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Evaluation and mapping of aerosol optical depth in Southeast Asia using ground-based and satellite data for solar energy applications

RUSMADEE SABOODING, JUNTAKAN TAWEEKUN*# and KITTINAN MALIWAN*

Energy Technology Program, Department of Specialized Engineering, Faculty of Engineering,

Prince of Songkla University, Hatyai, Songkhla, 90112, Thailand

**Department of Mechanical Engineering and Mechatronics, Faculty of Engineering,*

Prince of Songkla University, Hatyai, Songkhla 90112, Thailand

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e mails : #Juntakan2016@gmail.com; sabooding081@gmail.com

सार – यह अध्ययन उपग्रहों और दक्षिण पूर्व एशिया में चौदह सनफोटोमीटर से कॉलम एकीकृत एओडी रीडिंग प्रस्तुत करता है। तुलनात्मक परिणाम से पता चलता है कि एक्वा सैटेलाइट और सनफोटोमीटर से अनुमानित एओडी माप के साथ उचित समझौते में है, मासिक मामलों के लिए आरएमएसई 0.09-0.42 है। ओएमआई से प्राप्त डेटा की सनफोटोमीटर अवलोकन से प्राप्त डेटा के साथ तुलना करके प्राप्त एओडी को 0.27 के आरएमएसई और -0.01 के एमबीई के साथ अच्छा समझौता पाया गया। अध्ययन 2005-2020 की 16 साल की अवधि के लिए ओएमआई डेटा का का उपयोग करके जीआईएस, क्रिगिंग (भौगोलिक सूचना प्रणाली) द्वारा उत्पन्न एओडी संसाधन मानचित्र प्रस्तुत करता है। दक्षिण-पूर्व एशिया के मौसमों को गर्मी (मार्च-मई) और सर्दी (जून-फरवरी) के रूप में परिभाषित किया गया है। ऊपरी दक्षिण-पूर्व एशिया के मौसमी पैटर्न के अनुसार, एओडी अधिक था और गर्मियों में अपने अधिकतम तक तक पहुंच गया था, लेकिन कम था और सर्दियों में अपने न्यूनतम तक पहुंच गया। निचले दक्षिण पूर्व एशिया के मामले में, AOD सर्दियों में अधिकतम था लेकिन गर्मियों में न्यूनतम था। मानचित्रों से पता चलता है कि ग्यारह देशों देशों की भौगोलिक विशेषताओं और उष्णकटिबंधीय मानसून का एओडी के क्षेत्रीय वितरण पर महत्वपूर्ण प्रभाव पड़ा। यह कार्य MERRA-2 से कार्बनिक कार्बन और ब्लैक कार्बन और GLDAS से विशिष्ट आर्द्रता का उपयोग करके AOD निर्धारित करने के लिए एक मॉडल प्रस्तुत करता है। मॉडल इन स्टेशनों से 5-वर्ष (2012-2016) एओडी डेटा के आधार आधार पर दैनिक एओडी (आर = 0.71) और मासिक एओडी (आर = 0.83) का अनुमान लगाने के लिए बनाया गया गया था, और 4-वर्ष की अवधि (2017 से 2020) के लिए सत्यापन के लिए स्वतंत्र डेटा का उपयोग किया गया था। था। यह देखा जा सकता है कि मॉडल द्वारा अनुमानित मासिक एओडी के मूल्यों का आरएमएसई 0.20 था। मॉडल 2 मासिक एओडी (आर = 0.94) को एओडी के अनुमान को सक्षम करने के लिए दृश्यता (195 मौसम विज्ञान स्टेशन) और एंगस्ट्रॉम विशेषज्ञ (एक्वा) का उपयोग करके विकसित किया गया था। जब एक स्वतंत्र डेटा सेट से तुलना की जाती है, तो यह मॉडल 2 क्रमशः 0.23 और -0.01 के आरएमएसई और एमबीई के साथ उचित प्रदर्शन करता है।

ABSTRACT. This study presents column integrated AOD readings from satellites and from fourteen sunphotometers in southeast Asia. The comparison result shows that AOD estimated from Aqua satellite and sunphotometer is in reasonable agreement with the measurement, with RMSE of 0.09–0.42 for monthly cases. The AOD obtained by comparing data from the OMI with those obtained from sunphotometer observations was found to be of good agreement, with a RMSE of 0.27 and MBE of –0.01. The study presents AOD resource maps generated by GIS, Kriging (Geographic Information System) utilizing OMI data for 16-year period 2005–2020. The seasons for southeast Asia are defined as summer (March-May) and winter (June–February). According to upper southeast Asia seasonal patterns, the AOD was higher and reached its maximum in the summer but was lower and reached its minimum in winter. In the case of lower southeast Asia, the AOD was maximum in the winter but was minimum in summer. The maps reveal that geographic characteristics of eleven countries and the tropical monsoons had a significant impact on regional distribution of AOD. This work presents a model for determining AOD using organic carbon and black carbon from MERRA-2 and specific humidity from GLDAS. The model was created to estimate daily AOD (R = 0.71) and monthly AOD (R = 0.83) based on 5-year (2012–2016) AOD data from these stations, and independent data were used to validate for the 4-year period (2017 to 2020). It can be seen that values of monthly AOD predicted by the model had an RMSE of 0.20. The model2 monthly AOD (R = 0.94) was developed using visibility (195 meteorological stations) and angstrom expernent (Aqua) to enable the estimation of AOD. When compared to an independent data set, this model2 performs reasonably, with RMSE and MBE of 0.23 and –0.01, respectively.

Key words – AOD, Model, Sunphotometer, MERRA-2, Meteorological stations.

1. Introduction

Small solid or liquid particles that are suspended in air and travel across a wide range with the air currents in the troposphere are known as aerosols. The smallest aerosol particle sizes typically range from sub-microns to those between 10 and 100 µm (Ramanathan *et al.*, 2001).Aerosols may occur throughout the world both naturally and through anthropogenic activities and can directly affect radiative balance through scattering and absorption of shortwave and longwave radiation (Sokolik *et al.*, 2001; Wang *et al.*, 2010). In addition, it might be a significant factor in influencing regional and global climates. Regional level aerosols can affect stability of the atmosphere and photosynthesis by reducing amount of sunlight reaching the earth's surface (Xin *et al.*, 2005). The aerosol optical depth (AOD) can be measured directly using ground-surface sun photometer networks or can be derived from remote sensing. The estimation of optical aerosol particles from ground surface by a Cimelsunphotometer includes measurements of irradiance, both direct and indirect in distinct narrow solar spectrum bands (Bhaskaran *et al.*, 2011).

Modeling of these processes is challenging due to short residence time of atmospheric particles, which is approximately 7 days, and the complexity of the impact of aerosols on dynamics and circulation of clouds in region (Kaufman and Koren, 2006). Numerous studies have been carried out throughout the world as a result of the significance of light particles in aerosols (Alados-Arboledas *et al.*, 2008; Behnert *et al.*, 2007; Bi *et al.*, 2011; Caido *et al.*, 2022; Kumar *et al.*, 2011; Ma *et al.*, 2022; Markowicz *et al.*, 2021; Nurhayati and Nakajima, 2012; Nwofor *et al.*, 2007; Ogunjobi *et al.*, 2008; Pan *et al.*, 2010; Praseed *et al.*, 2012; Prats *et al.*, 2008; Saha *et al.*, 2008; Shen *et al.*, 2018; Tan *et al.*, 2022; Taschilin *et al.*, 2021; Yu *et al.*, 2011, 2007; Zhang *et al.*, 2019).In Southeast Asia, early studies reported that the majority of aerosols in the region originate from local pollution, biomass burning and forest fire events (Janjai *et al.*, 2009).

There is not enough data on the atmosphere in this tropical region, and there is very little knowledge of the optical aerosol particles present there. In response to the demand for more information, it is thus very urgent and necessary to workon AOD in southeast Asia to improve our knowledge of regional aerosol-climate interactions. The main objective of this articleis to develop an empirical model that uses inputs including organic carbon surface mass concentration (OC), black carbon surface mass concentration (BC) from MERRA2 reanalysis, specific humidity (Q) from GLDAS model, visibility (Vis) from meteorology stations, and angstrom expernent (α) from Aqua satellite to estimate AOD and examine the daily and monthly spatiotemporal variations in AOD values in southeast Asia from 2005 to 2020, based on OMI data on monitoring the spatial distributions of AOD. The outcomes are displayed in this article.

2. Measuring devices and acquisition of information

2.1. *Ground-based networks*

AERONET is a network of ground-based aerosol monitoring stations employing sunphotometers capable of measuring the AOD. The data from the stations is preserved in a database that is managed by NASA. Sun-photometers were spread over fourteen irradiance measurement stations located in the tropicalin South East Asia. These networks can be located in Luang Namtha (LN; 20.931° N, 101.416° E) in Laos, Chiangmai province (CM; 18.78° N, 98.98° E), Ubonratchathani province (UB; 15.25° N, 104.87° E), Nakhonpathom province (NP; 13.82° N, 100.04° E), Songkhla province (SK; 7.2° N, 100.60° E) in Thailand, Penang state (PN; 5.36° N, 100.30° E), Sarawak state (SW; 1.49° N, 110.35° E) in Malaysia, in Singapore (SG; 1.30° N, 103.78° E), Manila (MN; 14.635° N, 121.078° E), Koronadal (KD; 6.496° N, 124.843° E) in Philippines, Jambi (JB; 103.642° E, 1.632° S), Bandung (BD; 6.888° S, 107.610° E), Pontianak (PT; 0.075° N, 109.191° E) and Palangkaraya (PL; 2.228° S, 113.946° E) in Indonesia. The sun-photometers are all of same type CE-318 spectral radiometers manufactured by Cimel Electronique. These solar-powered, weather-resistant, robotically pointed sky and sun monitors. The data is transmitted from ground-based sunphotometer site to GSFC (Goddard Space Flight Center) for processing. There are three levels of processing, but this study chooses level 1.5 (cloud screening).

For meteorological data, visibility (Vis) is first defined as a quantity estimated by a human observer and observations made in that manner are widely used. However, visibility estimation is impacted by many subjective and physical factors (World Health Organization, 2006).

TABLE 1

Daily AOD comparison between Aquasatellite and sunphotometer

Stations	Number	RMSE	MBE
Luang Namtha	299	0.37	-0.13
Chiang Mai	977	0.37	-0.29
Ubon Ratchathani	490	0.15	-0.02
Nakhon Pathom	1012	0.21	0.07
Songkhla	112	0.22	0.06
Penang	267	0.22	-0.03
Sarawak	96	0.22	-0.01
Singapore	108	0.33	0.06
Manila	295	0.24	0.05
Koronadal	196	0.12	0.07
Jambi	121	0.59	0.07
Bandung	490	0.29	0.08
Pontianak	140	0.30	0.10
Palangkaraya	125	0.31	0.10
All stations	4728	0.29	-0.03

TABLE 2

Average monthly AOD comparison between Aqua and sun photometer measurements

Stations	Number	RMSE	MBE
Luang Namtha	56	0.34	-0.26
Chiang Mai	70	0.31	-0.24
Ubon Ratchathani	50	0.11	-0.01
Nakhon Pathom	76	0.17	0.09
Songkhla	19	0.09	0.05
Penang	51	0.18	-0.01
Sarawak	19	0.22	0.03
Singapore	13	0.27	0.05
Manila	49	0.11	-0.07
Koronadal	67	0.12	0.08
Jambi	18	0.42	0.13
Bandung	57	0.20	0.12
Pontianak	25	0.16	-0.02
Palangkaraya	23	0.25	-0.02
All stations	593	0.22	-0.02

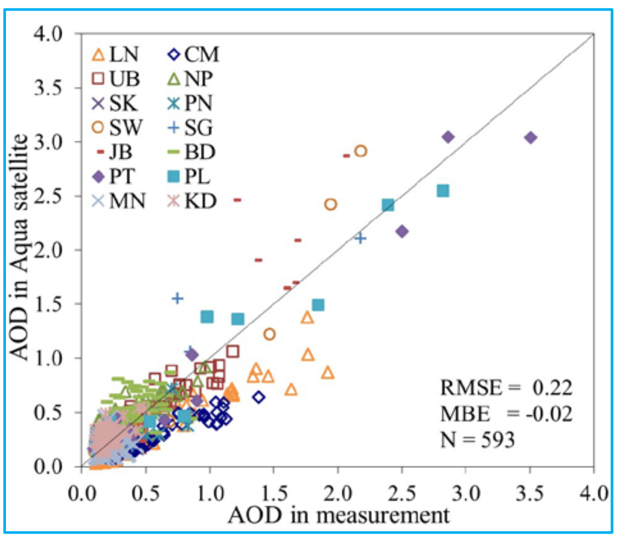


Fig. 1. Comparison of monthly average AOD between Aqua with sunphotometer observation

2.2. *Satellite data*

The Aqua satellite, launched in May 2002, is home to the rotating scan mirror-type MODIS (Moderate Resolution Imaging Spectroradiometer) instrument. MODIS measures solar radiation and reflected sunlight energy from measured areasof Earth in 36 spectrum channels ranging from 0.40 to 14.39 μm (http://modis.gsfc.nasa.gov/).

In this work, AOD data from Aqua's MODIS corresponding to the ground on observed surface was used for the period 2012 to 2020. The data was obtained in a daily format at a spatial resolution of about 10 km^2.

OMI (Ozone Monitoring Instrument) is a high-resolution spectrometer in ultraviolet and VIS (270–500 nm) ranges (ftp://toms.gsfc.nasa.gov/pub/omi/data/). It is one of the four instruments on Aura satellite. The Aura mission is part of EOS, launched in July 2004 (Gadde *et al.*, 2009; Torres *et al.*, 2007). The OMI operates over a wide area of 2600 km and provides daily AOD (OMAERUVd003) global coverage at a spatial resolution varying from 1° × 1° (Torres *et al.*, 2007). The surface ultra violet algorithm applied to OMI data is considered to be a continuation of the TOMS (Total Ozone Mapping Spectrometer) ultra violet algorithm developed by GSFC (Schoeberl *et al.*, 2006; Tanskanen *et al.*, 2006).

3. Experimental results

AOD data from instruments at fourteen sunphotometer stations and that from the Aqua satellites over southeast Asia. This check is made by comparing value to the ground value measured by CIMEL in the same area of a wavelength at 0.5 μm root mean square error (RMSE) during 0.09 to 0.42 (0.22 all-stations case) as presented of Tables 1, 2 and Fig. 1.

TABLE 3

Comparison of daily AOD between OMI and sunphotometer at fourteen stations

Stations	Number	RMSE	MBE
Luang Namtha	400	0.38	-0.14
Chiang Mai	511	0.35	-0.20
Ubon Ratchathani	209	0.19	-0.04
Nakhon Pathom	304	0.28	-0.08
Songkhla	181	0.25	0.16
Penang	193	0.56	0.06
Sarawak	106	0.31	0.09
Singapore	205	0.35	0.08
Manila	363	0.24	0.05
Koronadal	237	0.18	0.07
Jambi	108	0.38	0.01
Bandung	286	0.26	-0.09
Pontianak	170	0.25	0.08
Palangkaraya	149	0.82	-0.16
All stations	3422	0.35	-0.04

TABLE 4

Comparison of the monthly AOD between Aura satellite and sunphotometer

Stations	Number	RMSE	MBE
Luang Namtha	59	0.23	-0.07
Chiang Mai	74	0.20	-0.11
Ubon Ratchathani	72	0.17	0.01
Nakhon Pathom	91	0.19	-0.08
Songkhla	68	0.18	0.12
Penang	77	0.40	0.06
Sarawak	53	0.21	0.05
Singapore	86	0.25	0.02
Manila	82	0.12	0.02
Koronadal	76	0.10	0.07
Jambi	55	0.27	-0.08
Bandung	72	0.20	-0.13
Pontianak	75	0.47	-0.02
Palangkaraya	72	0.44	-0.07
All stations	1012	0.27	-0.01

Tables 3, 4 and Fig. 2 display the comparison of the AOD measured in southeast Asia and from Aura satellite using daily and monthly data. Overall, RMSE is in range of 0.10 to 0.82. The total station RMSE values are 0.27 for case monthly. The AOD conducted at the sunphotometer stations was taken at 500 nm, whereas the AOD obtained by Aura satellite was also taken at 500 nm.

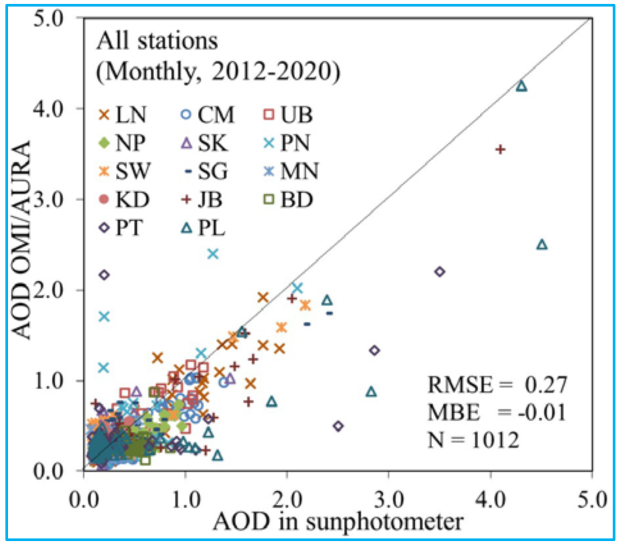


Fig. 2. Shows a comparison of the average monthly AOD between OMI with sunphotometer data at fourteen locations over the nine-year period from 2012 to 2020

Fig. 3. shows AOD maps monthly during sixteen-year period (2005-2020) for southeast Asia have decreased during July – August – September – October – November – December – January – February and higher values from March – April – May – June.

Fig. 4. shows seasonal average AOD for the period 2005 to 2020. The Southeast Asia's seasons are summer (March-May) and winter (June-February). According to South East Asia seasonal patterns, the AOD was higher and reached its maximum in the summer but was lower and reached its minimum in winter.From the yearly map (Fig.5), it is observed that most parts of Myanmar, Laos, Thailand, Cambodia and Vietnam receive higher AOD than Timor Leste, Malaysia, Singapore, Brunei and Indonesia.

Factors affecting the AOD include organic carbon surface mass concentration (OC, M2TMNXAER v5.12.4**)** and black carbon surface mass concentration (BC, M2TMNXAER v5.12.4) from MERRA 2 (spatial resolution of 0.5° ×0.625°) and specific humidity (Q, NOAH025 M v2.1) from GLDAS (0.25° latitude×0.25° longitude) data used in the proposed model. In order to evaluate the AOD in southeast Asia, these parameters were included in model. The model developed was defined as follows:

Daily data : $AOD = a_1 + a_2 InOC + a_3 BC + a_4 Q$ (1)

$R = 0.71$, $n = 11237$ where OC ($\mu g/m^3$); BC ($\mu g/m^3$); Q(-).

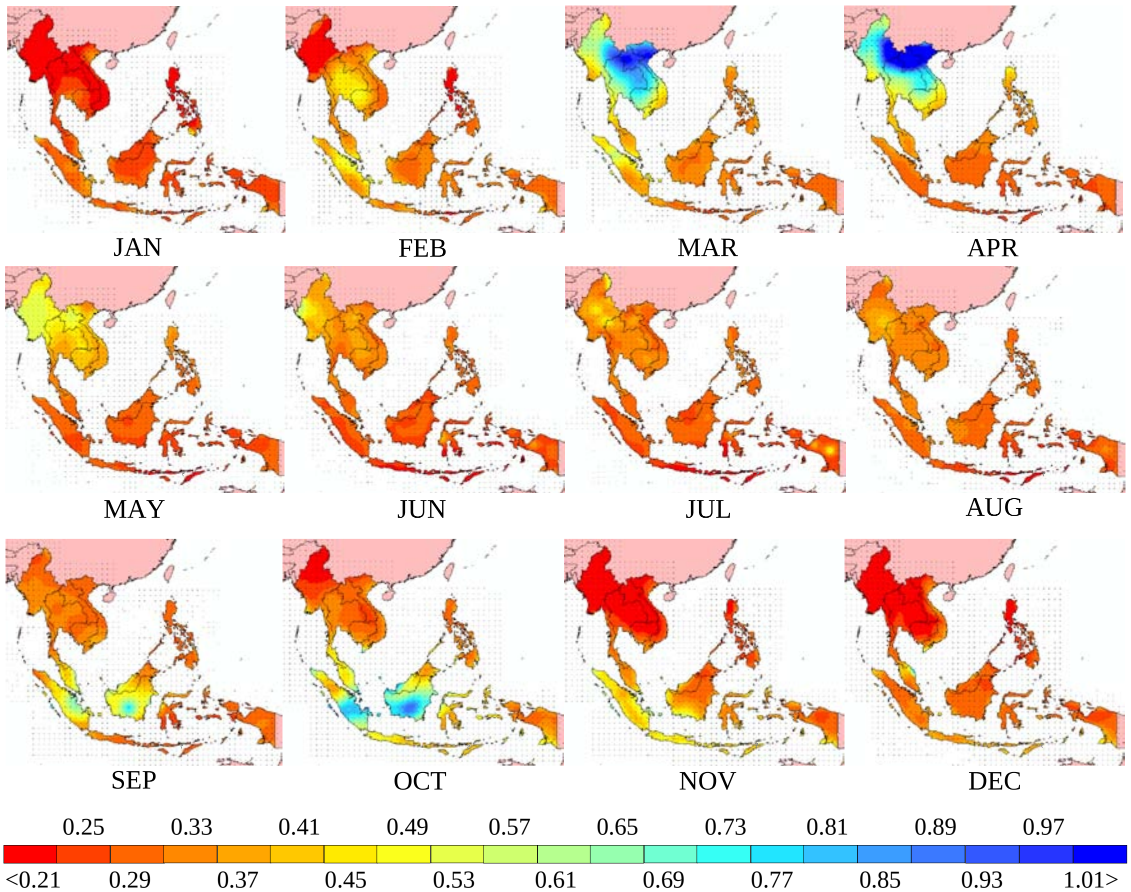


Fig. 3. Monthly average AOD (OMI) maps (the values of the AOD in maps were averaged from 16-year period of data for January-December)

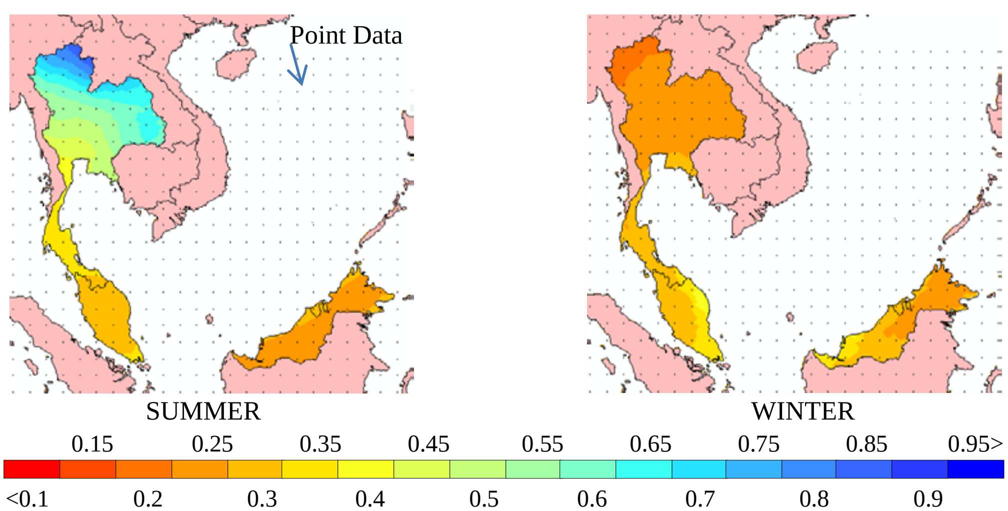


Fig. 4. Summer and winter maps of the seasonal average AOD. The values of the AOD in maps were from data collected over sixteen-year period

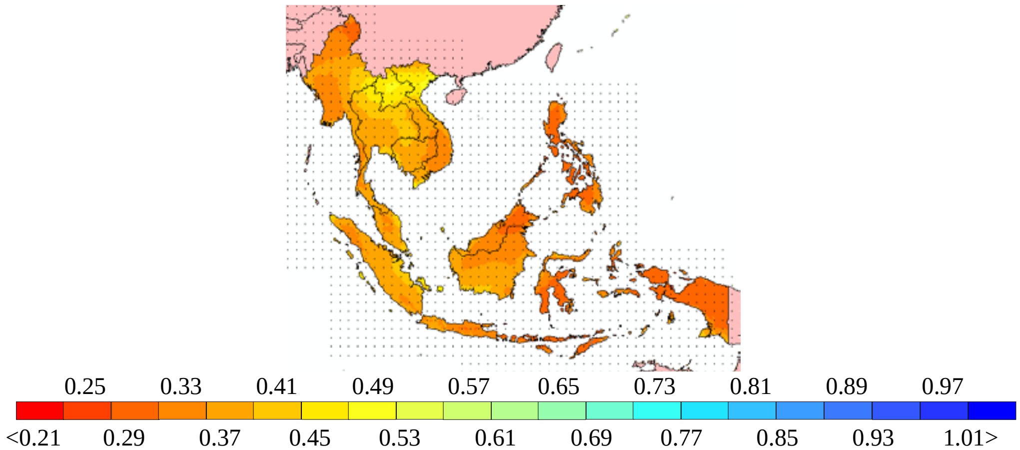


Fig. 5. Yearly average AOD map based on 16-year period of data, 2005 to 2020

TABLE 5

Coefficients from Eqn. (1) and corresponding t-statistics and p-values

Coefficient	Values of coefficient	t-values	p-statistics
a_1	-0.26421	-10.2450	<0.001
a_2	0.23132	42.2672	<0.001
a_3	0.11645	39.1849	<0.001
a_4	15.54178	10.7606	<0.001

TABLE 6

Values of coefficients from Eqn. (2) and corresponding t-values and p-statistics

Coefficient	Values of coefficient	t-statistics	p-values
a_1	-0.40894	-4.94620	<0.00001
a_2	0.12073	6.57474	<0.00001
a_3	0.25563	17.38275	<0.00001
a_4	24.21913	5.23369	<0.00001

Monthly data: $AOD = a_1 + a_2 InOC + a_3 BC + a_4 Q$ (2)

$R = 0.83$, $n = 633$ where OC ($\mu g/m^3$); BC ($\mu g/m^3$); Q(-).

The coefficients a_1, a_2, a_3 and a_4 in Eqns. (1) and (2) were derived from sunphotometer surface at fourteen stations and the satellite-based data for period 2012–2016 by using STATISTICA v10 program, according to methods of Buntoung *et al.*, 2021 and Choosri *et al.*, 2017.

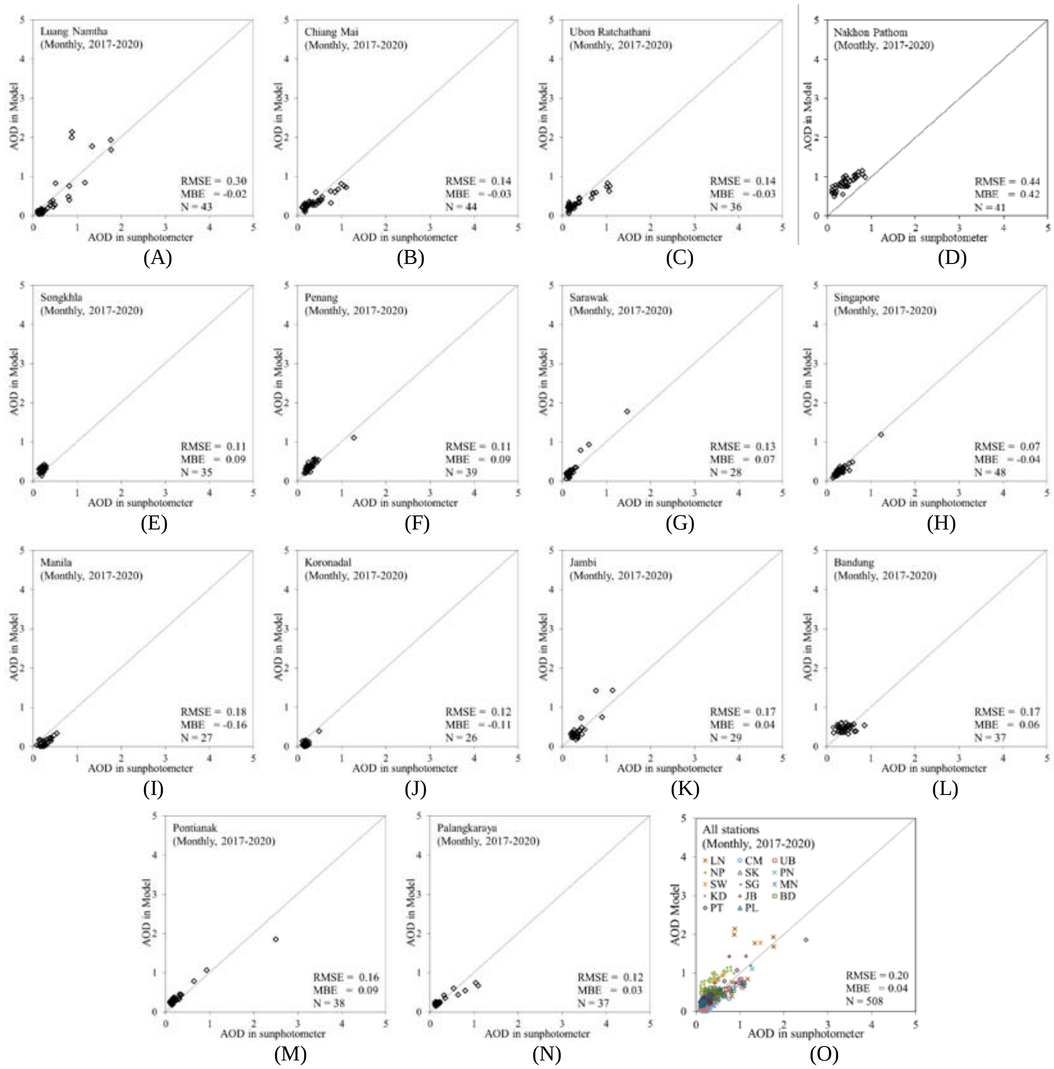
TABLE 7

Comparison of the daily AOD model with sunphotometer measured and all stations

Stations	Number	RMSE	MBE
Luang Namtha	921	0.42	0.00
Chiang Mai	897	0.23	-0.02
Ubon Ratchathani	732	0.21	0.02
Nakhon Pathom	786	0.33	0.26
Songkhla	520	0.17	0.10
Penang	703	0.24	0.13
Sarawak	349	0.26	0.10
Singapore	808	0.20	-0.01
Manila	360	0.35	-0.19
Koronadal	272	0.13	-0.05
Jambi	466	0.41	0.09
Bandung	629	0.25	0.06
Pontianak	663	0.35	0.17
Palangkaraya	695	0.38	0.06
Total stations	8801	0.30	0.06

The probability that the correction happened accidentally is shown by P value. The P-value of less than 0.0001 implies a higher influence of AOD, while a P value of less than 0.05 indicates a 5% possibility that this association happened by coincidence (Masiri *et al.*, 2017). The values of these coefficients and related statistics are shown in Tables 5 and 6.

Table 7 shows AOD calculated from model compared to that obtained from sunphotometer.



Figs. 6(A-O). Comparison between monthlyAOD from the model (OC, BC, Q) and from sunphotometer at fourteen stations: A) LN, B) CM, C) UB, D) NP, E) SK, F) PN, G) SW, H) SG, I) MN, J) KD, K) JB, L) BD, M) PT, N) PL, and O) Total stations

Furthermore, they were contrasted with those obtained from AOD measured daily and monthly at these stations and outcomes are displayed in Fig. 6.

Factors affecting the AOD include the visibility (Vis) and angstrom exponent (α) data used in the study proposed model2. In order to evaluate the AOD in southeast Asia, these parameters were included in the model2. The model2 developed was defined as follows:

$$\text{Monthly data: AOD} = b_1 + b_2\text{VIS} + b_3\text{VIS}^2 + b_4\alpha \qquad (3)$$

R = 0.94, n = 124 where VIS (km); α (unitless).

TABLE 8

Values of coefficients from Eqn. (3) and corresponding t-values and p-statistics

Coefficient	Values of coefficient	t-statistics	p-values
b_1	5.933565	15.0021	<0.00001
b_2	-0.747029	-16.0073	<0.00001
b_3	0.023330	13.7719	<0.00001
b_4	0.237221	2.1578	<0.00001

The coefficients b_1, b_2, b_3, and b_4 in Eqn. (3) were derived from sunphotometer surface at seven stations and satellite-based data for period 2011-2016. The values of these coefficients and related statistics are shown in Table 8.

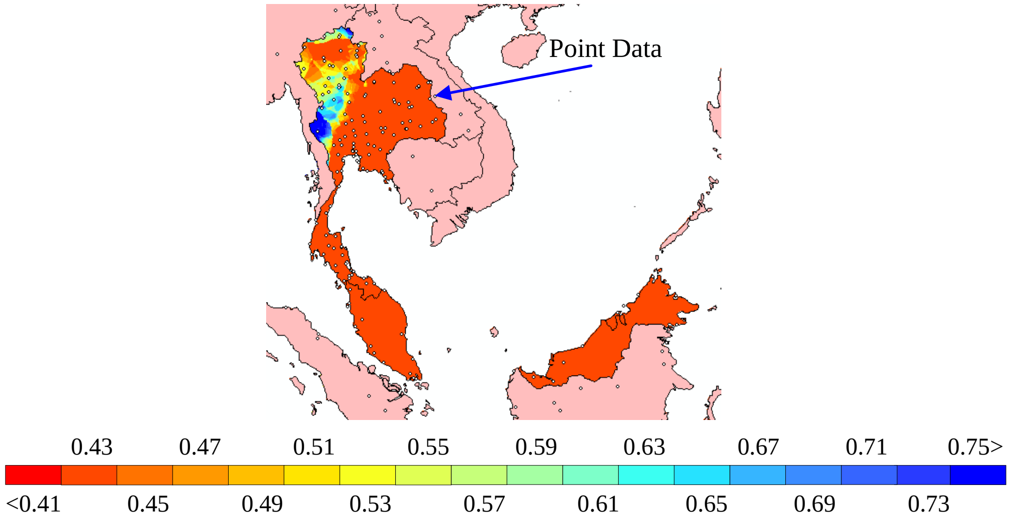


Fig. 8. Annual average monthly AOD (model2) map based on 195 meteorological stations for the nine-year period, 2012 to 2020

TABLE 9

Comparison of monthly AOD model with sunphotometer at seven stations and total stations

Stations	Number	RMSE	MBE
Chiang-Mai	31	0.23	-0.10
Ubon-Ratchathani	21	0.24	0.01
Nakhon-Pathom	31	0.19	-0.07
Songkhla	9	0.14	0.12
Penang	17	0.15	0.14
Sarawak	9	0.40	0.23
Singapore	11	0.27	-0.12
Total stations	129	0.23	-0.01

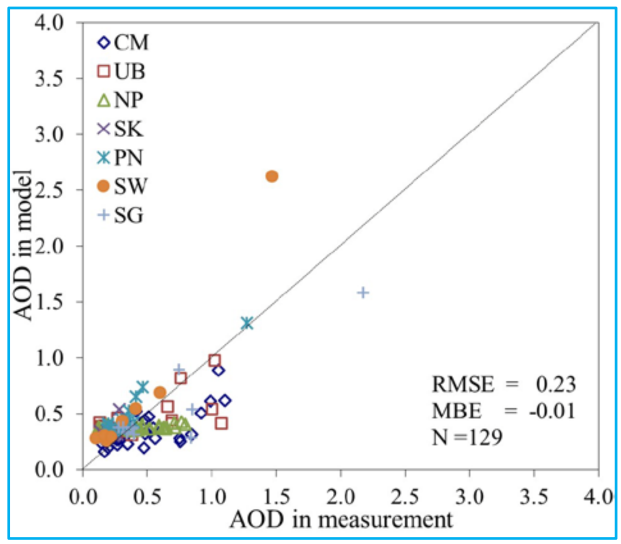


Fig. 7. Comparison between monthly AOD from model2 (Vis, α) and from sunphotometer at seven station

Table 9 shows AOD calculated from model2 compared to that obtained from measurements using tested with independent data for 2017-2020. However, they were contrasted with those obtained from AOD measured at these stations and outcomes are displayed over Fig. 7.

Moreover, the geographical distribution according to annual average AOD of regions displayed for Fig. 8. demonstrates a clear pattern that is heavily influenced by topography for four countries and tropical monsoons. However, visibility data were collected from 195 meteorological stations in 8 countries.

4. Discussion and conclusion

This study compared AOD data over MODIS/Aqua satellite, OMI/Aura satellite with those from ground on observed surfaces at fourteen sunphotometer locations: Luang Namtha, Chiangmai, Ubonratchathani, Nakhonpathom, Songkhla, Penang, Sarawak, Singapore, Manila, Koronadal, Jambi, Bandung, Pontianak and Palangkaraya. The RMSE between the AOD daily and monthly information obtained from the MODIS, OMI and from sunphotometer observation was between 0.09–0.82. The AOD maps reveal strong seasonality for Myanmar, Laos, Thailand, Cambodia and Vietnam with high values in summer months of March-May. In the case of Timor-Leste, Malaysia, Singapore, Bruneiand Indonesiaalso exhibit a similar seasonal pattern, with AOD being at its highest in winter months of September to November.The results were displayed as AOD maps. The variability of AOD in southeast Asia is largely influenced by topography of the eleven countries and the tropical monsoons. Based on validation findings at the fourteen stations, the proposed model predicted the daily and monthly AOD estimates using the organic carbon and black carbon from MERRA-2 reanalysis and specific humidity from GLDAS model, with an MBE and RMSE of 0.04 and 0.20, respectively (monthly).Based on validation findings at the seven stations, the proposed model2 predicted the monthly AOD estimates using the angstrom exponent data from Aqua and visibility observed at 195 meteorological stations, with an MBE and RMSE of -0.01 and 0.23, respectively.

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