Thai Environmental Engineering Journal Vol. 35 No. 3 (2021) : 1-11
www.eeat.or.th

Estimating Particulate Matter Concentrations in Central Thailand Using Satellite Data

Pichawan Phuengsamran and Pichnaree Lalitaporn*
Department of Environmental Engineering, Faculty of Engineering,
Kasetsart University, Bangkok 10900, Thailand
*E-mail : pichawan.p@ku.th, fengprla@ku.ac.th

Abstract

In this study, regression models were developed for estimating ground level particulates matter with aerodynamic diameter less than 10 micrometres (PM_{10}) and particulate matter with diameter of less than 2.5 micrometres ($PM_{2.5}$) concentrations by using satellite aerosol optical depths (AODs) data over central Thailand. Satellite data in this study were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on Terra platform with 3×3 km^2 and 10×10 km^2 resolution products. Daily satellite AODs and ground particulate matter data in Thailand were collected over 10 years from January 2008 to December 2018. The results of the study showed that the highest level of PM_{10} and $PM_{2.5}$ concentrations generally presented from November to April. The study also showed that meteorological parameters including temperature (T), relative humidity (RH), wind speed (WS) and boundary layer height (BLH) affected particulate matter concentrations. The comparison between satellite products presented that 10×10 km^2 product gave better correlations with PM_{10} and $PM_{2.5}$ compared to 3×3 km^2 product. Multiple linear regression models were developed to estimate particulate matter concentrations using AODs and meteorological data. The models gave coefficient of determination (R^2) of 0.26-0.65 with root mean square error (RMSE) of 15.90-45.90 $\mu g/m^3$ for PM_{10} and R^2 of 0.16-0.50 of with RMSE of 14.00-51.26 $\mu g/m^3$ for $PM_{2.5}$.

Keywords : PM_{10}; $PM_{2.5}$; MODIS-AODs; Regression model; Boundary layer height

Introduction

At present, Thailand's economy and industry have developed. By using various technologies, it is possible to help labour skills in the industrial sector to develop Thailand's 4.0 value-based economy, leading to sustainable development. When developing industrial sectors, an increased release of waste and pollution follows. There are two major sources of air pollution in the atmosphere: natural and those generated by human activity [1].

Air quality monitoring in Thailand is currently done by a total of 61 air quality monitoring stations that collect air quality data from the ground with accuracy and precision. Most of the locations are in urban regions that have heavy traffic and industrial areas. They do not cover the entire central region of Thailand. Therefore, the measured air pollution value does not cover all areas.

Particulates matter with aerodynamic diameter less than 10 μm (PM_{10}) and particulates matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) is a complex mixture of various gases and particulate components mainly derived from human activities (transportation, industry, waste burning, and power plant emissions) that cause emissions [2, 3]. Epidemiological studies have shown that long-term (year and month) and short-term (day and hour) exposure to PM_{10} and $PM_{2.5}$ can lead to adverse effects on human health increase in the long-term risk of cardiopulmonary [4, 5].

The current AODs products for ground PM_{10} and $PM_{2.5}$ estimation are mainly from MODIS [6-9] is located onboard two satellite platforms (Aqua and Terra), which differ in their overpass time (∼3 h apart) [10]. MODIS is a scanning radiometer flying as a facility instrument on Terra satellites. It records data electromagnetically once per day at around 10.30 a.m. local time for Terra satellites and 1.30 p.m. for Aqua satellites [11].

For the application of MODIS products, previous studied [11] air quality over south-eastern Italy, collected over three years (2006-2008). A first assessment of the regression relationship was carried out between daily average. PM_{10} mass concentrations and MODIS-AODs show that linear correlation coefficients (R) vary within the 0.20–0.35 range and are affected by sampling year and site location. The PM_{10}-AODs correlation becomes stronger ($0.34 \leq R \leq 0.57$) when the analysis is restricted to clear-sky MODIS measurements. Koelemeijer et al. [12] also explored the relation between MODIS-AODs and particulate matter (both PM_{10} and $PM_{2.5}$) in Europe. They found that R-values between AODs and 24 hour-average PM_{10} and $PM_{2.5}$ mass concentrations varied within the 0.15–0.35 and 0.18–0.27 range, respectively. [13] Estimating daily PM_{10} and $PM_{2.5}$ in Israel period 2005-2015 using a spatiotemporal hybrid modelling approach it was found that in certain urban areas the measured and estimated PM_{10} and $PM_{2.5}$ concentrations during the satellite overpass (Terra or Aqua) were higher than the mean daily PM_{10} and $PM_{2.5}$. The model performed well showing cross-validated R^2 that ranged between 0.82 and 0.92.

The specific objectives of this research are to determine the relationship of satellite AODs (3×3 km^2 and 10×10 km^2) versus ground PM_{10} and $PM_{2.5}$ concentrations in the central region of Thailand and to develop models for estimating PM_{10} and $PM_{2.5}$ concentrations.

Methodology

Study area

The study area was central Thailand covering 17 provinces, the population in the central region of Thailand was approximately 22.5 million as of 2019 data [14] in an area of 685,400 km² [15]. Thailand is located between vast areas of land and water; therefore it is impacted by both the summer and the winter monsoons. As a result, Thailand's weather consists of six months of rainfalls during the wet season (mid-May to mid-October) and six months of dry season (mid-October to mid-May).

Ground monitoring data

The ground level particulate matter monitors in central Thailand are distributed mainly in the major industrial cities (Bangkok, Saraburi, Samut Prakan). The locations of all monitoring stations are presented in Figure 1. Ten years (January 2008 – December 2018) of daily average PM_{10} and $PM_{2.5}$ observed data from 26 stations in the central region of Thailand were acquired from the Pollution Control Department (PCD). The measurements are performed using tapered-element oscillating microbalance (TEOM) and beta ray attenuation. Meteorological parameters: RH, T, and WS from PCD were also collected from the 26 PCD stations as hourly data from 2008 to 2018 to investigate the effects of these parameters on pollutant concentrations. One-hour ground PM_{10} and $PM_{2.5}$ concentrations data from 10.00-11.00 a.m. covering satellite over past time (10.30 a.m.) were compared with AODs from MODIS aboard Terra satellites data both at 3×3 km² and 10×10 km².

Boundary layer height was obtained from modelled data of the European Centre for Medium-Range Weather Forecasts (ECMWF) at a spatial resolution of approximately 13.9 km and temporal resolution of 3-hours. In each day the corresponding BLH measurement (daily mean or measurement around Terra/Aqua overpass) was assigned to the 0.25°×0.25° grid cells. They were used to improve satellite and ground PM_{10} and $PM_{2.5}$ relationships.

Satellite data

The AODs measure light extinction at given wavelengths due to aerosol and gaseous compounds scattering absorption along the measured atmospheric column, therefore making it useful for estimating PM_{10} and $PM_{2.5}$ concentrations. The AODs product is available from several algorithms of the MODIS sensor onboard the two satellite platforms (Terra and Aqua). In this study, we used MODIS-AODs data from Terra satellites, scientific dataset Optical_Depth_Land_And_Ocean and retrieval algorithm at 550 nm wavelength. The satellite-derived MOD04_3K (3×3 km² spatial resolution) and MOD04_L2 (10×10 km² spatial resolution) are the MODIS level-2 atmospheric aerosol product. They were obtained from the Level-2 and Atmosphere Archive & Distribution System Distributed Active Archive Center (LAADS DAAC) NASA from January 2008 to December 2018. Terra was launched on 18 December 1999 [16-18]. For the study area, Terra has satellite overpass local time in the morning of approximately 10.30 local time.

Comparison of satellite and ground data

Seven of 0.25°×0.25° grid boxes were set around the 26 PCD stations over central Thailand. The details and illustration of the locations are presented in Figure 1 and Table 1, respectively. The comparison between satellite and ground data in this study was not straightforward satellite data are monitoring at a single time (10.30 a.m. at the local time) whereas ground data are time (hourly averaged) when the satellite was overpassing the study area [19]. Therefore, 1-h average concentrations of ground PM_{10} and $PM_{2.5}$ obtained from hourly PCD data were calculated from 10.00-11.00 local time corresponding to the Terra overpass times, for comparison with satellite data. Meteorological parameters (RH, T, WS and BLH) were also processed using the same method as the ground pollutant data to investigate the effect of these parameters on the pollutant levels.

Table 1 Locations of ground-level monitoring stations in this study

Satellite grid box 0.125°×0.125°			**Ground monitoring station**				
Box	Latitude (north)	Longitude (east)	ID	Station Name	Province	Latitude (north)	Longitude (east)
1	13.91-14.16	99.40-99.65	1	Kanchanaburi Meteorological Station	Kanchanaburi	14.02	99.54
2	13.41-13.66	99.68-99.93	2	Regional Environment office 8th	Ratchaburi	13.53	99.81
3	14.49-14.74	100.79-101.04	3	Na Phralan Police Station	Saraburi	14.69	100.87
			4	Phra Lak Fire Station	Saraburi	14.53	100.93
4	14.23-14.48	100.43-100.68	5	Ayutthaya Wittayalai School	Ayutthaya	14.35	100.57
5	13.68-13.93	100.43-100.68	6	Bangkok University Rangsit campus	Pathum Thani	14.04	100.61
			7	Sukhothai Thammathirat Open University	Nonthaburi	13.91	100.54
6	13.68-13.93	100.43-100.68	8	Electricity Generating Authority of Thailand	Nonthaburi	13.81	100.51
			9	The Government Public Relations Department	Bangkok	13.78	100.54
			10	Bansomdejchaopraya Rajabhat University	Bangkok	13.73	100.49
			11	Thai Meteorological Department	Bangkok	13.67	100.61
			12	Bodindecha (Sing Singhaseni) School	Bangkok	13.77	100.61
			13	Klong Jan Housing Authority	Bangkok	13.78	100.65
			14	Huai Khwang Housing Authority	Bangkok	13.78	100.57
			15	Nonsi Witthaya School	Bangkok	13.71	100.55
			16	King Chulalongkorn Memorial Hospital	Bangkok	13.73	100.54
			17	Thonburi Power Sub-Station	Bangkok	13.73	100.49
			18	Chokchai Police Station	Bangkok	13.80	100.59
			19	Din Daeng Housing Authority	Bangkok	13.76	100.55
			20	Phra Pradaeng Crippled Songkro Place	Samut Prakan	13.66	100.54
			21	South Bangkok Power Plant	Samut Prakan	13.62	100.56
			22	Residence for Dept. of Mineral Resources	Samut Prakan	13.65	100.53
			23	Samut Prakan City Hall	Samut Prakan	13.60	100.60
7	13.56-14.06	100.31-100.81	24	Highway NO.3902 km.13+600	Bangkok	13.64	100.41
			25	Samut Sakhon Hightway District	Samut Sakhon	13.71	100.32
			26	Samut Sakhon Wittayalai School	Samut Sakhon	13.55	100.26

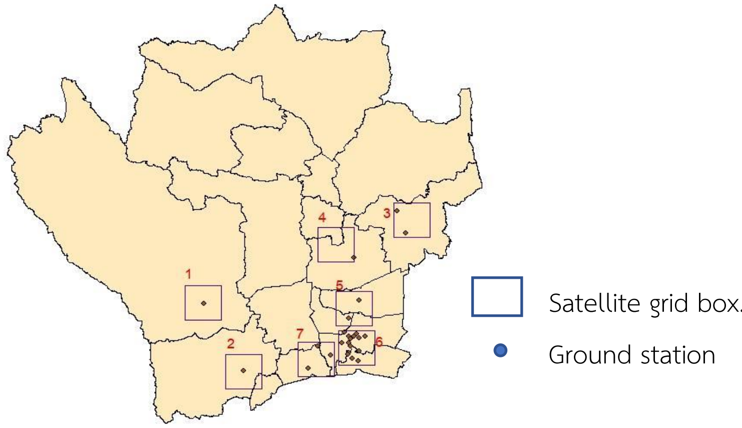


Figure 1 Location of PM measuring sites in central Thailand

Model development and validation

In this study, we developed model for the multiple linear regression (MLR) applied to estimate PM_{10} and $PM_{2.5}$ concentrations by using MODIS AODs and meteorological data based on 10-years period. Meteorological data is an important tool in the field of air pollution research. Individual parameters such as RH, T, WS, and BLH affect PM_{10} and $PM_{2.5}$ transport process, but an individual parameter is not solely responsible for the spread and dispersion of PM_{10} and $PM_{2.5}$ [20]. The relationships of AODs, particulate matter (PM_{10} and $PM_{2.5}$) concentrations and meteorological data were statistically analysed by multiple linear regression with an IBM SPSS statistics at the 0.05 confidence level. These models were compared for the accuracy of ground data estimation. The models were validated using 2019 datasets of AODs, particulate matter and meteorological parameters.

Results and Discussion

Time series

Time series of satellite AODs and ground PM_{10} and $PM_{2.5}$ data were offer for 10 years as shown in Figure 2 from 2008-2018 over central Thailand. The satellite AODs data of both 3×3 km² and 10×10 km² products showed the same trend particulate matter concentrations. The high levels of ground PM_{10} and $PM_{2.5}$ concentrations and AODs presented during the dry season of every year, from November to April, which is due to less rainfall during this period. The low levels of ground data and AODs presented during the wet season from June to August. These results are similar to previous studies in Thailand [21]. Figure 3 shows the series of monthly satellites AODs and ground particulate matter in central Thailand. AODs levels were significantly higher in March, while particulate matter concentrations were higher from November to February. These results are similar to previous studies in central Thailand [22]. It was found that the air mass transported into the central region from the north at various altitudes, both from neighbouring countries and the Gulf of Thailand, as well as the air mass transported from the north of Thailand, which passed the area with high burning activities during March, caused high dust aloft in the atmosphere. However, particulate matter ground measurement is normally restricted to surface layer or boundary layer height (BHL). Therefore, satellites that can detect AODs values at all vertical altitudes provide higher AODs values during March, but the ground monitoring stations cannot detect particulate matter values at a high altitude.

If the temperature rises, particulate matter concentrations trends to decrease. High temperatures will cause the air to rise. The air in a lower temperature area will flow in instead, causing wind and reducing particulate matter. For the relationship between particulate matter concentrations and relative humidity, it was found that the particulate matter would be reduced if the relative humidity was high. Due to high water vapor in the atmosphere, the dust absorbs the water vapor until it is saturated. Subsequently, the dust falls back into the ground, resulting in lower particulate matter values as well [23].

Correlation of ground and satellite data

Figure 4 (a-d) presents scattering plots of PCD PM_{10} and $PM_{2.5}$ versus AODs of satellites with the local time in the morning for Box 1. The results indicated that the correlation coefficients (R) of 10×10 km² AODs with PM_{10} (R= 0.581) and $PM_{2.5}$ (R = 0.553) were slightly higher than 3×3 km² product AODs. Table 2 shows the correlation of ground and satellite data for Box 1-7 R-values of AODs and particulate matter concentrations of 10×10 km² product higher than 3×3 km² product. A previous study in China by He et al. [24] also explains that the 3×3 km² product for China generally performs slightly worse than the 10×10 km² product.

Model development

Referring to the previous study by Dinoi et al., the relation between ground PM_{10} and $PM_{2.5}$ concentrations and AODs is expected to depend on meteorological condition data which has an effect on change in ground particulate matter concentrations [25].

Multiple linear regression models were developed using AODs data and meteorological data to estimate ground PM_{10} and $PM_{2.5}$ concentrations in central Thailand. Hourly ground data during 10.00-11.00 from 2008-2018 were used to develop the models. Since 10×10 km² product of AODs was correlated better with ground PM_{10} and $PM_{2.5}$ than 3×3 km² AODs, 10×10 km² product were used for the models. All data from 7 boxes were used to develop models for PM_{10} and $PM_{2.5}$. Table 3 shows that the model results were highly significant ($p<0.05$). The analysis BLH had hardly significance on ground particulate matter concentrations. When RH, T and WS decreases, ground particulate matter concentrations increase.

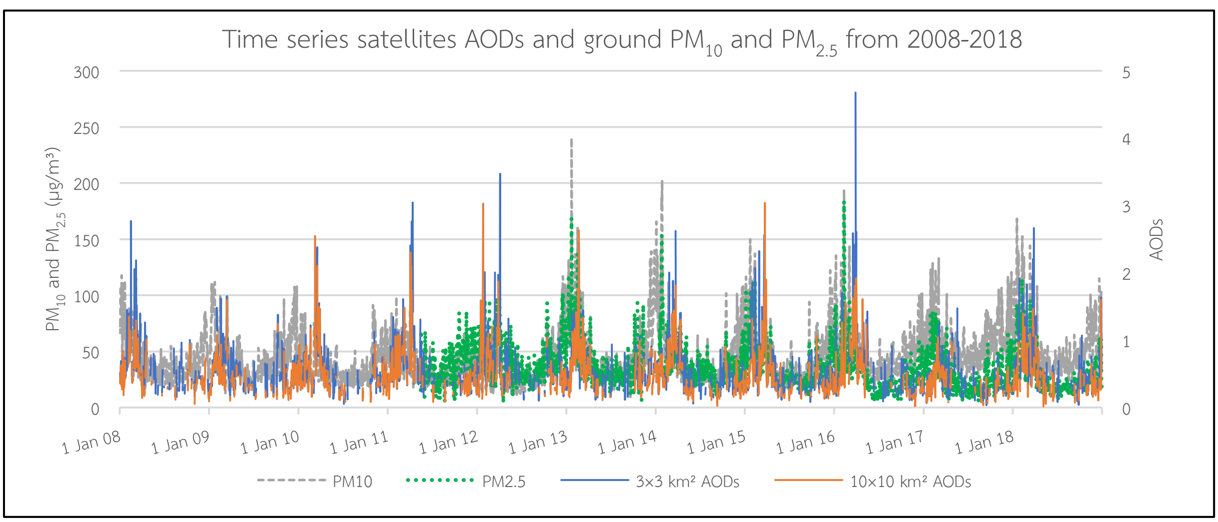


Figure 2 Time series of satellite AODs and ground particulate matter concentrations from 2008-2018 over central Thailand

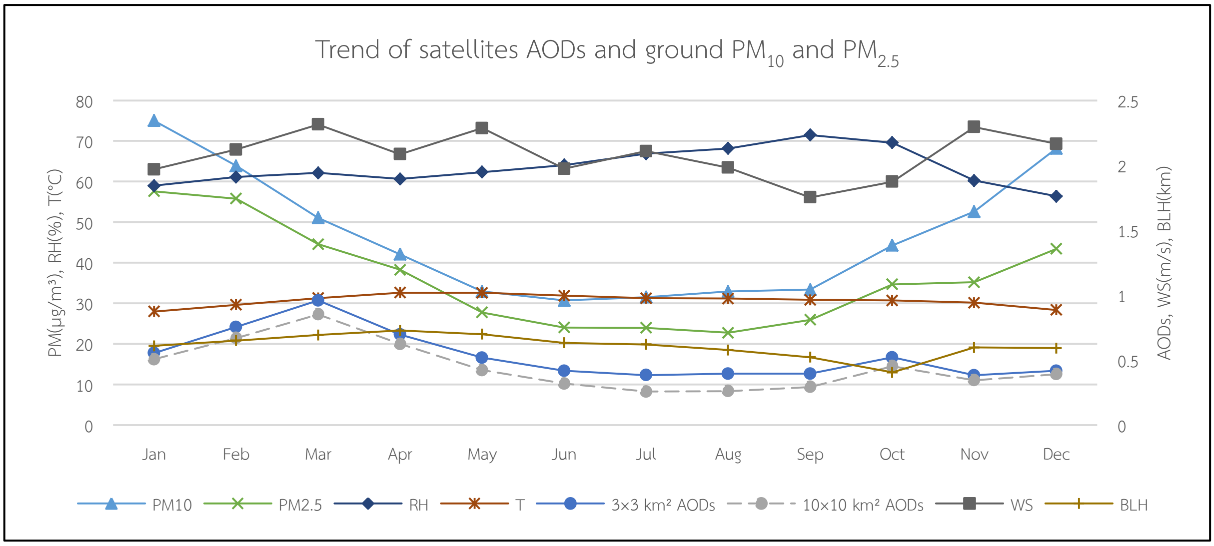


Figure 3 Trend of satellites AODs and ground particulate matter concentrations from 2008-2018 over the central of Thailand

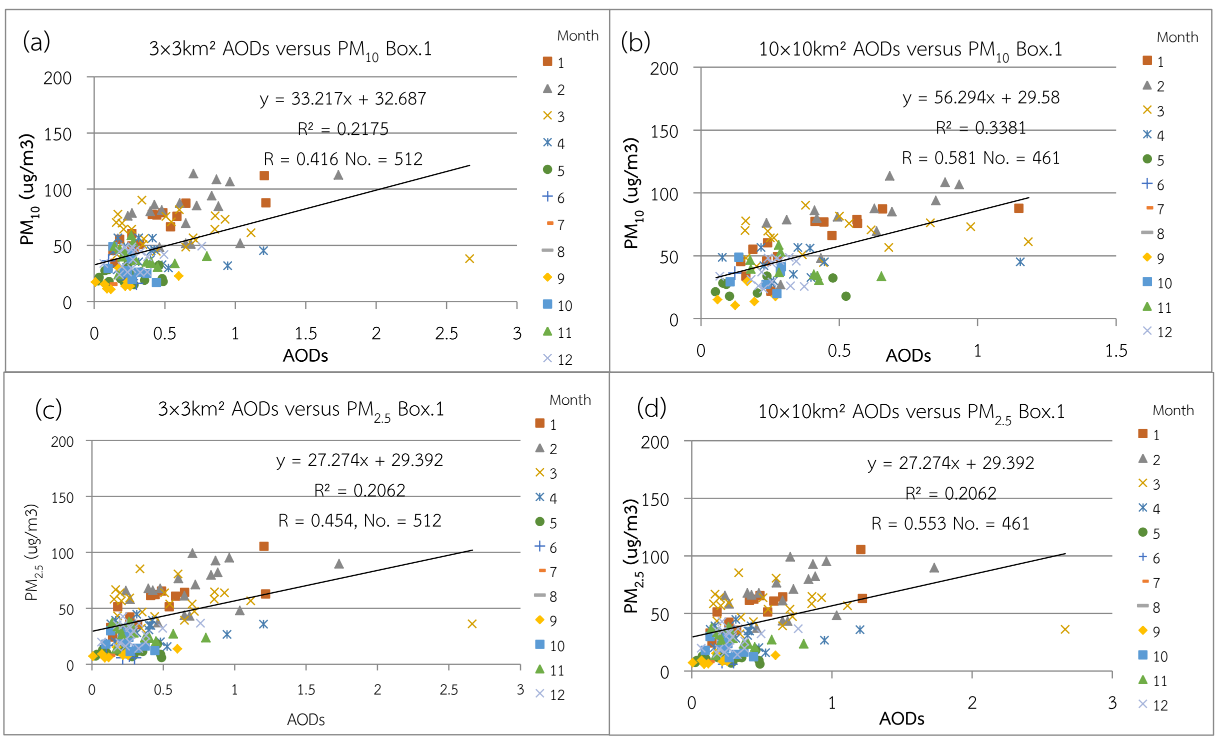


Figure 4 Scattering plots of PM_{10} and $PM_{2.5}$ versus AODs (a) PM_{10} and 3x3km²AODs, (b) PM_{10} and 10x10km²AODs, (c) $PM_{2.5}$ and 3x3km²AODs (d) $PM_{2.5}$ and 10x10km²AODs

Table 2 Correlation of ground and satellite data

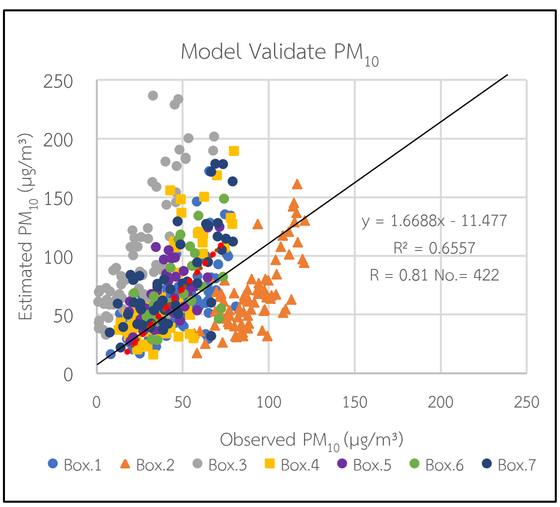
	3x3 km² AODs-PM_{10}			10x10 km²AODs-PM_{10}			3x3 km²AODs-$PM_{2.5}$			10x10 km²AODs-$PM_{2.5}$		
	R	R^2	No.	R	R^2	No.	R	R^2	No.	R	R^2	No.
Box.1	0.47	0.22	512	**0.58**	**0.34**	461	0.45	0.21	512	**0.55**	**0.31**	461
Box.2	0.34	0.11	2285	**0.34**	**0.11**	2285	0.36	0.13	2241	**0.36**	**0.13**	2241
Box.3	0.01	0.00	5661	**0.02**	**0.00**	5011	0.28	0.08	2998	**0.31**	**0.09**	2592
Box.4	0.21	0.04	4991	**0.25**	**0.06**	4393	0.20	0.04	146	**0.42**	**0.17**	130
Box.5	0.16	0.03	4846	**0.28**	**0.08**	3545	**0.43**	**0.18**	116	0.36	0.13	104
Box.6	0.18	0.03	5083	**0.26**	**0.07**	4629	0.13	0.02	3309	**0.24**	**0.06**	2981
Box.7	0.16	0.03	5129	**0.24**	**0.06**	4597	0.40	0.16	432	**0.50**	**0.25**	287
Box.1-7	0.19	0.03	6493	**0.23**	**0.05**	5860	0.33	0.11	5153	**0.33**	**0.11**	4520

Table 3 Multiple linear regression model of AODs and particulate matter included meteorological factors

Regression model	No.	R	R²	p-value
PM_{10}= 258.758 + 22.867(AODs) – 1.026(RH) -5.046(T) – 12.294(WS) – 0.002(BLH)	1844	0.68	0.46	0.017
$PM_{2.5}$= 140.505 + 25.783(AODs) – 0.646(RH) -2.237(T) – 1.895(WS)	1184	0.52	0.27	0.005

Model validation

The regression models were validated with observed hourly PM_{10} and $PM_{2.5}$ during January 2019 to June 2019. Table 4 presents the validation by R-values between observed hourly PM_{10} and $PM_{2.5}$ versus estimated PM_{10} and $PM_{2.5}$ from models (R-values = 0.51-0.81 of PM_{10} and R-values = 0.40-0.71 of $PM_{2.5}$), which can be explained by approximately 26-65% of PM_{10} and 16-50% of $PM_{2.5}$. Figure 5 shows that PM_{10} and $PM_{2.5}$ estimated by the model and observed results were similar trends. The R-values of modeled box 1-7 validated with observed data in the central region are 0.81 for PM_{10} and 0.70 for $PM_{2.5}$. For PM_{10} it is observed to be higher than estimated. On the other hand, $PM_{2.5}$ is observed to be lower than estimated. Overall, the PM_{10} model provides higher R-values than the $PM_{2.5}$ model. The overall RMSE was valued at 15.90-45.90 µg/m³ of PM_{10} and 14.00-51.26 µg/m³ of $PM_{2.5}$. The results showed that regression models seven boxes together could be used to estimate the amount of ground particulate matter concentrations for central Thailand.



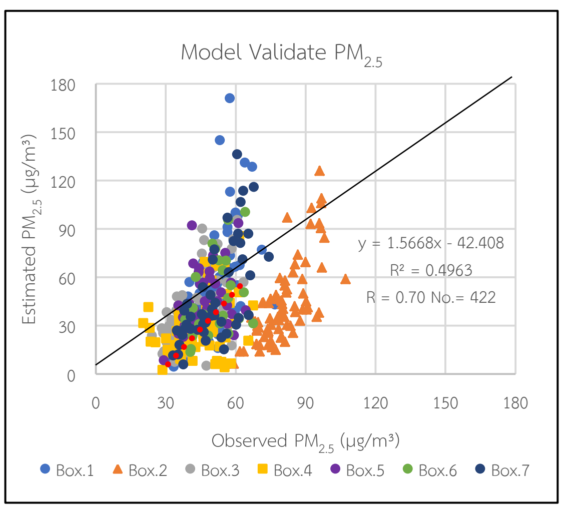


Figure 5 Observed and estimated PM_{10} and $PM_{2.5}$ in central Thailand from January 2019 to June 2019

Table 4 Model validation performances estimation of PM_{10} and $PM_{2.5}$

		PM_{10}			$PM_{2.5}$		
Box.	No.	R^2	R	RMSE	R^2	R	RMSE
No.1	84	0.37	0.61	22.52	0.42	0.65	23.76
No.2	78	0.50	0.71	22.38	0.50	0.71	18.58
No.3	71	0.61	0.78	45.90	0.36	0.60	19.64
No.4	68	0.56	0.75	30.90	0.17	0.41	17.68
No.5	44	0.39	0.63	22.40	0.16	0.40	51.26
No.6	26	0.26	0.51	28.65	0.19	0.44	22.64
No.7	51	0.50	0.71	42.95	0.46	0.68	26.90
No.1-7	422	0.65	0.81	15.90	0.49	0.70	14.00

*RMSE is estimated as the root mean squared differences between predicted and measured PM_{10} and $PM_{2.5}$ concentrations (μg/m³).

Conclusion

In this study, MODIS-AODs data were used to observe the trend of PM_{10} and $PM_{2.5}$ in central Thailand from 2008-2018 and develop a mathematics model with AODs and meteorological data, including temperature, relative humidity, wind speed and boundary layer height. High levels of AODs and ground PM_{10} and $PM_{2.5}$ concentrations were observed during the period from November to April. When relative humidity, temperature, and wind speed decreased, PM_{10} and $PM_{2.5}$ increased. The assessment results showed that the MODIS-AODs model, combining with other meteorological factors, could be applied to estimate PM_{10} and $PM_{2.5}$ concentrations. The models can explain approximately 26-65% of PM_{10} and 16-50% of $PM_{2.5}$. The RMSE is valued at 15.90-45.90 μg/m³ of PM_{10} and 14.00-51.26 μg/m³ of $PM_{2.5}$. For further study, validity should be investigated for other factors (such as the number of transportations and industrial plants) that should be applied in the models.

Acknowledgments

This research was supported by the Department of Environmental Engineering, Kasetsart University. The authors would like to thank NASA for providing the satellite data in LAADS, particulate matter ground data and data prepared by the Thailand Pollution Control Department (PCD). Thanks also to the Thai Meteorological Department for meteorological data, which was necessary to develop the model for this study, including boundary layer height from the European Center for Medium-Range Weather Forecasts (ECMWF).

References

[1] Samuel. 1973. Fundamentals of air pollution. Addison-Wesley Publishing Comp. (New York University): 107-111.

[2] Xinpeng, W., Wenbin S., Kangning Z., Xiangyu R., Peiwen H. 2019. Estimating hourly PM2.5 concentrations using MODIS 3km AOD and an improved spatiotemporal model over

Beijing-Tianjin-Hebei, China. Atmos. Environ. (2019).

[3] Kloog, I., Chudnovsky, A. A., Just, A. C., Nordio, F., Koutrakis, P., Coull, B. A., Lyapustin, A., Wang, Y. and Schwartz, J. 2014. A new hybrid spatio-temporal model for estimating daily multi-year PM2.5 concentrations across northeastern USA using high resolution aerosol optical depth data. Atmos. Environ. 95: 581-590.

[4] Crouse, D. L., Peters, P. A., Van, D. A., Goldberg, M. S., Villeneuve, P. J., Brion, O., Khan, S., Atari, D. O., Jerrett, M. and Pope, C. A. 2012. Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: a Canadian national-level cohort study. Environ Health Perspect 120: 708-714.

[5] Xie, Y., Wang, Y., Zhang, K., Dong, W., Lv, B. and Bai, Y. 2015. Daily estimation of ground-level PM2.5 concentrations over Beijing using 3 km resolution MODIS AOD. Environ. Sci. Technol. 49: 12280-12288.

[6] Chen, G., Li, S., Knibbs, L. D., Hamm, N. A. S., Cao, W., Li, T., Guo, J., Ren, H., Abramson, M. J. and Guo, Y. 2018. A machine learning method to estimate PM2.5 concentrations across China with remote sensing, meteorological and land use information. Sci. Total Environ. 636: 52-60.

[7] Hu, X., Waller, L. A., Al-Hamdan, M. Z., Crosson, W. L., Estes Jr, M. G., Estes, S.M., Quattrochi, D. A., Sarnat, J. A. and Liu, Y. 2013. Estimating ground-level PM2. 5 concentrations in the southeastern US using geographically weighted regression. Environ. Res. 121: 1-10.

[8] Ma, Z., Hu, X., Huang, L., Bi, J. and Liu, Y. 2014. Estimating ground-level PM2.5 in China using satellite remote sensing. Environ. Sci. Technol. 48: 7436-7444.

[9] Wei, Y., Li, Z., Zhang, Y., Chen, C., Xie, Y., Lv, Y., & Dubovik, O. 2021. Derivation of PM10 mass concentration from advanced satellite retrieval products based on a semi-empirical physical approach. Remote Sensing of Environment, 256, 112319.

[10] Kumar, N., Chu, A., Foster, A. 2007. An empirical relationship between PM2.5 and aerosol optical depth in Delhi Metropolitan. Atmospheric Environment. 41(21): 4492-4503.

[11] Adelaide D., Maria R.P., Pasquale B., Application of MODIS Products for Air Quality Studies Over Southeastern Italy. Remote Sensing (2010): 1767-1796.

[12] Koelemeijer, R.B.A.; Homan, C.D.; Matthijsen, J. Comparison of spatial and temporal variations of aerosol optical thickness and particulate matter in Europe. Atmos. Environ. 2006, 40: 5304-5315.

[13] Shtein, A., Karnieli, A., Katra, I., et.al. Estimating daily and intra-daily PM10 and PM2.5 in Israel using a spatiotemporal hybrid modeling approach. Atmospheric Environment. 191(2018): 142-152.

[14] The Bureau of Registration Administration. 2019. Population data. Retrived Feb 10, 2021 from https://bps.moph.go.th/new_bps.

[15] Office of the National Economic and Social Development Council 2019 Central and Bangkok Area Development Plan 2017 to 2022. Retrived Feb 10, 2021 from https://www.nesdc.go.th/

[16] Papadimas, C.D., Hatzianastassiou, N., Mihalopoulos, N., Kanakidou, M., Katsoulis, B.D., Vardavas, I., 2009. Assessment of the MODIS Collections C005 and C004 aerosol optical depth products over the

Mediterranean basin. Atmos. Chem. Phys. 9: 2987-2999.

[17] You, W., Zang, Z., Zhang, L., Zhang, M., Pan, X., Li, Y. 2016. A nonlinear model for estimating ground-level PM10 concentration in Xi'an using MODIS aerosol optical depth retrieval. Atmos. Res. 168: 169-179.

[18] Zeeshan, M., & Kim Oanh, N. T. 2014. Assessment of the relationship between satellite AOD and ground PM10 measurement data considering synoptic meteorological patterns and Lidar data. Science of the Total Environment, 473-474: 609-618.

[19] Lalitaporn, P., Mekaumnuaychai, T., 2020. Satellite measurements of aerosol optical depth and carbon monoxide and comparison with ground data. Environ Monit Assess. (2020): 192-369.

[20] Anzel, de, Langea., Rebecca, M. Garland., Liesl, L. Dyson., Estimating particulate matter (PM) concentrations from a meteorological index for data-scarce regions: A pilot study. Atmospheric Pollution Research. 10(2019): 1553-1564.

[21] Wongkaewsakul, P., Lalitaporn, P., 2017. Satellite observed data of aerosol optical depths and fire hotpots over Thailand. M.E. Thesis, Kasetsart University.

[22] Mongkolphew, S., Lalitaporn, P., 2019. Assessment of the Relationship of Particulate Matter between Satellite and Ground based Measurements in Thailand. M.E. Thesis, Kasetsart University.

[23] Kwanma, P., Pukngam, S., Arunpraparu, W., 2019. Meteorological factors affecting concentration of pm10 at naphra lan sub-district, chaloem phra kiat district, Saraburi province. PSRU Journal of Science and Technology. 4(2): 85-94.

[24] He, Q., Zhang, M., Huang, B., Tong, X., MODIS 3 km and 10 km aerosol optical depth for China: Evaluation and comparison, Atmospheric Environment (2017).

[25] Zhang, H., Hoff, R. M., Engel-Cox, J. A. 2009. The relation between Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth and PM2.5 over the United States: a geographical comparison by U.S. Environmental Protection Agency regions. Journal of the Air & Waste Management Association. 59(11): 1359-1369.