RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2022.001

ScienceAsia 48 (2022): **75–81**

Applying surface reflectance to investigate the spatial and temporal distribution of $PM_{2.5}$ in Northern Thailand

Supachai Nakapan[a,c], **Anuttara Hongthong**[b,*]

[a] Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200 Thailand
[b] Department of Environmental Health, School of Health Science, Mae Fah Luang University, Chiang Rai 57100 Thailand
[c] Research Center in Physics and Astronomy, Chiang Mai University, Chiang Mai 50200 Thailand

[*]Corresponding author, e-mail: anuttara.hon@mfu.ac.th

Received 19 Jan 2021
Accepted 16 Jun 2021

ABSTRACT: The MODIS surface reflectance (SR) product (MOD09) was used to predict $PM_{2.5}$ concentrations with a regression model. The predicted results were compared with the MAIAC-AOD model and the ground based measurements. The output from the MODIS product is regularly employed to predict air pollution and emissions, while the AOD model is normally used to predict $PM_{2.5}$ concentrations. This study investigated $PM_{2.5}$ concentrations in Northern Thailand by using SR via a linear regression model. The results showed that the highest value of SR was observed in Band-2 (0.17–0.27), followed by Band-1 and Band-4 (0.10–0.14) and Band-3 (0.07–0.10). Moreover, the correlation coefficient between SR-band-2 versus the measured $PM_{2.5}$ from the master stations with $PM_{2.5}$ sensor was greater than those of the other bands. The correlation coefficients between the predicted $PM_{2.5}$ by the MODIS-SR and by the MAIAC-AOD models and the measured $PM_{2.5}$ from the master stations varied between 0.3871–0.8588 and 0.3913–0.7802, respectively. The range of prediction efficiency by the SR model was 10.8%–27.2%, which was greater than the AOD model. It should be concluded that the distribution of spatial $PM_{2.5}$ concentrations obtained from surface reflectance and MAIAC-AOD predictions was similar.

KEYWORDS: $PM_{2.5}$, surface reflectance, MOD09, GIS, Northern Thailand

INTRODUCTION

Investigations of $PM_{2.5}$ concentrations and emissions in Northern Thailand have been conducted continuously for the past decade. An extreme level of $PM_{2.5}$ emission from biomass burning was happened during the dry season [1, 2]. The concentrations of $PM_{2.5}$ in Northern Thailand during this period regularly exceeded the Thai Air Quality Standard, and the number of days when $PM_{2.5}$ concentrations exceeded the standard in 2017, 2018, and 2019 were 67, 83, and 52 days, respectively. Furthermore, the high concentration of $PM_{2.5}$ is associated with health problems, such as chronic bronchitis, premature death, as well as economic losses [3, 4]. The $PM_{2.5}$ concentrations and emission sources in Northern Thailand were investigated using various satellite methodologies [2, 5]. The Aerosol Optical Depth (AOD) from the MODIS platform was used to investigate $PM_{2.5}$ concentrations in upper Northern Thailand [6–8]. However, the uncertainty of $PM_{2.5}$ investigations using AOD retrievals was found in several studies because of a lack of AOD data due to cloud cover [9–11]. The Geo-Informatics and Space Technology Development Agency (Public Organization) (GISTDA) used other new AOD retrievals from the Himawari-8 to monitor the $PM_{2.5}$. However, the resolution of 5 km of this satellite still does not fully represent the site's measurements [12].

Another possible method is the use of MODIS surface reflectance product (MOD09), which generates a clearer result with 500 m-resolution that can be derived from a finer resolution and a larger spatial coverage of $PM_{2.5}$ than the AOD-derived $PM_{2.5}$. The surface reflectance (SR) is an estimate of the surface spectral reflectance by atmospheric scattering or absorption, which is affected by atmospheric gases and aerosols, as well as $PM_{2.5}$. The predicted $PM_{2.5}$ concentrations from the use of the SR method are significant when correlated with ground measurements and MODIS-AOD [13], and they are relatively powerful in the determination of spatial-temporal coverage because of the finer resolution [14]. The Multi-Angle Implementation of Atmospheric Correction (MAIAC) is the daily algorithm-based Level-2 gridded (L2G) aerosol optical thickness over land surfaces produced from the MCD19A2 instrument, which is derived from both Terra and Aqua MODIS inputs at 1 km pixel resolution. The MAIAC-AOD was applied to estimate the $PM_{2.5}$ concentrations in many countries in Asia such as India and China [15, 16] with a significant correlation between predicted $PM_{2.5}$ concentrations and measurements; however, there was still uncertainty as a result of missing AOD. Geographic Information Systems (GIS) were frequently applied to generate the spatial distribution of $PM_{2.5}$ [16, 17] by using the most accurate interpolation method, which is the Inverse Distance Weight (IDW) technique, with the highest correlation and the lowest root mean square error (RMSE) in comparing between the ordinary kriging and the surface trend methods [18]. The performance

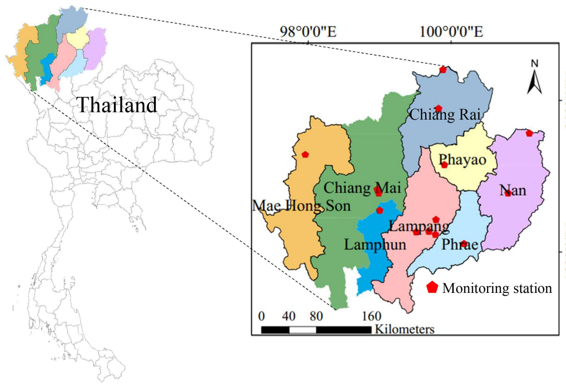

Fig. 1 Study domain.

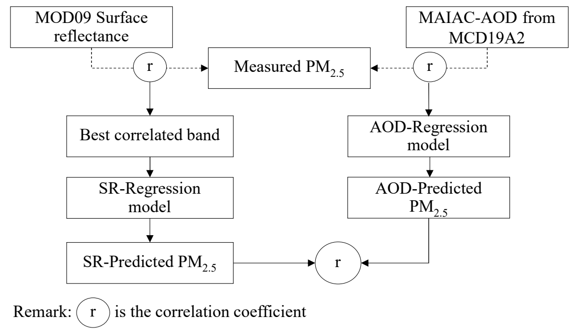

Fig. 2 Data analysis flowchart.

of the SR model using $PM_{2.5}$ predictions was normally validated by ground measurements, and the SR modeling performed better than the AOD modeling [13]. The predictive power of the SR model in terms of spatial-temporal coverage is greater than that of the traditional AOD [14].

As a result of the investigation of $PM_{2.5}$ concentrations using the SR method, valuable data were collected from the higher spatial distribution resolution (500 m-resolution). Therefore, this study aimed to determine the concentrations of $PM_{2.5}$ using the satellite SR method from the MOD09 of the MODIS instrument via the regression correlation model. The predicted $PM_{2.5}$ concentrations from the SR regression model were directly compared with the MAIAC-AOD (1 km-resolution) to investigate the correlation efficient. The possibility and efficiency of using the SR product to investigate the concentration of $PM_{2.5}$ from this study would be useful in the areas where $PM_{2.5}$ monitoring sensors are not available.

MATERIALS AND METHODS

Study domain

The eight provinces in upper Northern Thailand including Chiang Rai, Chiang Mai, Mae Hong Son, Lampang, Lamphun, Phrae, Nan, and Phayao are located between latitudes 18.28° N–20.46° N and longitudes 97.32° E–101.40° E. The study domain covered 90 690 km^2 with a total population of 5.84 million. The main geographical features are mountainous areas with a variety of forests and agricultural farms. The average daily $PM_{2.5}$ concentrations in most of the provinces in the domain regularly exceed the daily ambient air quality standard (50 $\mu g/m^3$) for many days during the dry season [7, 19]. The 14 ground-based monitoring stations of the Pollution Control Department (PCD) are located in all provinces except Uttaradit (Fig. 1 and Table S1).

Data collection and regression model analysis

The daily SR, a resolution of 500-m and 5-min in the format of an HDF file, was collected from MOD09 of the MODIS Terra/Aqua instrument via the website of Level-1 and Atmosphere Archive & Distribution System and Distributed Active Archive Center (LAADS DAAC). It consisted of four combined bands, namely Bands 1–4, at the wavelengths of 646, 855, 466, and 553 nm, respectively. Because of the limited time the satellite passes through the study area during the day; therefore, the average weekly SR data were used to compare with the $PM_{2.5}$ measurements. The daily $PM_{2.5}$ measurements from February to May 2018 and 2019 were obtained from the four PCD monitoring master stations, 35T, 36T, 40T, and 75T. The measured $PM_{2.5}$ concentrations were averaged weekly between 10 a.m. and 2 p.m., which corresponded to the time when the satellite passed through the study area; and February to May is the period of haze in the study area.

The regression model was chosen based on the strongest correlations between each SR band and the $PM_{2.5}$ measurements. The best regression model could be used to predict $PM_{2.5}$ concentrations for other PCD monitoring stations where $PM_{2.5}$ monitoring instruments are not available. The performance of the regression model was evaluated by the MAIAC-AOD product (1 km-resolution) gathered from the LAADS DAAC, and the correlation coefficient (r) between the predicted SR-$PM_{2.5}$ and MAIAC-AOD was found to be higher than 0.6, which is considered as a significant correlation for this study [13, 14]. The flowchart of the data analysis is shown in Fig. 2.

The daily variation of $PM_{2.5}$ concentrations obtained from the master stations started to increase and exceeded the air quality standard during the study period. Furthermore, an even higher concentration of $PM_{2.5}$ was found in March 2019, which was three times higher than the air quality standard (Fig. 3).

Temporal and spatial distribution

The variations of the predicted $PM_{2.5}$ concentrations from the SR model were analyzed. A layer map of pre-

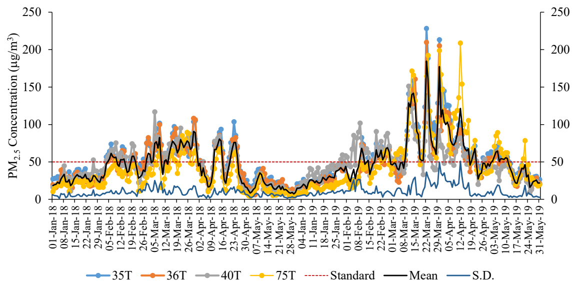

Fig. 3 Daily variations of $PM_{2.5}$ concentrations obtained from the master stations during January-May of 2018 and 2019.

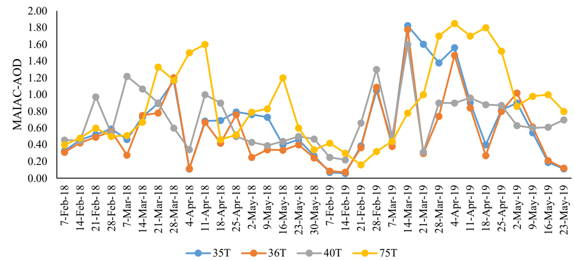

Fig. 5 MAIAC values from February to May of the years 2018 and 2019 obtained from the master stations.

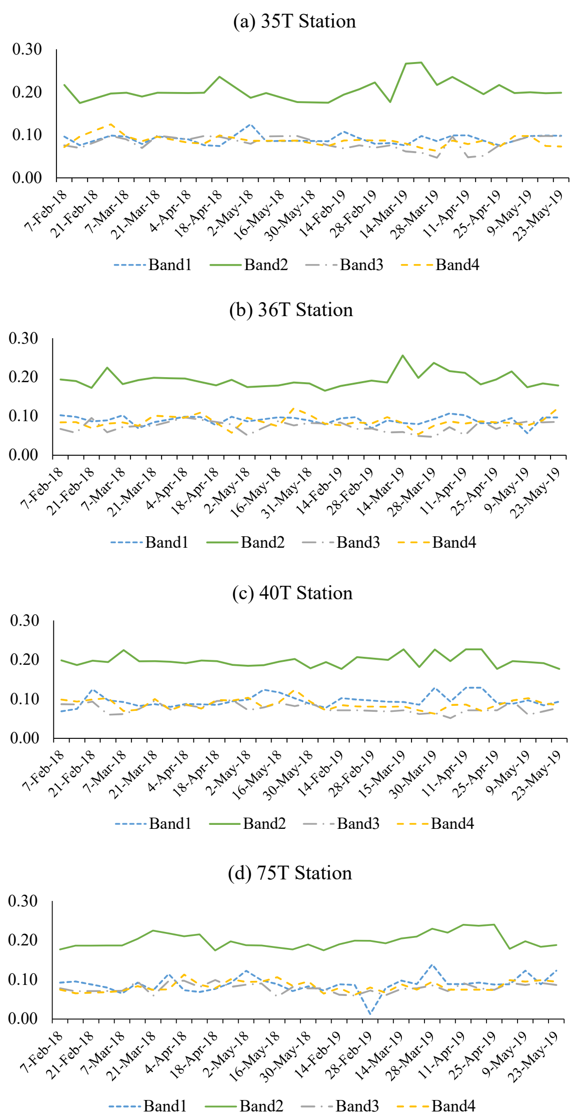

Fig. 4 Variations in surface reflectance of Bands 1 to 4 obtained from the 35T, 36T, 40T, and 75T master stations.

dicted $PM_{2.5}$ concentrations was applied to the layer of the study domain. Then the concentrations of $PM_{2.5}$ in the areas without monitoring stations were predicted by the Inverse Distance Weight (IDW) technique in the GIS program [20]. Similarly, the concentrations and distribution of $PM_{2.5}$ from the MAIAC-AOD results were analyzed.

RESULTS AND DISCUSSION

Surface reflectance (SR)

The SR value of Bands 1–4 from the MOD09 instrument fluctuated between 0.07–0.27 during the 33 weeks of sampling from February to May of 2018 and 2019, with the mean values of 0.13, 0.23, 0.09, and 0.12, respectively. The highest value of SR was observed in Band-2 (0.17–0.27), followed by Band-1 and Band-4 (0.10–0.14) [21], and Band-3 (0.07–0.10), as shown in Fig. 4. In addition, the correlation coefficient between SR-Band-2 versus the $PM_{2.5}$ measurements was higher than the values of other bands, and also higher than the value between MAIAC-AOD versus $PM_{2.5}$ measurements (Table 1). Therefore, the SR-Band-2 provided a good result which matched the $PM_{2.5}$ predictions in this study.

MAIAC-AOD

The MAIAC-AOD values varied between 0.06–1.90 during 2018–2019, with the highest AOD values observed in March (Fig. 5). The normal AOD values from MODIS varied between 0.1–1.2 and were significantly higher during March to April 2014–2017 [22]. The advantage of using SR to predict $PM_{2.5}$ concentrations is the finer resolution and the higher number of sample sizes that the AOD provides. Moreover, during the study period, there were 31 out of 120 days when the surfaces were either over bright or under cloud cover, and the MAIAC-AOD results could not be accurately retrieved [15, 23]. Hence, 25.8% of the results were missing.

Linear regression model estimation

The best regression model was adopted by selecting the highest correlation coefficient value of the trained SR-

Table 1 Comparison of the correlation coefficients between SR and MAIAC-AOD results versus measured $PM_{2.5}$.

Station	Linear correlation equations of SR-Band-2 vs. measured $PM_{2.5}$	Correlation coefficient between	
		SR-Band-2 vs. measured $PM_{2.5}$	MAIAC-AOD vs. measured $PM_{2.5}$
35T	$y = 1623x - 266$	0.8710	0.7802
36T	$y = 1219x - 181$	0.7964	0.7042
40T	$y = 1137x - 179$	0.5887	0.5806
75T	$y = 1166x - 183$	0.5645	0.3913

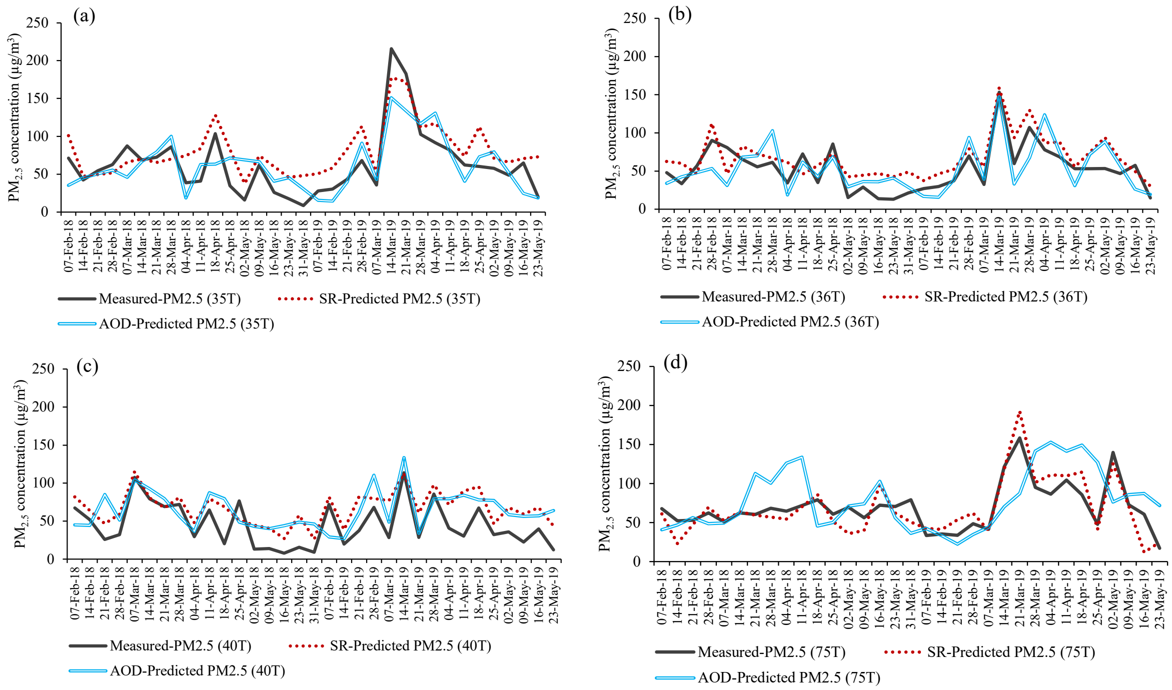

Fig. 6 Weekly variations between the predicted SR-$PM_{2.5}$ vs. the measured $PM_{2.5}$ and the predicted AOD-$PM_{2.5}$ vs. the measured $PM_{2.5}$ of the master stations: (a) 35T; (b) 36T; (c) 40T; and (d) 75T.

Band-2 result compared with the $PM_{2.5}$ measurements at the same co-location of the master stations 35T, 36T, 40T, and 75T which showed the highest correlation coefficient values of 0.8631, 0.7985, 0.6600, and 0.7854, respectively. Then, the $PM_{2.5}$ concentrations for the other locations with no $PM_{2.5}$ monitoring sensors (Table S1) was predicted by EQ. (1) using the Band-2 value.

$$PM_{2.5} = -268.89 + 1633.48X \tag{1}$$

where X is the SR-Band-2 surface reflectance value.

Temporal distribution and model validation

Fig. 6 shows the pattern of predicted $PM_{2.5}$ concentrations from the master stations which revealed the pattern of the predicted SR-$PM_{2.5}$ and the predicted AOD-$PM_{2.5}$ models. The variation of $PM_{2.5}$ from both models was similar to the master stations' data, and the peak $PM_{2.5}$ concentration was found in March 2019.

Table 2 Correlation coefficients (r) between measured $PM_{2.5}$, predicted SR-$PM_{2.5}$, and predicted AOD-$PM_{2.5}$.

Station	r between predicted SR-$PM_{2.5}$ vs. measured $PM_{2.5}$	r between predicted AOD-$PM_{2.5}$ vs. measured $PM_{2.5}$	% Difference of model prediction compared with data of the master stations	
			SR-$PM_{2.5}$	AOD-$PM_{2.5}$
35T	0.8588	0.7802	27.2	1.7
36T	0.7985	0.7170	13.7	0.0
40T	0.5888	0.5806	17.5	41.7
75T	0.3871	0.3913	10.8	58.8

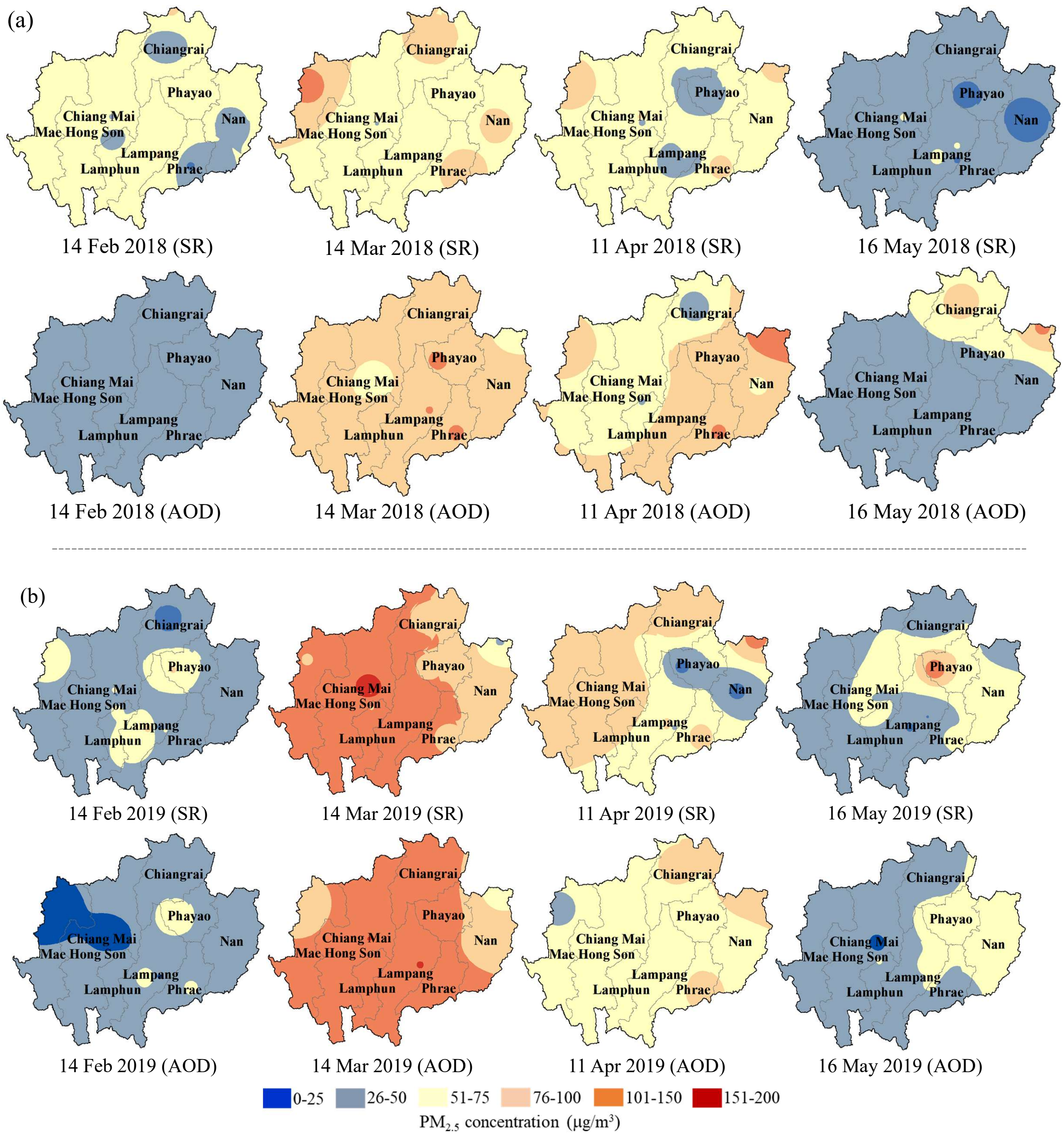

Fig. 7 Comparison of predicted $PM_{2.5}$ distribution from SR and MAIAC-AOD during February-May of: (a) 2018; and (b) 2019.

The predicted $PM_{2.5}$ concentrations from both models were validated against the measured values of the master stations. The correlation coefficients between the predicted SR-$PM_{2.5}$ and the measured $PM_{2.5}$ from the 35T, 36T, 40T, and 75T stations were 0.8588, 0.7985, 0.5888, and 0.3871, respectively; while the correlation coefficients between the predicted AOD-$PM_{2.5}$ and the measured $PM_{2.5}$ were 0.7802, 0.7170, 0.5806, and 0.3913, respectively. The overall correlation coefficient of prediction by SR was higher than that of the AOD. The prediction efficiency of the SR model was in the range of 10.8%–27.2%. The missing AOD data due to the irretrievability caused by cloud cover was the main reason for the lower correlation rate [24] as shown in Table 2.

The pattern of predicted SR-$PM_{2.5}$ concentrations from the PCD monitoring stations with no $PM_{2.5}$ sensors varied between individual weeks. However, the level of SR-$PM_{2.5}$ was extremely high and exceeded the daily air quality standard (50 $\mu g/m^3$) for March–

April of 2018 and 2019, and the $PM_{2.5}$ concentrations of 2019 were clearly higher than those of 2018. Nonetheless, the trend of $PM_{2.5}$ concentrations from this study was in line with the PM_{10} concentrations of this area [25]. Because the value of SR is determined by the scattering or absorption of aerosols in the atmosphere [26] and the concentrations of $PM_{2.5}$ during the remaining eight months of the year are low, $PM_{2.5}$ concentrations can be predicted if the SR is available. The correlation coefficients (r) between predicted SR-$PM_{2.5}$ and AOD-$PM_{2.5}$ for the remaining nine stations with no $PM_{2.5}$ sensors varied between 0.5175–0.7721, with high correlations ($r > 0.7$) found in the provinces of Lampang (Stations 37T and 39T), Lamphun (Station 68T), and Phrae (Station 69T), as shown in Fig. S1.

Spatial distribution

The high concentrations of both SR-predicted $PM_{2.5}$ and AOD-predicted $PM_{2.5}$ mostly occurred during March and April of 2018 and 2019. It was found that extremely high $PM_{2.5}$ concentrations that exceed the Daily Thai Air Quality Standard (50 $\mu g/m^3$) covered all the nine provinces in the area on 14 March of 2018 and 2019. It was also found that there were severe concentrations of $PM_{2.5}$, which were 2–3 times higher than the standard quality, covering more than half of the study area on 14 March 2019. However, in both years, these levels clearly decreased in May as shown in Fig. 7 [19].

CONCLUSION

We adopted the best fit model for the prediction of $PM_{2.5}$ concentrations using MODIS SR instrument in the areas with no $PM_{2.5}$ monitoring sensors of Northern Thailand during February–May of 2018 and 2019. The SR product from MODIS, MOD09, was applied to predict the $PM_{2.5}$ concentrations instead of using the traditional AOD method. The results from the SR predictions were validated by the ground $PM_{2.5}$ concentration monitoring measurements and the MAIAC-AOD model. A good correlation between the predicted $PM_{2.5}$ concentrations with the SR ground measurements and the MAIAC-AOD model was found. The best fit SR model was applied to predict the concentration of $PM_{2.5}$ for the remaining monitoring stations without $PM_{2.5}$ sensors. The spatial distribution of the predicted $PM_{2.5}$ concentrations from SR was not much different from the predicted by the MAIAC-AOD model. Thus, the SR model approach, which is different from the traditional $PM_{2.5}$ estimation by AOD, can provide useful information for the monitoring and the control of $PM_{2.5}$ concentrations. However, to obtain greater accuracy of $PM_{2.5}$ predictions using the SR method, it may be necessary to consider other types of relevant information such as meteorology or the planetary boundary layer.

Appendix A: Supplementary data

Supplementary data associated with this article can be found at http://dx.doi.org/10.2306/scienceasia1513-1874.2022.001.

Acknowledgements: This work was partially supported by Chiang Mai University. The MOD09 data was collected from the Level-1 and Atmosphere Archive & Distribution System (LAADS), and the MAIAC-AOD data was gathered from the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Centre (DAAC). The $PM_{2.5}$ data were obtained from the Thailand Pollution Control Department. We thank the investigators and their staff for recording and maintaining the important data used in this investigation.

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Appendix A. Supplementary data

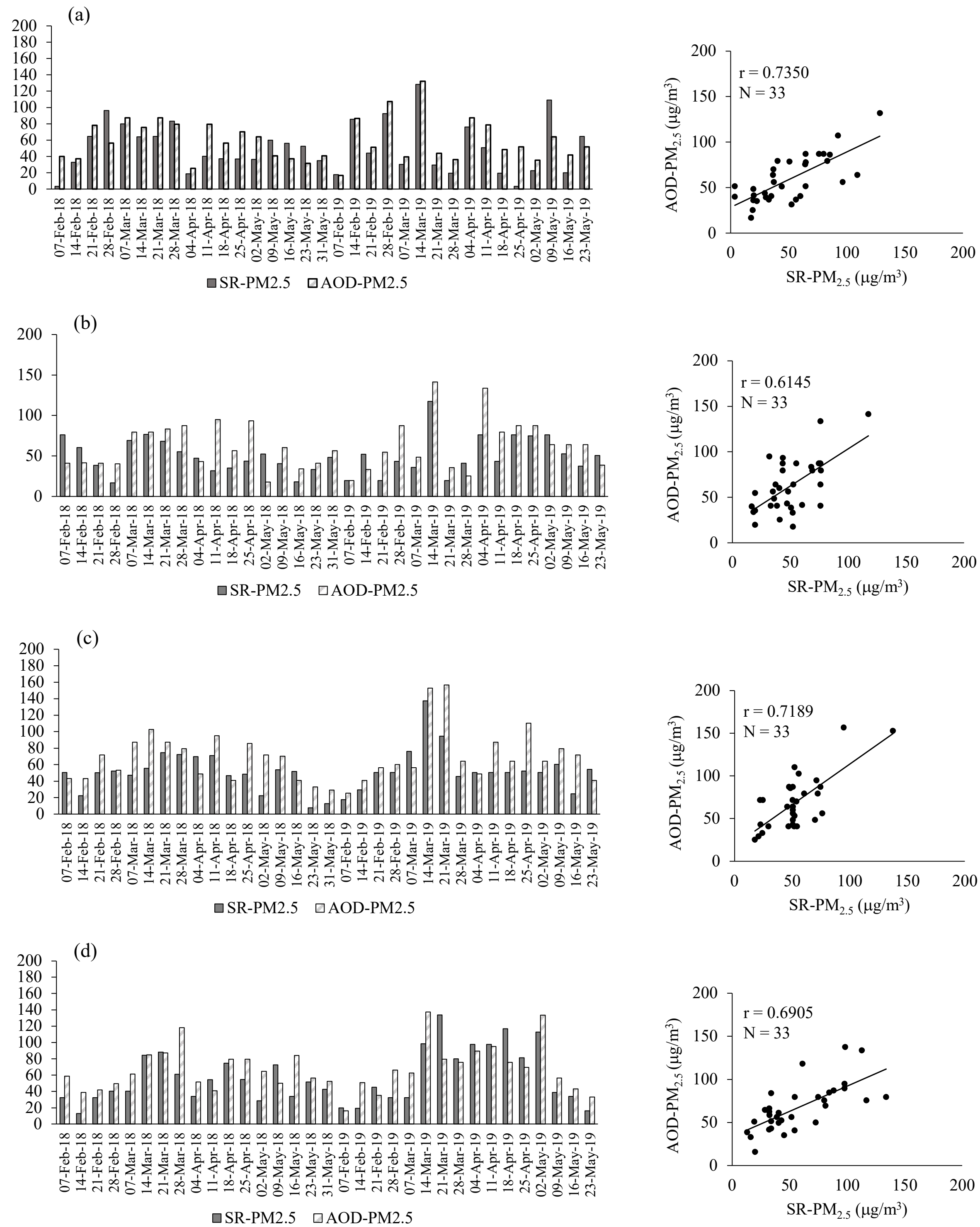

Fig. S1 Comparisons of predicted $PM_{2.5}$ concentration between the surface reflectance Band-2 (SR-$PM_{2.5}$ and MAIAC-AOD).

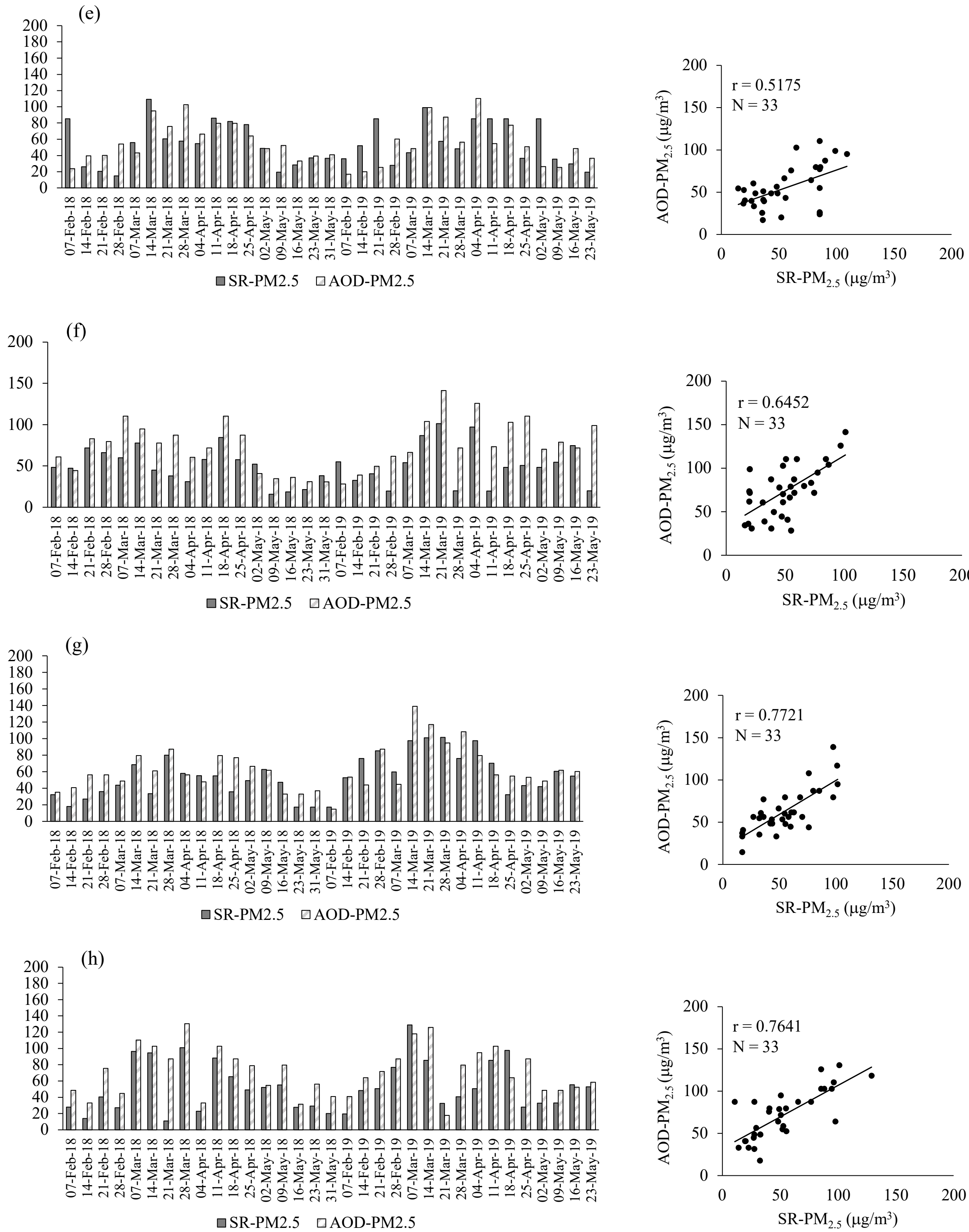

Fig. S1 continued ....

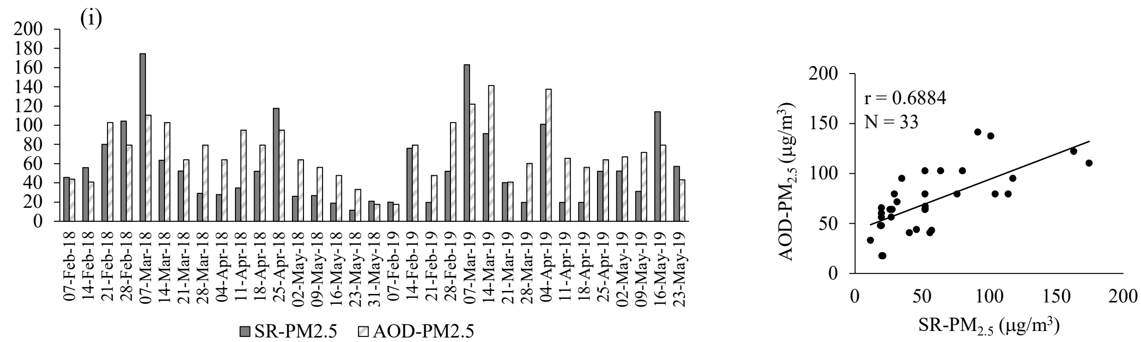

Fig. S1 continued ....

Table S1 Information of PCD monitoring stations in the study domain.

Province	Station code	Station name	Latitude (°N)	Longitude (°E)
Chiang Mai	35T	Provincial office	18.8377	98.9729
	36T	Yupparaj Wittayalai School	18.7883	98.9932
Chiang Rai	57T	Provincial office of Natural Resources and Environment	19.9023	99.8234
	73T	Provincial Public Health Office, Mae Sai	20.4271	99.8833
Mae Hong Son	58T	Provincial office of Natural Resources and Environment	19.3045	97.9715
Lamphun	68T	Meteorological Office	18.5668	99.0388
Lampang	37T	Meteorological Office	18.1642	99.3025
	38T	Sobpad, Mae Moh	18.2495	99.7627
	39T	Tha-see, Mae Moh District	18.4247	99.7531
	40T	Provincial Waterworks Authority, Mae Moh	18.2820	99.6590
Phayao	70T	Phayao Provincial Administrative Organization	19.1670	99.8962
Phrae	69T	Meteorological Office	18.1128	100.1622
Nan	67T	Nan Municipality	18.7861	100.7795
	75T	Chaloem Pra Kiat Hospital	19.5751	101.0812