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Research Article

Performance of MODIS Deep Blue Collection 6.1 Aerosol Optical Depth Products Over Indonesia: Spatiotemporal Variations and Aerosol Types

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This study aims to evaluate the performance of the long-term Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue (DB) Collection 6.1 (C6.1) in determining the spatiotemporal variation of aerosol optical depth (AOD) and aerosol types over Indonesia. For this purpose, monthly MODIS DB AOD datasets are directly compared with Aerosol Robotic Network (AERONET) Version 3 Level 2.0 (cloud-screened and quality-assured) monthly measurements at 8 sites throughout Indonesia. The results indicate that MODIS DB AOD retrievals and AERONET AOD measurements have a high correlation in Sumatra Island (i.e., Kototabang ($r = 0.88$) and Jambi ($r = 0.9$)) and Kalimantan Island (i.e., Palangkaraya ($r = 0.89$) and Pontianak ($r = 0.92$)). However, the correlations are low in Bandung, Palu, and Sorong. In general, MODIS DB AOD tends to overestimate AERONET AOD at all sites by 16 to 61% and can detect extreme fire events in Sumatra and Kalimantan Islands quite well. Aerosol types in Indonesia mostly consist of clean continental, followed by biomass burning/urban industrial and mixed aerosols. Palu and Sorong had the highest clean continental aerosol contribution (90%), while Bandung had the highest biomass burning/urban-industrial aerosol contribution to atmospheric composition (93.7%). For mixed aerosols, the highest contribution was found in Pontianak, with a proportion of 48.4%. Spatially, the annual mean AOD in the western part of Indonesia is higher than in the eastern part. Seasonally, the highest AOD is observed during the period of September–November, which is associated with the emergence of fire events.

1. Introduction

Aerosol is a collection of liquid and solid particles measuring 0.001–100 microns that are suspended in the atmosphere, except for hydrometeors (raindrops, cloud droplets, ice crystals, and snowflakes) [1]. Based on the source, aerosols consist of natural sources and anthropogenic sources [2, 3]. Natural sources include sea spray, mineral dust, vegetation fires, and volcanic ash. Anthropogenic sources, for example, are the combustion of fossil fuels, biofuels, or vegetation fires caused by humans [4]. Aerosols can act as solar and terrestrial radiation absorbers and scatterers, as well as condensation nuclei in water droplets and ice crystals, potentially affecting climate change [5, 6], human health [7, 8], and air quality [9]. As solar radiation scatterers, aerosols (e.g., sulfate aerosols) play the opposite role to greenhouse gases in the atmosphere, causing a direct effect such as cooling the Earth's surface and also having an indirect effect by altering cloud formation and their properties [10, 11]. However, some aerosols (e.g., black carbon) can act as solar radiation absorbers, causing warming in the troposphere and affecting atmospheric stability and cloud microphysics [5, 12].

Indonesia is an archipelagic country that has approximately 17,000 islands, with five major islands, namely Sumatra, Java, Kalimantan, Sulawesi, and Papua. Currently, Indonesia's total population reaches more than 270 million people and ranks as the fourth most populous country in the world. Only about 30% of Indonesia's territory is land, and it has a complex topography with vegetation cover dominated by forestland. Naturally, Indonesia produces aerosols derived from organic components of vegetation, forest fires, sea salt, and volcanic ash. Furthermore, man-made aerosols are also generated by urban/industrial activities such as burning fossil fuels and burning biomass.

Aerosol optical depth (AOD) is a parameter used to determine the quantity of aerosol in the atmosphere. AOD is obtained by calculating the amount of light absorbed or scattered in an atmospheric column [13]. AOD can be obtained from direct sunlight measurements on the Earth's surface using a sun photometer and indirectly from reflected radiation from the Earth's surface captured by satellite sensors [14]. Ground-based AOD measurements provide aerosol properties at specific locations that have a high temporal and spectral resolution but have a weakness in spatial resolution. In contrast, satellite-based AOD retrievals provide aerosol information with high spatial resolution but low accuracy [15].

Aerosol Robotic Network (AERONET) is a global ground-based remote sensing network established by NASA (National Aeronautics and Space Administration) and PHOTONS (Photométrie pour le Traitement Opérationnel de Normalization Satellitaire) that aims to conduct long-term aerosol observations and analyze local aerosol optical properties. Additionally, AERONET data can be used to validate satellite remote sensing data [16, 17]. Although ground-based aerosol measurements have a high temporal resolution, global-scale AOD data from satellites are required for a better understanding of the distribution and influence of aerosols on a larger scale.

Remote sensing can acquire aerosol properties on a wider scale. The moderate resolution imaging spectroradiometer (MODIS) instrument on Aqua and Terra satellites can provide aerosol information spatially and temporally at global and regional scales [18]. MODIS has a spectral range of 36 bands at a wavelength of 0.4–1.44 nm. This satellite is a polar orbital satellite that operates at an altitude of 705 km with a width of view of 2230 km and a temporal scale of 1-2 days. The Terra spacecraft crossed the equator at 10:30 am local standard time (LST), and the Aqua spacecraft crossed the equator at 13:30 LST [19]. Many studies have validated AOD between satellite-based and ground-based measurements in various parts of the world and found a high correlation [20–23].

The MODIS collection 6.1 (C6.1) AOD dataset is the most recent version in which the aerosol data collection process has been improved. There are two well-known official aerosol retrieval algorithms, including the dark target (DT) algorithm over land and ocean and the deep blue (DB) algorithm over land. In this study, we used MODIS DB C6.1 AOD products with the following considerations, and the DB algorithm has been developed to have a good performance on bright surfaces such as deserts and snowy areas but also be good at interpreting surfaces that have high vegetation, such as those in the tropics [24]. In addition, the DB product is superior at the site scale [25].

Several studies examining the performance of MODIS in conducting AOD retrieval in Indonesia, especially Kalimantan forest fires in 2015, show that the MODIS satellite is good at capturing fire events [26]. There is no study that has been conducted to investigate the performance of the MODIS DB C6.1 satellite in Indonesia. This study aims to examine the performance of the Terra MODIS DB C6.1 AOD retrievals over Indonesia by comparing them with ground-based AERONET measurements over a long-term period. Previous studies have also utilized AOD and its properties to detect aerosol types over the Middle East [27]. Therefore, MODIS DB C6.1 AOD datasets were analyzed to classify aerosol types and assess their contribution to aerosol composition at AERONET sites in Indonesia. Finally, spatial and seasonal variations of aerosols over Indonesia were discussed.

2. Methods

AERONET measures aerosols on the ground using a Cimel sun photometer, which is a multichannel, automatic sun-and-sky scanning radiometer that measures the direct solar irradiance and sky radiance at the Earth's surface. The instrument serves to measure direct sun and diffuse sky radiances at wavelengths of 340, 380, 440, 500, 675, 870, 1020, and 1640 nm where these measurements will produce AOD and Ångström exponent (AE) [28]. AE is often used as a qualitative indicator of aerosol particle size. The greater the AE value, the smaller the aerosol particle size and vice versa [29]. There are three levels of data on AERONET, namely data level 1.0 (unscreened), level 1.5 (cloud-screened and quality controlled), and level 2.0 (cloud-screened and quality-assured). AERONET data can be downloaded on the AERONET website (https://aeronet.gsfc.nasa.gov).

There are ten AERONET sites in Indonesia, but only eight of them provide level 2.0 data. The eight AERONET sites used in this study include GAW Kototabang, Jambi, Bandung, Pontianak, Palangkaraya, Makassar, GAW Palu, and Sorong (Figure 1). This study uses monthly AERONET AOD data level 2.0 version 3.0 from 2009 to 2019 (11 years). However, at several sites, the installation of sun photometers started in 2012 and 2015, so the length of the available AERONET AOD data is limited.

The Terra MODIS DB C6.1 level 3 AOD monthly data (M x 08_M3) with $1^{\circ} \times 1^{\circ}$ horizontal resolution were derived from level 1 and atmosphere archive & distribution system (LAADS) (https://ladsweb.nascom.nasa.gov) from 2009 to 2019 (11 years) [30]. MODIS DB C6.1 has better spatial coverage, including vegetated and bright surfaces [31]. The MODIS DB C6.1 AOD at 550 nm was obtained by

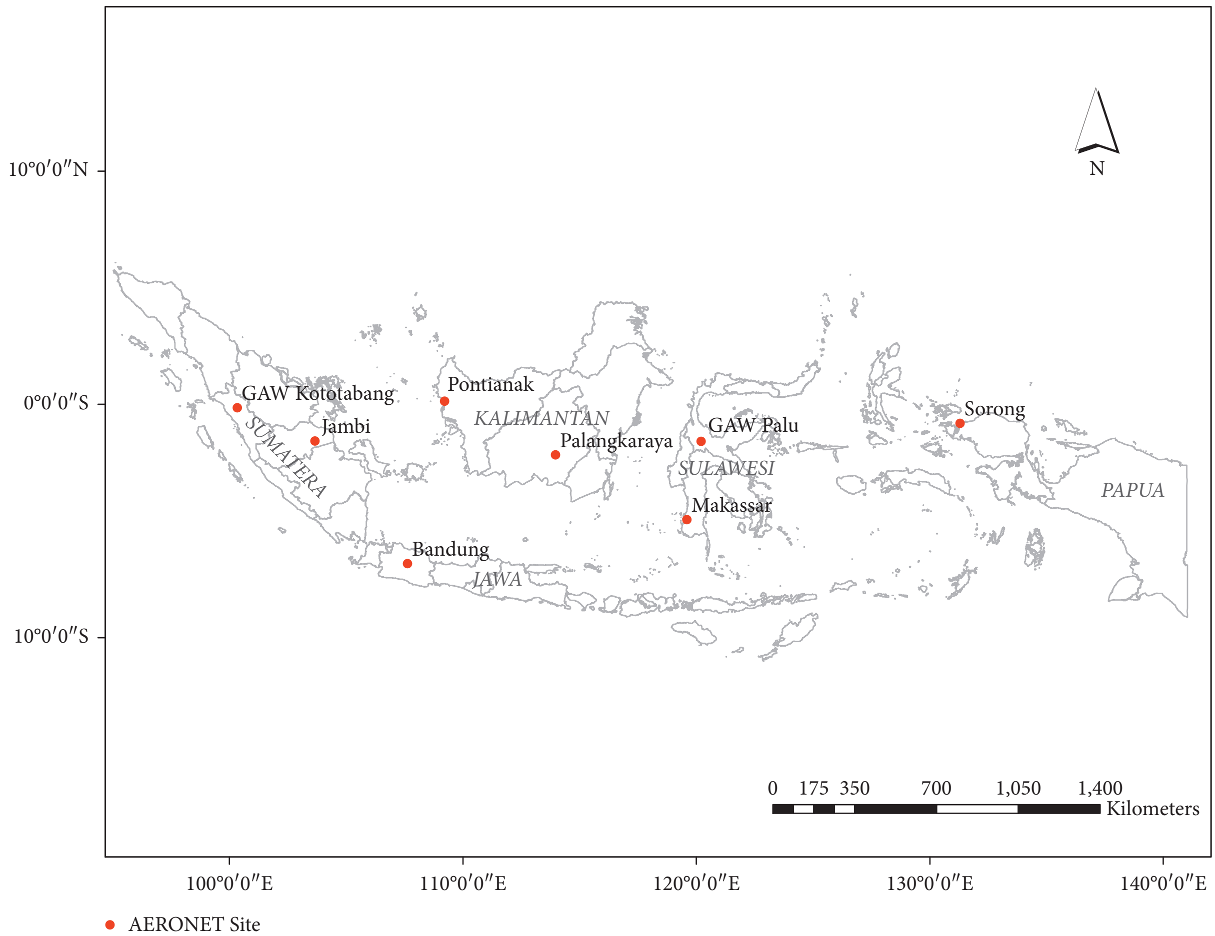

FIGURE 1: Aerosol robotic network (AERONET) sites used in this study.

interpolation at 470 nm and 670 nm wavelengths. In global climate modeling, the 550 nm wavelength is very important because it is the most scattered in the atmosphere and is widely used in various chemistry models [32].

In this study, the monthly MODIS AOD retrievals were derived from the Scientific Data Set (SDS) "Deep_Blue_Aerosol_Optical_Depth_550_Land_Mean_Mean" and defined by centering the nearest pixel on the AERONET site. The corresponding monthly AERONET AOD measurement was regarded as the true value. The MODIS AE was obtained from SDS "Deep_Blue_Aerosol_Optical_Depth_Land_Mean_Mean". Since the SDS provides only 3 visible wavelengths (412 nm, 470 nm, and 660 nm), then the MODIS AE value is calculated using equation (1).

In addition, the MODIS Terra active fire products were derived from NASA Fire Information for Resource Management System (FIRMS) (https://firms.modaps.eosdis.nasa.gov/active_fire) [33] with an 80% confidence level to investigate the effect of fire events (e.g., forest fires and agricultural residues) on AOD in Indonesia.

$$\text{Ångström Exponent}\,(\text{AE or }\alpha) = -\frac{\ln(\text{AOD470}/\text{AOD660})}{\ln(470/660)}. \quad (1)$$

Furthermore, since AERONET does not directly measure AOD at 550 nm, then AERONET AOD at 550 nm wavelength is interpolated using the power law given in equation (2). α in equation (2) represents the value of AERONET AE at 440–870 nm.

$$\text{AERONETAOD}_{550\text{nm}} = \text{AERONETAOD}_{500\text{nm}}\left(\frac{550}{500}\right)^{-\alpha}. \quad (2)$$

The performances of the MODIS AOD retrievals are evaluated by calculating relative mean bias (RMB) (Equation (3)), root mean-square-error (RMSE) (Equation (4)), mean absolute error (MAE) (Equation (5)), and Pearson correlation coefficient (r). Quantitative evaluation of the AOD retrieval uncertainty is described using the expected error (EE) envelope that encompasses the sum of absolute and relative errors as shown in Equation (6a) [34, 35]. The slope and intercept between collocated MODIS AOD and AERONET AOD were calculated using the reduced major axis (RMA) method, which incorporates errors in both independent (AERONET) and dependent (MODIS) variables [36].

$$\text{RMB} = \frac{\left(\overline{\text{AOD}}_{550\text{nmMODIS}} - \overline{\text{AOD}}_{550\text{nmAERONET}}\right)}{\overline{\text{AOD}}_{550\text{nmAERONET}}} \times 100, \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\text{AOD550nm}_{(\text{MODIS})i} - \text{AOD550 nm}_{(\text{AERONET})i}\right)^2}, \quad (4)$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|\text{AOD550 nm}_{(\text{MODIS})i} - \text{AOD550nm}_{(\text{AERONET})i}\right|, \quad (5)$$

$$\text{EE} = \pm\left(0.05 + 0.15 \times \text{AOD}_{\text{AERONET}}\right), \quad (6a)$$

$$\text{Upper EE envelope} = \text{AOD}_{\text{AERONET}} + |\text{EE}|, \quad (6b)$$

$$\text{Lower EE envelope} = \text{AOD}_{\text{AERONET}} - |\text{EE}|, \quad (6c)$$

$$\%\text{EE} = \left(\text{Lower EE envelope} \le \text{AOD}_{\text{MODILS}} \le \text{Upper EE envelope}\right) \times 100, \quad (6d)$$

$$+\%\text{EE} = \left(\text{AOD}_{\text{MODIS}} \ge \text{Upper EE envelope}\right) \times 100, \quad (6e)$$

$$-\%\text{EE} = \left(\text{AOD}_{\text{MODIS}} \le \text{Lower EE envelope}\right) \times 100, \quad (6f)$$

where |EE| is the absolute value of EE. RMB > 0 and RMB < 0 represent over- and under-estimation of MODIS AOD retrievals compared to AERONET AOD, respectively. RMSE = 0 represents the collocated points on the 1 : 1 ($x = y$) line, and RMSE > 0 represents the collocated points scattered away from the 1 : 1 line.

Several studies have shown that a relationship between AOD 550 nm and AE can be utilized to determine aerosol types as shown in Table 1. In this study, aerosols have been classified into (1) clean continental, (2) biomass burning/urban industrial, (3) clean marine, (4) desert dust, and (5) mixed type aerosols. This classification method is based on previous studies [37, 38].

3. Results and Discussions

Figure 2 illustrates the comparison of monthly AOD 550 nm from ground observation (AERONET) and MODIS at AERONET sites in Indonesia. The number of observations (n) at each AERONET site varies due to the sun photometer's varying installation dates and poor data quality. The MODIS AOD retrievals exhibited good correlations with AERONET AODs in Sumatra and Kalimantan Islands. In Sumatra, the correlation in Kototabang ($r = 0.88$, $n = 23$) was slightly lower than in Jambi ($r = 0.90$, $n = 46$). But MODIS AODs in Kototabang exhibited 52.17% of retrievals falling within EE with an average MAE of 0.09 and an RMSE of 0.21, showing slightly better performance compared to that in Jambi (50% of retrievals falling within EE, MAE = 0.22, and RMSE = 0.42). In Kalimantan, MODIS AODs in Pontianak ($r = 0.92$, $n = 59$, 42.37% of retrievals falling within EE, MAE = 0.08, and RMSE = 0.237) indicated better performance compared to those in Palangkaraya ($r = 0.89$, $n = 52$, 28.85% of retrievals falling within EE, MAE = 0.134, and RMSE = 0.38).

Low correlations between MODIS AODs and AERONET AODs were found in Bandung ($r = 0.30$, $n = 90$) with 52.81% of retrievals falling within EE, GAW Palu ($r = 0.23$, $n = 24$) with 20.83% of retrievals falling above EE, and Sorong ($r = 0.35$) with 10% of retrievals falling above EE. While in Makassar, the correlation is a bit high ($r = 0.64$, $n = 15$), but only 26.67% of retrievals fall within EE. Poor performance of MODIS AODs at GAW Palu, Makassar, and Sorong may be caused by the small number of available observations, but it is not the case in Bandung. However, if we look in detail, the similarity of the four sites was having low AOD variations, and AERONET AOD values are less than 1. This may suggest that MODIS was unable to capture low AOD variations at that site, which is probably due to coarse spatial resolution. The RMB values are always more than 0 at all AERONET sites, meaning overestimation of MODIS AOD retrievals compared to AERONET AOD. In general, MODIS AOD tends to overestimate AERONET AOD by 16.28% (Sorong) to 61.11% (GAW Palu).

The time series plot of monthly MODIS AOD and AERONET AOD is depicted in Figure 3. It is shown that MODIS AOD can capture the peak AOD, which represents extreme events from the AERONET observation data. An extreme event could cause AOD to increase significantly in Indonesia, such as forest fires. In Indonesia, forest fires are rarely caused by nature but mainly by local communities clearing agricultural or plantation land. Forest fires often

Table 1: Aerosol classification.

Aerosol type	AOD	AE
Clean continental (CC)	<0.2	>1.0
Biomass burning/urban industrial (BB/UI)	>0.3	>1.0
Clean marine (CM)	<0.2	<0.9
Desert dust (DD)	>0.5	<0.7
Mixed	Remaining	Remaining

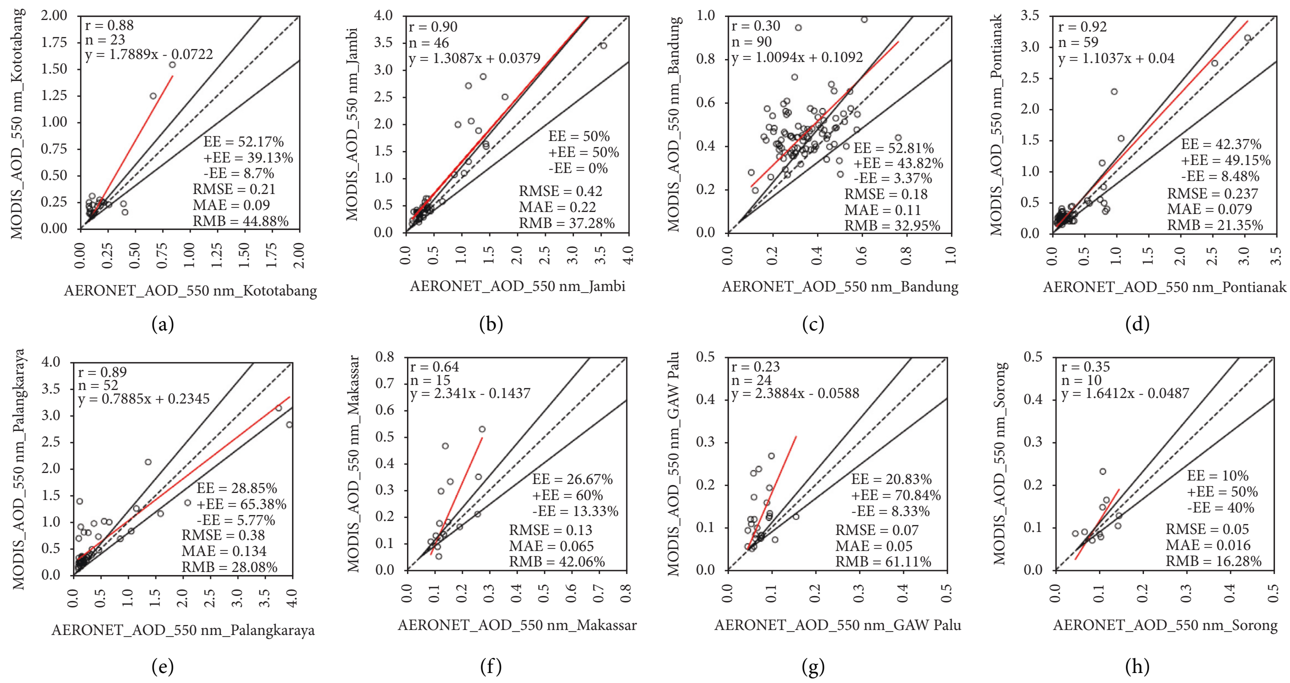

Figure 2: Density scatterplot of monthly MODIS DB AOD 550 nm retrievals against AERONET AOD measurements at 550 nm at AERONET sites over Indonesia, which include Kototabang (a), Jambi (b), Bandung (c), Pontianak (d), Palangkaraya (e), Makassar (f), GAW Palu (g), and Sorong (h). The solid lines are the envelopes of the expected error (EE), while the black dashed line is the 1 : 1 line, and the dashed black lines represent the upper and lower EE envelope. +EE indicates the overestimated tendency, while −EE indicates the underestimated tendency.

occur in Sumatra (Jambi) and Kalimantan (Pontianak and Palangkaraya), which cause regional air pollution [39]. The seasonality of Indonesia is mainly driven by the Asian monsoon (wet season) and the Australian monsoon (dry season) [40]. During the dry season (June–November), AOD has increased in several areas in Indonesia, such as Jambi, Pontianak, and Palangkaraya (Figure 3). This is likely related to forest fires that occur in the area since it is favourable to trigger forest fires during the dry season than during the wet season. In addition, the highest peak of AOD with a value of 3-4 occurred in September–October 2015 recorded in Jambi, Pontianak, and Palangkaraya. This extreme event was closely related to forest fires which were exacerbated by the strong El Niño event in 2015/2016.

Low AOD variations were found in Kototabang, GAW Palu, Sorong, Bandung, and Makassar. The first three locations (Kototabang, Palu, and Sorong) are the locations of global atmospheric watch (GAW) stations, which are located in remote areas. Although Bandung is one of the big cities in Indonesia, Bandung still has a low AOD variation. This condition may be influenced by the humid and cool highland climate to prevent the spread of pollutants. Similar to Bandung, Makassar is also a big city in Indonesia, but the AERONET AOD measurement in this city is still very limited. High AOD variations in Indonesia are generally caused by forest fires [41]. The increase in AOD value at Kototabang in September 2019 was influenced by forest fires in Sumatra that occurred during that period [42]. Despite the lack of time series data, Figure 3 shows that MODIS is generally able to capture the temporal pattern of AOD in Indonesia, especially since MODIS is quite good at detecting extreme values at the observation site.

In order to classify the aerosol types according to Table 1, Figure 4 shows the relationship between MODIS AOD and MODIS AE from 2009 to 2019. The x-axis is the AOD at 550 nm obtained from the MODIS DB C6.1, while the y-axis is the Ångström exponent (AE) value of the MODIS DB C6.1. The contribution of each aerosol type at

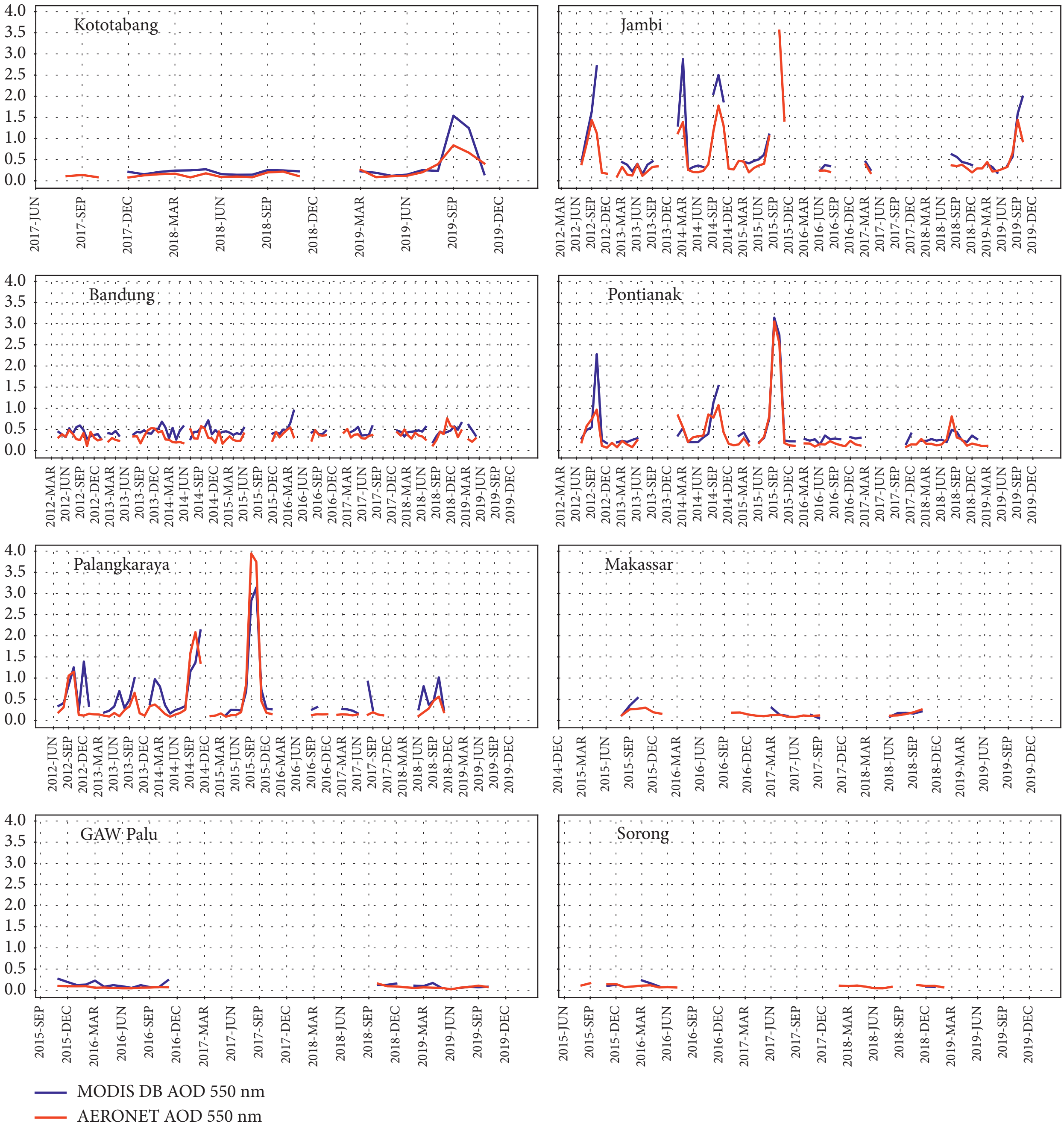

Figure 3: Time series plot of monthly MODIS DB AOD 550 nm retrievals against AERONET AOD measurements at 550 nm at AERONET sites over Indonesia.

each site was then calculated as a percentage and shown in Figure 5.

The contribution of aerosol types at AERONET sites in Indonesia is depicted in Figure 5. Most of the aerosols are clean continental (CC), followed by biomass burning/urban-industrial (BB/UI). The highest contribution of CC aerosol was found in GAW Palu and Sorong, with a contribution of more than 90%, while the highest contribution of BB/UI aerosol was found in Bandung, with a contribution of 93.7%. For mixed aerosols, the highest contribution was in Pontianak, with a contribution of 48.4%, while CM and DD aerosols were not found at all observation sites.

CC aerosols are natural aerosols that originate from areas that still have a lot of forests or urban areas that have large power plants or petrochemical refining [43, 44]. The observation stations at GAW Palu and Sorong have a dominant contribution from CC aerosols. Both sites are located in remote areas surrounded by tropical forests where there are fewer human activities related to fossil fuel combustion, such as industry and motor vehicles, that produce air pollution.

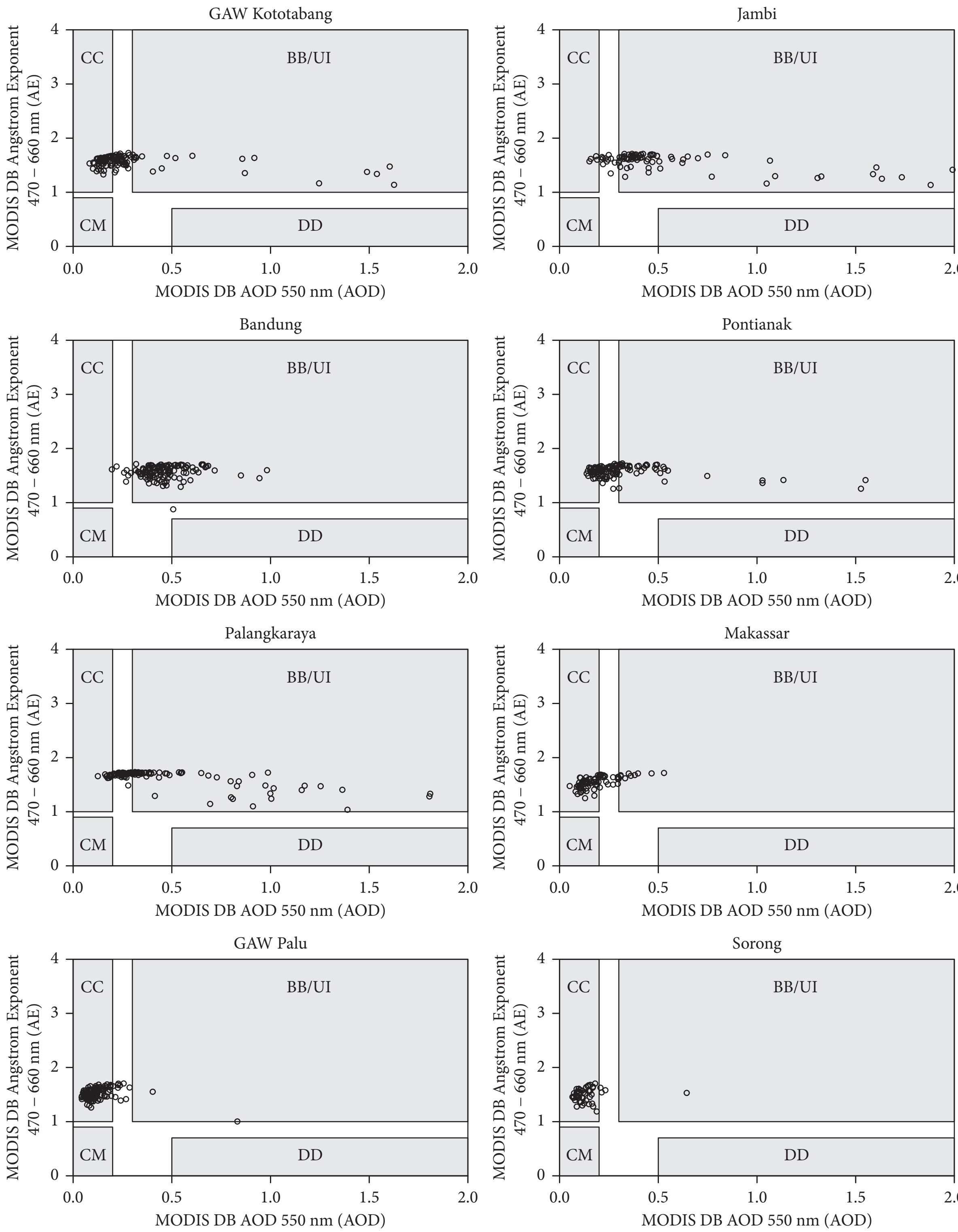

Figure 4: Relationship between monthly MODIS AOD 550 nm and AE at AERONET sites over Indonesia from 2009 to 2019 according to aerosol classification in Table 1.

BB/UI aerosols are aerosols that come from fossil fuels burning in industrial areas [45, 46]. These aerosols enter into an energy balance that is useful either for scattering solar radiation directly into space (direct effect) or by increasing cloud albedo through microphysical processes (indirect effect) [47–49]. These aerosols also have an indirect effect on the radiative and microphysical properties of clouds, which together influence the formation of precipitation [50]. Atmospheres containing a

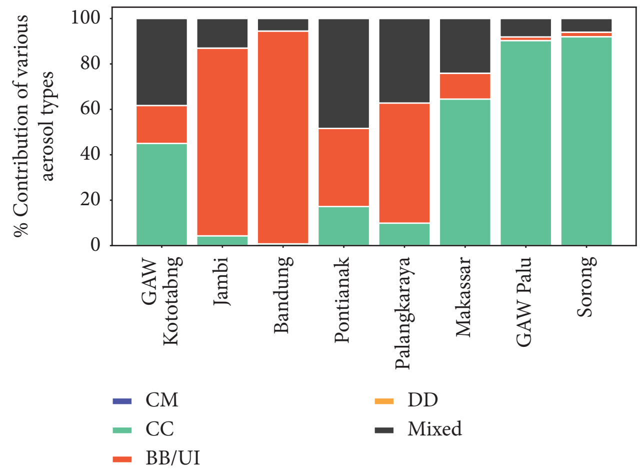

FIGURE 5: Aerosol types' contribution to atmospheric composition at AERONET sites over Indonesia from 2009 to 2019 obtained from the relationship between MODIS AOD 550 nm and AE (Figure 4) according to aerosol classification in Table 1.

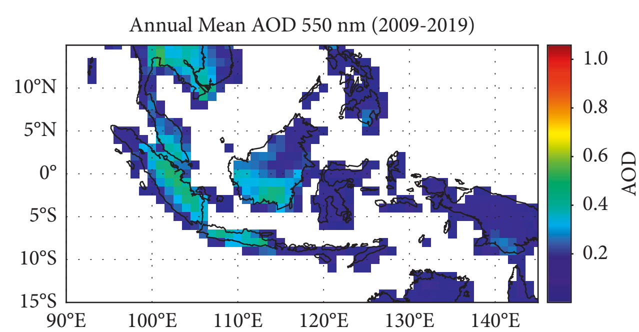

FIGURE 6: The spatial variation of the annual mean MODIS DB C6.1 AOD at 550 nm over land in Indonesia during the period 2009 to 2019.

high concentration of aerosols are associated with reduced light precipitation and increased moderate and heavy rainfall [51].

GAW Palu, Sorong, and Makassar are the three locations that have the lowest BB/UI contribution, namely 1.6%, 2%, and 11.4%, respectively. This means that industrial or fossil fuel burning activities are still minimal in these areas. In the meantime, GAW Kototabang has a BB/UI contribution of 16.7%, indicating the area has started to be affected by the impact of fossil fuel burning or industrial activities. On the other hand, capital cities like Palangkaraya, Bandung, Pontianak, and Jambi have BB/UI contributions of 52.9%, 93.7%, 34.4%, and 82.6%, respectively, which have been affected by industrial activities or the burning of fossil fuels.

Based on the annual mean MODIS AOD at 550 nm from 2009 to 2019, Figure 6 illustrates that the western region of Indonesia, which includes Sumatra, Kalimantan, and parts of western Java, has a higher AOD value than other parts of Indonesia, which reaching an AOD value of 0.6. Meanwhile, the central and eastern parts of Java, Nusa Tenggara, Sulawesi, Maluku, and Papua (eastern region of Indonesia) have an AOD value that is relatively lower, only in the range of 0–0.2. This is likely because of two main factors. First, Sumatra and Kalimantan are home to seasonal forest fire events in Indonesia that can increase the AOD significantly. Second, urban and industrial development has been concentrated in the western part of Indonesia for the last few decades, so the AOD value is higher than in the eastern part of Indonesia.

The spatial and seasonal variation of MODIS AOD at 550 nm is depicted in Figure 7 for December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). The AODs were low and evenly distributed over Indonesian land during DJF, which is associated with the rainy season in most of Indonesia's regions. Previous studies showed that light precipitation decreases air quality while heavy rainfall improves the air quality [52, 53]. Meanwhile, the highest AOD values were observed during SON (the transition period from the dry to wet season), especially for Sumatra, Kalimantan, and most parts of Java. This condition was related to the emergence of forest fire events that caused an increase in AOD in Sumatra and Kalimantan during August, September, and October (Figure 8). In Java, where urban and industrial development has been established, the spatial average of AOD is consistently high during all seasons, but it seems that the spatial average of AOD is higher during the transition

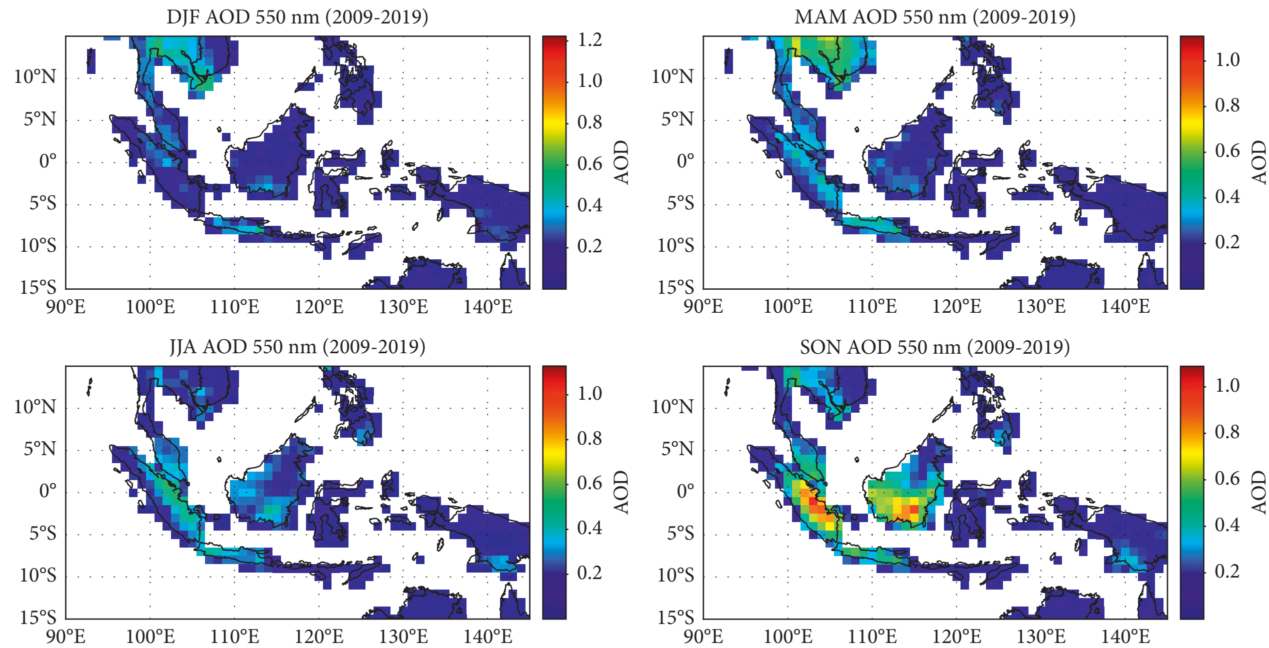

Figure 7: The spatial and seasonal variation of the annual mean MODIS DB C6.1 AOD at 550 nm over land in Indonesia during the period 2009 to 2019.

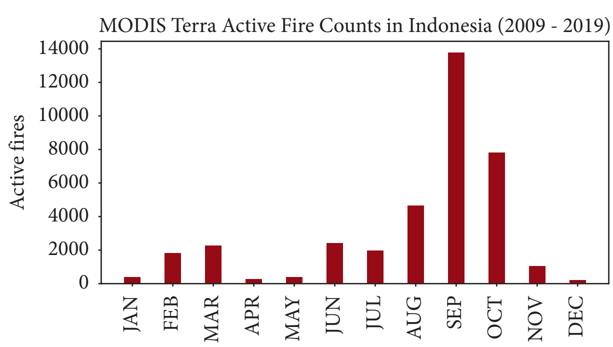

Figure 8: The monthly average of the MODIS Terra active fire counts in Indonesia during the period 2009 to 2019.

periods (MAM and SON) than during other seasons. It is also worth noting that a bit of AOD during JJA and SON in the southern part of Papua Island may also be related to forest and land fires.

Figure 8 shows the seasonality of fire events derived from MODIS Terra active fire products in Indonesia from the period 2009 to 2019. The highest active fire count occurred in September, followed by November. The months with the lowest active fire counts were December–January and April–May. This figure clarifies the positive relationship between the number of fire events and AOD in Indonesia. During June–September, an increase in active fire events is likely to induce an increase in AOD values and AOD variations, with the dominant contribution coming from fire events in Sumatra and Kalimantan. This supports the results of a previous study that found high AOD variations in Indonesia are generally caused by forest fires [41].

4. Conclusions

The objective of this study is to investigate the performance of Terra MODIS Deep Blue (DB) Collection 6.1 (C6.1) AOD over Indonesia from the period of 2009–2019. For this purpose, monthly MODIS DB AOD retrievals were collected and compared against ground-based monthly AERONET AOD measurements from 8 AERONET sites in Indonesia during the same period. Performance of these monthly AOD retrievals at site scales and determination of the annual mean AOD spatial distributions and seasonal variations as well as aerosol types are carried out for the first time.

The results illustrated that MODIS DB AOD retrievals and AERONET AOD measurements have a high correlation in Sumatra Island (i.e., Kototabang ($r = 0.88$) and Jambi ($r = 0.9$)) and Kalimantan Island (i.e., Palangkaraya ($r = 0.89$) and Pontianak ($r = 0.92$)). However, the correlations are low in Bandung, Palu, and Sorong, which is likely due to low AOD variations and a lack of observation data. Generally, MODIS DB AOD tends to overestimate AERONET AOD at all sites by 16 to 61% and can detect extreme fire events in Sumatra and Kalimantan Islands quite well. For spatial distributions, the annual mean AOD in the western part of Indonesia is higher than in the eastern part. Furthermore, for seasonal variations, the highest AOD is observed during the period of September–November, which is associated with the emergence of fire events, especially the ones that occurred in Sumatra and Kalimantan.

Aerosol types in Indonesia mostly consist of clean continental, followed by biomass burning/urban industrial and mixed aerosols. The highest clean continental aerosol contribution (90%) was identified in Palu and Sorong, which are located in remote areas, while the highest biomass burning/urban-industrial aerosol contribution (93.7%) was found in Bandung, one of the big cities in Indonesia.

Data Availability

MODIS Deep Blue Collection 6.1 data can be found at https://ladsweb.nascom.nasa.gov. AERONET data are available at https://aeronet.gsfc.nasa.gov. MODIS Terra active fire counts are available at https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms.

Conflicts of Interest

The authors declare no conflicts of interest.

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