victoria K.L	22	0.19	0.27	27	0.27	0.50	81	0.42	0.45
Petaling Jaya	44	> 0.10	0.13	54	0.11	0.23	157	0.17	0.38
Kajang	36	0.19	0.25	41	0.34	0.47	124	0.22	0.38
Shah Alam	29	0.37	0.51	47	0.28	0.44	149	0.29	0.38
Putra Jaya	29	0.24	0.42	30	0.39	0.17	90	0.26	0.48
Cheras K.L	41	0.29	0.24	50	0.38	0.34	141	0.23	0.35

values were obtained when real-time of PM_{10} mass was used in the analysis. The highest LCC value between these WSs and PM_{10} was observed when 24 h mean of PM_{10} was used in the analysis. In most cases, the amount of LCC between average of AOT in three WSs and PM_{10} in 24 h mean was higher than the

Table 2. Descriptive statistics of PM_{10} (μg m^{-3}) mass concentration corresponding to (7×7) pixels in annually analysis of eight AQMS in Klang Valley.

Station name	PM_{10} (real-time)		PM_{10} (24 h mean)		MODIS AOT (7 × 7)	
	Mean	SD	Mean	SD	Mean	SD
Gombak	50.51	27	53.42	22	0.46	0.34
Klang	62.87	43	73.09	30	0.59	0.49
Victoria K.L	60.47	37	75.91	33	0.47	0.37
Petaling Jaya	64.73	34	60.24	22	0.47	0.35
Kajang	43.54	30	49.27	21	0.46	0.38
Shah Alam	53.17	26	63.59	24	0.53	0.44
Putra Jaya	48.52	33	49.82	23	0.50	0.44
Cheras K.L	61.16	33	62.05	26	0.49	0.39

Table 3. Correlation statistics between WS in (5 × 5) pixels of MODIS AOT and PM_{10} (μg m^{-3}) in 24 h mean for the dry season in eight AQMS in Klang Valley.

Station name	No. of points	*p*-value	Correlation coefficient	PM_{10} (μgm^{-3})		MODIS AOT (0.55 μm)	
				Mean	SD	Mean	SD
Gombak	59	< 0.0001	0.34	59.08	21.29	0.48	0.42
Klang	22	0.0014	0.41	68.78	20.73	0.55	0.45
Victoria K.L	20	0.0002	0.53	83.13	39.25	0.49	0.39
Petaling Jaya	40	< 0.0001	0.42	68.15	20.94	0.48	0.39
Kajang	32	< 0.0001	0.58	55.05	18.36	0.53	0.40
Shah Alam	36	< 0.0001	0.59	69.05	23.49	0.57	0.46
Putra Jaya	25	0.0458	0.16	53.96	16.12	0.63	0.43
Cheras K.L	36	< 0.0001	0.41	65.92	22.95	0.50	0.41

results of PM_{10} in real-time, but no significant differences were found between the results.

As shown in Table 1, LCC values between average of MODIS AOT in the (3 × 3) pixels and real-time of PM_{10} measurements ranged from just under 0.1 in Petaling Jaya to 0.37 in Shah Alam. The average measurements of AOT in the (7 × 7) pixels in Gombak, Victoria KL, Petaling Jaya, Kajang Sealngor, and Putra Jaya were reported with very small differences (Table 2). On the other hand, PM_{10} mean for these stations turned out to be different (Table 2).

Relationship between PM_{10} mass and window size of MODIS AOT in (5 × 5) pixels in rainy and dry seasons

Over southwest Malaysia, October and November have a maximum and February has a minimum rainfall (MMD, 2009). Based on the amount of humidity, temperature and rainfall, Malaysian climate is classified into the rainy season from October to January, and dry season from February to September. Correlation analyses were also performed to determine any relationship between satellite observations in (5 × 5) pixels and PM_{10} in 24 h mean during the dry season (Table 3). Klang Valley station (column 1), and the number of MODIS AOT and AQMS observation pairs (column 2) represent the sample size used for successive correlation tests. Correlation coefficients are reported in columns 4, and columns 5 to 6 contain means and standard deviations on the 24-hourly mean of PM_{10} and MODIS AOT, respectively. The *p*-value reported in Table 3 and 4, column 3 is important in linear analysis. The variability into given data and a number of observations are directly and indirectly affected on *p*-value.

The *p*-value lowers than 0.05 means that there is a great deal of confidence and the coefficient is truly different from zero.

Correlation analyses were also used to determine any relationship between MODIS AOT in (5 × 5) pixel group and PM_{10} in 24 h mean during the rainy season (Table 4).

Except for that of Klang, the *p*-values obtained were more than 0.05 for the other stations, which means there is no significant relationship between MODIS AOT and PM_{10} mass in the rainy season (Table 4). Nonlinear correlation coefficients (NLCC) with polynomial equation were used to analyze the correlations between MODIS AOT statistics and PM_{10} in 24 h mean.

Table 4. LCC and NLCC between WS in (5 × 5) pixels of MODIS AOT and 24 h mean of PM_{10} (µg m^{-3}) mass for the rainy season in eight AQMS in Klang Valley.

Station name	No. of points	*p*-value	LCC	NLCC
Gombak	27	0.305	< 0.10	0.11
Klang	10	0.010	0.58	0.76
Victoria K.L	7	0.514	< 0.10	0.10
Petaling Jaya	14	0.314	< 0.10	0.21
Kajang	9	0.744	< 0.10	< 0.10
Shah Alam	11	0.434	< 0.10	< 0.10
Putra Jaya	5	0.625	< 0.10	0.56
Cheras K.L	14	0.323	< 0.10	0.17

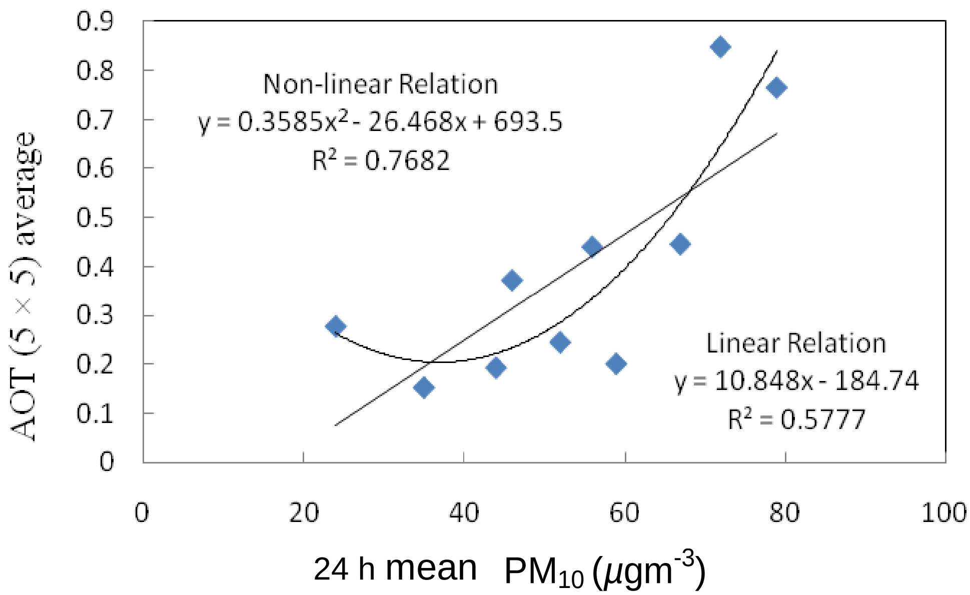

Figure 4. Correlation coefficient between MODIS AOT in (5 × 5) pixels and 24 h mean PM_{10} in the rainy season using linear and nonlinear analysis in Klang.

NLCC values obtained for Kajang and Shah Alam were indicated the same LCC. NLCC values at the other stations were acquired more than LCC values. High NLCC and LCC values were observed for Klang (Figure 4). However, LCC was reliable for Klang, but the NLCC value was obtained more than LCC.

DISCUSSION

The LCC range for this WS and PM_{10} in 24-hourly mean was observed to be 0.13 in Petaling Jaya and 0.51 in Shah Alam. The lowest amount of AOT data was obtained in the (3 × 3) pixels WS among the three sizes (Table 1). Reportedly, the LCC range between average of MODIS AOT in the (5 × 5) pixels and real-time of PM_{10} was lower than 0.1 in Klang and 0.39 in Putra Jaya. Further, the LCC range for this WS and PM_{10} in 24 h mean was 0.14 in Gombak and 0.5 in Victoria K.L. The LCC values between the average of AOT in the (7 × 7) pixels and PM_{10} in 24 h mean in the stations were close to each other. For example, in Petaling Jaya, Kajang and Shah Alam the LCC values were 0.38 (Table 1). The same AOT result in the (7 × 7) pixels may be due to the short distance between the ground stations. Although, no significant differences were observed between the results of the three WSs, the results showed that for annual statistics validation between MODIS AOT and PM_{10} mass, the (5 × 5) pixels was the best alternative. The (3 × 3) pixels with a dimension of (30 × 30) km correspond with a small statistical sample and may cause limitation to distribution investigation of PM_{10} values in larger areas.

The (7×7) pixels group is a big WS. The pixels in big WSs are used in the averaging process of AOT for all ground stations creating the same average of AOT value or AOT value with minor differences (Table 2). No significant differences were found in results of analysis between real-time and 24 h mean PM_{10} with MODIS AOT in (5×5) pixels. But in most cases (that is, five stations) the LCC values for PM_{10} in 24 h mean were higher than PM_{10} real-time analysis; then, 24 h mean PM_{10} seems to be a better choice to describe the relationship between MODIS AOT in (5×5) pixels and PM_{10} mass in Klang Valley. MODIS AOTs are strongly correlated with PM_{10} in the dry season compared with the rainy season. Except for the values observed for Gombak and Putra Jaya, the LCC values for other areas turned out to be more than 0.4 in the dry season (Table 3). The high values of LCC in the dry season may be due to high amount of PM_{10} in the dry season in comparison with the rainy season. It can be concluded that the LCC values between PM_{10} mass and MODIS AOT are high when air quality is poor and vice versa. In Klang Valley, some reasons such as transportation of haze from forest fire Sumatra (Keywood et al., 2003), seasonal variations 'El Niño' modulations, and regional low level winds cause to aggravate poor air quality conditions during the dry season. On the other hand, cloud cover in the rainy season may transport the gases and PM from the mixing layer to free troposphere. This could redistribute aerosols in the troposphere, and subsequently decrease air pollution in the rainy season. Swelling hygroscopic particles or condensation of hydrophobic particles due to moisture in the rainy season is another reason for large differences between the measurements recorded by the ground stations as compared to those recorded by the satellite.

Conclusions

This study analyzed the PM_{10} data collected by eight AQMS over Klang Valley. The PM pollution in the dry season was observed to be higher than in the rainy season. Two ranges of ground based PM_{10} concentrations and three different MODIS AOT WSs were analyzed to find the best correlation coefficient from 2004 to 2006. The LCC and NLCC analyses were utilized to better describe the correlation coefficient between these data in the rainy season. In the case of the (3×3) pixels of MODIS AOT, only a small statistical sample size was available. This could cause limitation in investigating the distribution of PM_{10} values in large areas. The (7×7) pixels created the same average of AOT value which was due to using the same pixels in averaging process of AOT for all the ground stations. In (5×5) pixels good statistical sample and also different AOT were found due to different PM_{10} masses at ground. In most of the cases, the LCC values between MODIS AOT in the (5×5) pixel group and 24 h mean PM_{10} were reportedly higher than real-time PM_{10} analysis. NLCC values were higher than LCC values in the rainy season. It could be concluded that the LCC analysis is recommended to acquire correlation coefficient between MODIS AOT and PM_{10} mass in the dry season, while NLCC is advisable for analysis in the rainy season. MODIS AOT in the (5×5) pixels is able to recognize the region and distribution of SPM over a large scale of tropical area.

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