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# PM2.5 modeling based on CALIPSO in Bangkok

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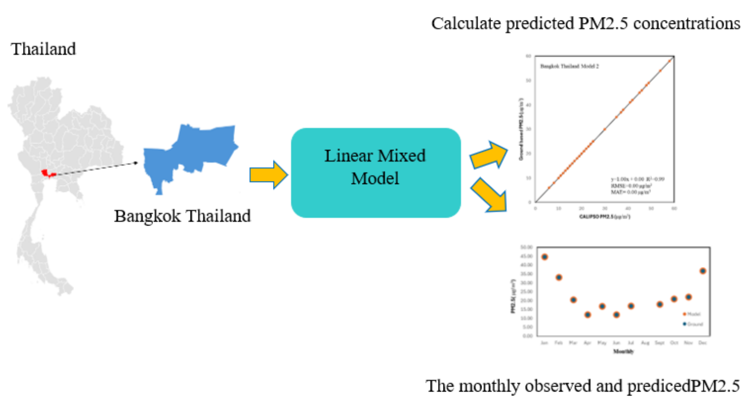
## Abstract

Air quality has become a severe issue in Bangkok, mainly due to PM2.5 (fine particulate matter with particle size less than 2.5 µm). Aerosol optical depth (AOD) obtained for active satellite data has been widely used to estimate PM2.5 near the ground. Nevertheless, passive satellite data are rarely used to estimate PM2.5 near the ground. In this study, a total AOD in troposphere data achieved from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) was used to determine PM2.5 with climate parameters (Temperature (TEM), relative humidity (RH), wind speed (WS), boundary layer height (BLH), and the normalized difference vegetation index (NDVI) using Linear Mixed Effect Method (LMEM). It was found that the coefficient ($R^2$) increases from model 1 (0.87) to model 6 (0.99), and the root mean square error (RMSE) reduces from 2.65 to 0.00 µg/m$^3$. The best model gives an $R^2$=0.99 (models 5 and 6). PM2.5 patterns between observed and predicted show similar representative patterns. Therefore, our study provides CALIPSO AOD data with a potentially helpful estimation of PM2.5.




**Keyword**: PM2.5; AOD; CALIPSO; Satellite data; Linear mixed effect



## 1. Introduction

Atmospheric aerosol has become a big issue in Bangkok, especially PM2.5, which substantially impacts the worldwide climate, environmental change, and human health [1 – 3]. PM2.5 warning and monitoring are essential for human protection. Nevertheless, due to a lack of budget, PM2.5 monitoring is limited and only covers some areas. A previous study confirmed that PM2.5 obtained from satellite AOD correlates well with ground-based data [4, 5]. Currently, many studies are focused on the PM2.5-AOD model achieved from satellite data such as the Moderate-resolution Imaging Spectroradiometer (MODIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), the Goddard Earth Observing System Data

(GEOS), and the geostationary meteorological satellite Himawari [6, 7].

PM2.5 models are obtained from various methods [8, 9]. Recent studies have focused on the variation in PM2.5 concentrations at the Earth's surface [1, 2]. A few studies have investigated PM2.5 only in the troposphere. CALIPSO satellite monitors atmospheric clouds and aerosols with a cloud-aerosol lidar with orthogonal polarization in a vertical column of high-resolution clouds and aerosols to resourcefully produce the cloud and the aerosol categories. Much of the current literature on aerosol models pays particular attention to using CALIPSO [10, 11].

Therefore, this work focused on estimating ground-based PM2.5 concentrations obtained from the CALIPSO AOD observation data with climate parameters, BLH, and NDVI using LMEM. Hourly PM2.5 concentrations from ground observation were addressed with PM2.5 concentrations obtained from the best models.

## 2. Materials and Methods

Bangkok (13.60 N, 100.60 E) is a populated and overcrowded city. In 2022, about 11 million people lived in about 1,570 km$^2$ along the Chao Phraya Delta.


**Fig. 1** Map of Bangkok

*AODs and PM2.5 data*

CALIPSO satellite was established to produce aerosol and cloud data in a vertical distribution at one depolarization and two scattering channels. The CALIPSO onboard instrument enhances the accuracy for estimating aerosol radiative effect and assessing clouds' feedback. AOD data obtained from CALIPSO were used daily level 2 data with 1 km x 1 km spatial resolution products downloaded from https://search.earthdata.nasa.gov/search. PM2.5 data were collected from department.

*Climate, NDVI, and BLH parameters*

TEM, WS, and BLH are obtained from the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) (a spatial resolution of 2.5 × 2.5). NDVI data (a spatial resolution of 1 km) were downloaded from https://search.earthdata.nasa.gov.

*Linear mixed effect method*

PM2.5 concentrations were retrieved by using the LMEM [12, 13], which is described in Equation (1). Data were separated into two groups: train (80%) and test (20%).

$$PM2.5 = (\beta_0 + \mu_0) + (\beta_1 + \mu_1) \times AOD + (\beta_2 + \mu_2)TEM + (\beta_3 + \mu_3)RH + (\beta_4 + \mu_4)WS + (\beta_{5+}\mu_5)BLH + (\beta_6 + \mu_6)NDVI + \varepsilon_r \quad (1)$$

where PM2.5 is a fine particular matter.

$\beta$ is the fixed intercept.

$\mu$ is the random intercept.

ε is the residual error.

AOD, TEM (°C), RH (%), WS (m/s), NDVI, and BLH (m) are the factors at Bangkok station. $\beta_1 \sim \beta_6$ are the fixed slopes and $\mu_1 \sim \mu_6$ are random slopes.

## 3. Results

*Descriptive statistics*

Ground-based PM2.5 concentrations were obtained from January 2017 to December 2021, Bangkok's seasons can be classified as summer (February to June), rainy (June to October), and winter (October to February). Average PM2.5 concentrations were high in winter months, reaching a peak in January at 48.00 µg/m$^3$. Low levels were found in summer months, reaching the lowest in April at 11.00 µg/m$^3$. AOD data range from 0.02 to 2.05 with an average of 0.47. Average meteorological factors are TEM, RH, and WS, which are 28.60°C, 63.38%, and 10.13 m/s, respectively. The averages of BLH and NDVI are 672.51 m and 0.38, respectively.

*MODIS AOD Validation*

As shown in Fig. 2, CALIPSO AODs have been compared to AERONET AOD and MODIS AOD data. CALIPSO AOD at 10 km products (a 1×1-pixel sampling area with 10×10 km$^2$) were compared to AERONET and MODIS AOD.

The results of comparing CALIPSO with AERONET AODs ($R^2$=0.41 , RMSE=0.33 µg/m$^3$, and MAE=0.07 µg/m$^3$) and CALIPSO with MODIS AODs ($R^2$=0.54, RMSE = 0.33 µg/m$^3$, and MAE=0.07 µg/m$^3$) are given a lower RMSE and MAE, respectively, implying tiny aerosol estimation uncertainty.

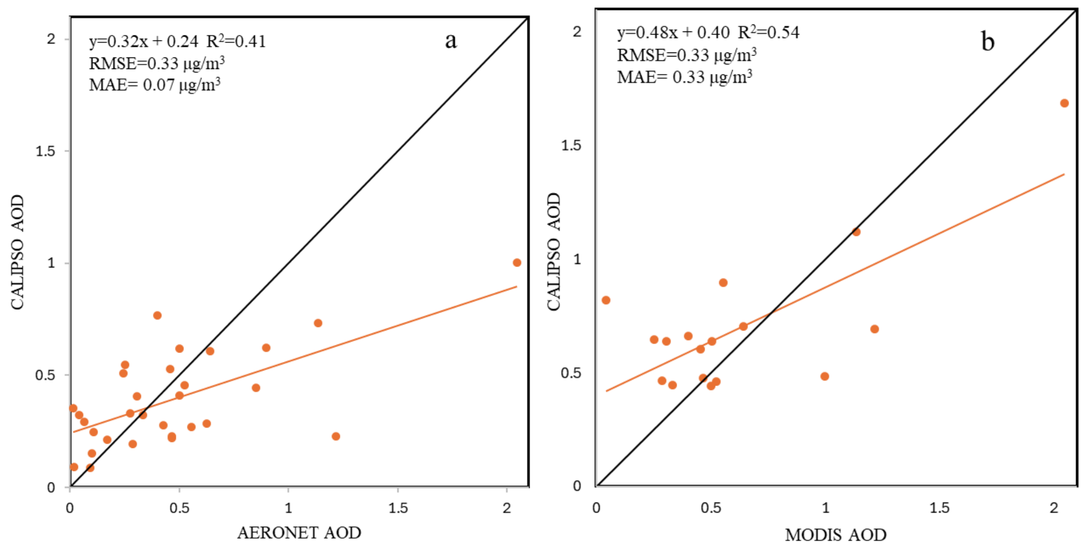



**Fig. 2** Comparing CALIPSO AODs with AERONET and MODIS AODs from 2017 – 2021

*PM2.5 model*

The LMEM was used in PM2.5 model with AOD, TEM, RH, WS, BLH, and NVDI. AOD is the most critical parameter because it implies how many aerosol particles are in a vertical column from the earth to the top atmosphere. The other factors were additional to improving the predictive capabilities of PM2.5. In addition, weather conditions are necessary for assessing because they influence PM2.5 concentrations near the ground [14 – 16]. All factors were included to the LMEM with significant level at α = 0.001, 0.01, and 0.05. Table 1 exhibits LMEM models. Table 1 shows the results using the 5$^{th}$ model compared with Model 1, $R^2$ significantly raises 15%, and RMSE falls 100 %. The best model is in the 5$^{th}$ and 6$^{th}$, giving an $R^2$ of 0.99 and an RMSE of 0.00 µg/m$^3$ (Table 2).

**Table 1** The fixed effect of the LMEM model was used to predict the ground-level PM2.5 concentrations collected from 2017-2021.

| Model | $\beta_{0(Intercept)}$ | $\beta_{1(AOD)}$ | $\beta_{2(RH)}$ | $\beta_{3(NDVI)}$ | $\beta_{4(WS)}$ | $\beta_{5(TEM)}$ | $\beta_{6(BLH)}$ | RMSE (μg/m$^3$) | MAE |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 17.76$^{***}$ | 15.92$^{*}$ | | | | | | 2.65 | 2.09 |
| 2 | 42.41$^{***}$ | 5.90 | -0.31$^{*}$ | | | | | 1.78 | 1.44 |
| 3 | 7.48 | 5.58 | -0.50$^{*}$ | 122.92 | | | | 1.51 | 1.22 |
| 4 | 1.47 | 5.89 | -0.49$^{*}$ | 133.98$^{*}$ | 0.11 | | | 1.50 | 1.25 |
| 5 | 72.69$^{***}$ | 11.53$^{*}$ | -0.60$^{***}$ | 135.39$^{***}$ | -0.23$^{***}$ | -2.25$^{***}$ | | 0.00 | 0.00 |
| 6 | 148.99$^{***}$ | 9.95. | -0.65$^{***}$ | 112.28$^{***}$ | -0.18$^{**}$ | -3.00$^{**}$ | -0.06 | 0.00 | 0.00 |

***independent parameter is significant at the α = 0.001 level
**independent parameter is significant at the α = 0.01 level
*Independent parameter is significant at the α = 0.05 level

**Table 2** PM2.5 concentrations (μg/m$^3$) is observed at Bangkok in Thailand.

| Model | PM2.5 | PM2.5$_{predicted}$ (μg/m$^3$) | Bias | $R^2$ | RMSE (μg/m$^3$) | MAE (μg/m$^3$) |
|---|---|---|---|---|---|---|
| 1 | | 26.77 | -1.15 | 0.87 | 2.65 | 2.09 |
| 2 | | 26.39 | -0.77 | 0.93 | 1.78 | 1.44 |
| 3 | 25.62 | 26.38 | -0.76 | 0.94 | 1.51 | 1.22 |
| 4 | | 26.42 | -0.08 | 0.93 | 1.50 | 1.25 |
| 5 | | 25.62 | 0 | 0.99 | 0.00 | 0.00 |
| 6 | | 25.66 | -0.04 | 0.99 | 0.00 | 0.00 |

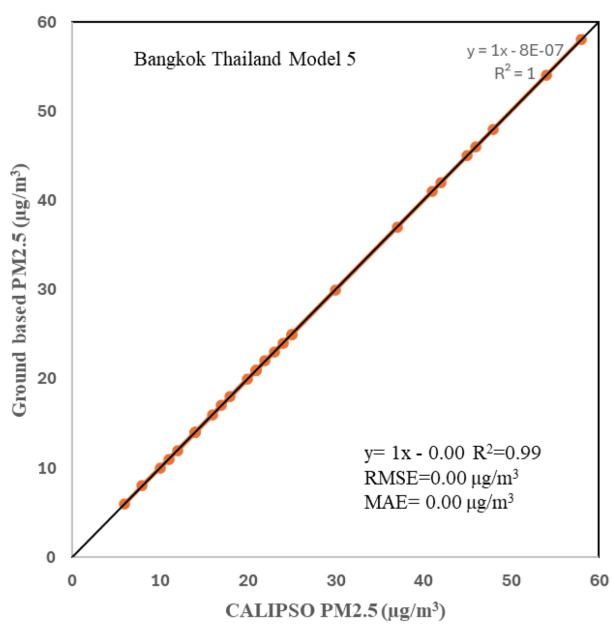



**Fig. 3** LMEM was calculated by 38 for predicted PM2.5 concentrations (μg/m$^3$)

All factors are essential for estimating PM2.5 concentrations. Table 2 establishes the model's fixed intercept ($\beta_0$) and slopes ($\beta_1 \sim \beta_5$). RH, and TEM are significant at α = 0.01 and 0.01 (Table 2). $R^2$ of model 5$^{th}$ give the highest value, with all parameters being significant. Therefore, the 5$^{th}$ model showed the best performance. Positive relations were observed between AOD and other NDVI. At the same time, negative β (RH, TEM, and WS) imply a negative relationship with PM2.5.

*PM2.5 predictions*

Fig. 4 shows the monthly observed PM2.5 and predicted PM2.5 from 2017 to 2021. PM2.5 values give a high value in 2021 compared with 2017. A similar pattern is detected between observed and predicted PM2.5. PM2.5 from two sources is an insignificant rise from 2017 to 2021. High PM2.5 was found in winter compared to the rainy season due to low temperature, light wind, and non/less rain.

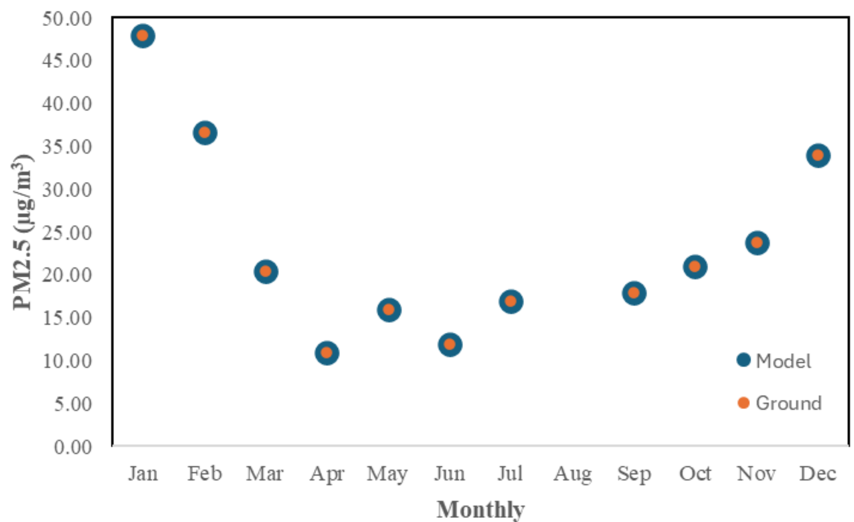



**Fig. 4** The monthly observed and predicted PM2.5 from 2017 – 2021.

## 4. Conclusion and Discussion

PM2.5 concentrations in Bangkok from 2017 to 2021 were estimated using LMEM. Active satellite data is more reasonable in spatial and temporal resolutions to achieve precise data for measuring aerosol particles in a vertical profile. The aerosol profile will encourage more information to investigate aerosol health effects. Since AOD satellite data is easy to access, the PM2.5 model can be an effective prediction tool.

All factors are essential in the PM2.5 model. For example, reducing PM2.5 may explain a negative association between WS and PM2.5 during high wind speeds. Wind speed can spread aerosol particles and decrease concentrations [17, 18]. In winter and summer, TEM and WS have a negative relation, causing the formation of secondary aerosols [19]. A slight negative relation between RH and PM2.5 indicates a slightly antagonistic association. BLH and NDVI also affect PM2.5 because adding those parameters improves the models. Increased PM2.5 concentrations in winter may be related to biomass-burning seasons[20, 21]. Necessary weather conditions retain aerosol particles suspended in the air for an extended time.

This work can improve the estimation of PM2.5 concentrations near the ground in Bangkok, revealing information on harmful pollutant air and possible health risks.

## 5. Acknowledgement

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## 6. References

[1] W. Kumharn, S. Sudhibrabha, K. Hanprasert, S. Janjai, I. Masiri, S. Buntoung, S. Pattarapanitchai, R. Wattan, O. Pilahome, W. Nissawan, Y. Jankondee, Improved Hourly and long-term PM2.5 Prediction Modeling Based on MODIS in Bangkok, Remote Sens. Appl.: Soc.

Environ. 28 (2022) 100864 . 10.1016/j.rsase.2022.100864.
[2] W. Kumharn, S. Sudhibrabha, K. Hanprasert, S. Janjai, I. Masiri, S. Buntoung, S. Pattarapanitchai, R. Wattan, C. Homchampa, T. Srimaha, O. Pilahome, W. Nissawan, Y. Jankondee, Estimating hourly full-coverage PM2.5 concentrations model based on MODIS data over the northeast of Thailand, MODEL EARTH SYST ENV. 10 (2024) 1273 – 1280. 10.1007/s40808-023-01839-7.
[3] O. Pilahome, W. Ninssawan, Y. Jankondee, S. Janjai, W. Kumharn, Long-term variations and comparison of aerosol optical properties based on MODIS and ground-based data in Thailand, Atmos.Environ. 286 (2022) 119218. 0.1016/j.atmosenv.2022.119218.
[4] Q. Yang, Q. Yuan, L. Yue, T. Li, H. Shen, L. Zhang, The relationships between PM2.5 and aerosol optical depth (AOD) in mainland China: About and behind the spatio-temporal variations, Environ. Pollut. 248 (2019) 526 – 535. 10.1016/j.envpol.2019.02.071.
[5] L. Yang, H. Xu, Z. Jin, Estimating ground-level PM2.5 over a coastal region of China using satellite AOD and a combined model, J.Clean. Prod. 227 (2019) 472 – 482. 10.1016/j.jclepro.2019.04.231.
[6] X. Ma, J. Wang, F. Yu, H. Jia, Y. Hu, Can MODIS AOD be employed to derive PM2.5 in Beijing-Tianjin-Hebei over China?, Atmos.Res. 181 (2016) 250 – 256. 10.1016/j.atmosres.2016.06.018.
[7] H. Zhao, K. Gui, Y. Ma, Y. Wang, Y. Wang, H. Wang, Y. Zheng, L. Li, L. Zhang, H. Che, X. Zhang, Climatological variations in aerosol optical depth and aerosol type identification in Liaoning of Northeast China based on MODIS data from 2002 to 2019, Sci. Total Environ. 781 (2021), 146810. 10.1016/j.scitotenv.2021.146810.
[8] G. Geng, X. Meng, K. He, Y. Liu, Random forest models for PM2.5 speciation concentrations using MISR fractional AODs, Environ. Res. Lett. 15(3) (2020) 034056. 10.1088/1748-9326/ab76df
[9] Z. Ma, S. Dey, S. Christopher, R. Liu, J. Bi, P. Balyan, Y. Liu, A review of statistical methods used for developing large-scale and long-term PM2.5 models from satellite data, Remote Sens. Environ. 269 (2022) 112827. 10.1016/j.rse.2021.112827.
[10] Z. Fang, H. Yang, M. Zhao, Y. Cao, C. Li, K. Xing, X. Deng, C. Xie, and D. Liu, Assessing PM2.5, Aerosol, Aerosol Optical Depth Concentrations in Hefei Using Modis, Calipso, and Ground-Based Lidar, J. Appl. Spectrosc. 88(4) (2021) 794 – 801 10.1007/s10812-021-01242-z.
[11] C. Lin, L. D. Labzovskii, H. W. Leung Mak, J. C. H. Fung, A. K. H. Lau, S. T. Kenea, M. Bilal, J. D. Vande Hey, X. Lu, J. Ma, Observation of PM2.5 using a combination of satellite remote sensing and low-cost sensor network in Siberian urban areas with limited reference monitoring, Atmos. Environ. 227 (2020) 117410. 10.1016/j.atmosenv.2020.117410.
[12] D. Fu, Z. Song, X. Zhang, X. Xia, J. Wang, H. Che, H. Wu, X. Tang, J. Zhang, M. Duan, Mitigating MODIS AOD non-random sampling error on surface PM2.5 estimates by a combined use of Bayesian Maximum Entropy method and linear mixed-effects model, Atmos. Pollut. Res. 11(3) (2020) 482 – 490. 10.1016/j.apr.2019.11.020.
[13] S.L.K. Unnithan, L. Gnanappazham, Spatiotemporal mixed effects modeling for the estimation of PM2.5 from MODIS AOD over the Indian subcontinent, GIScience Remote Sens. 57(2) (2020) 159 – 173 10.1080/15481603.2020.1712101.
[14] F.-Y. Cheng, C.-Y. Feng, Z.-M. Yang, C.-H. Hsu, K.-W. Chan, C.-Y. Lee, S.-C. Chang, Evaluation of real-time PM2.5 forecasts with the WRF-CMAQ modeling system and weather-pattern-dependent bias-adjusted PM2.5 forecasts in Taiwan, Atmos. Environ.244 (2021) 117909. 10.1016/j.atmosenv.2020.117909.

[15] Z. Luo, F. Huang, H. Liu, PM2.5 concentration estimation using convolutional neural network and gradient boosting machine, J. Environ. Sci. 98 (2020) 85 – 93. 10.1016/j.jes.2020.04.042.
[16] F. L. Luo, J. L. Jing, A. N. Wang, L. S. Liang, research on PM2.5 mass concentration retrieval method based on himawari-8 in beijing, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-3/W10 (2020) 903 – 910. 10.5194/isprs-archives-XLII-3-W10-903-2020.
[17] X. Wang, R. Zhang, W. Yu, The Effects of PM2.5 Concentrations and Relative Humidity on Atmospheric Visibility in Beijing, J. Geophys. Res. 124(4) (2019) 2235 – 2259. 10.1029/2018JD029269.
[18] F. Liu, Q. Tan, X. Jiang, F. Yang, W. Jiang, Effects of relative humidity and PM2.5 chemical compositions on visibility impairment in Chengdu, China, J. Environ. Sci. 86 (2019) 15 – 23. 10.1016/j.jes.2019.05.004.
[19] X. Liu, X. Yu, Z. Zhang, PM2.5 Concentration Differences between Various Forest Types and Its Correlation with Forest Structure, J. Atmos. 6(11) (2015) 1801 – 1815. 10.3390/atmos6111801.
[20] J. Kayee, P. Sompongchaiyakul, N. Sanwlani, S. Bureekul, X. Wang, R. Das, Metal Concentrations and Source Apportionment of PM2.5 in Chiang Rai and Bangkok, Thailand during a Biomass Burning Season, ACS Earth Space Chem. 4(7) (2020) 1213 – 1226. 10.1021/acsearthspacechem.0c00140.
[21] S. Pongpiachan, M. Hattayanone, J. Cao, Effect of agricultural waste burning season on PM2.5-bound polycyclic aromatic hydrocarbon (PAH) levels in Northern Thailand, Atmos. Pollut. Res. 8(6) (2017) 1069 – 1080. 10.1016/j.apr.2017.04.009.