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Evaluation of Aerosol Optical Thickness over Malaysia Based on Multi-Source Ground and Satellite Data

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ABSTRACT

This study evaluates the spatiotemporal distribution of aerosol optical thickness (AOT) over Malaysia. The significance of aerosols in regional and global climate change assessment has become a pressing topic in recent climate discussions. Two different approaches are used in measuring AOT; satellite imagery and ground measurement approaches. However, the satellite approach is deemed the best way for monitoring the patterns and transport of aerosols largely due to its extensive spatial coverage and reliable repetitive measurements. The data in this study were obtained from a Sea-viewing Wide Field-of-view Sensor (SeaWiFS), a Multi-angle Imaging Spectroradiometer (MISR), and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensors based on a NASA-operated Giovanni portal. Ground-based Aerosol Robotic Network (AERONET) datasets from two sites over the study area were also used. The results show that the highest AOT ground values of 1.93 and 2.00 were recorded in September 2015, at USM station and Kuching station, respectively. Throughout the 15 years of recorded data, the monthly average value of AOT reached its highest values in September, October, and November. In these months, the value of AOT went above 0.40, unlike in other months of the year. Significantly, the results indicate that Malaysian air quality can be evaluated based on AOT values, as these show the variation in optical properties of aerosol.

Keywords: AERONET, AOT, Malaysia, MISR, MODIS, SeaWiFS

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INTRODUCTION

Aerosol is mainly distributed between the ground surface and stratospheric layer of the earth's atmosphere. Another terminology used in place of aerosols is atmospheric particulate matter (PM) (Fang & Chang, 2010). The effects of particulate matter depends on its size. Therefore, the aerodynamic diameter of PM significantly influences PM on health. A PM with a diameter of more than 10 μm (PM_{10}) has less effect on the respiratory system of human beings because it hardly goes beyond the human nostrils. However, if the aerodynamic diameter of PM is between 2.5 μm and 10 μm, the PM will usually be absorbed into the human respiratory system (Pope et al., 1995; Shaadan et al., 2018).

Satake et al. (2004), in their study, indicated that the distribution of particulate matter in the Asian mainland was influenced by the transportation of man-made pollutants. Additionally, the problem of smoke and haze concentration in this area was aggravated by recurring slash-and-burn agricultural practices; however, the haze density depended on prevailing weather conditions. Thus, the Southeast Asian haze density is largely determined by local particulate generation, which has complicated regional air pollution issues (Xu, et al., 2015). For instance, in Klang Valley in Malaysia, the slash-and-burn practice has become a common practice in the past few years. Temporally, haze typically occurs in the southwest season from July to September (Radzi et al., 2004).

Despite the presence of different satellite sensors in the region, only a few aerosol-related studies based on satellite remote sensing data have been conducted in Malaysia due to the recurrent cloud cover in the country. The studies that have been conducted used devices such as an Advanced Very High Resolution Radiometer (AVHRR), MODIS, a Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), an Atmospheric Infrared Sounder (AIRS), and Medium Resolution Imaging Spectrometer (MERIS) data (Kanniah et al., 2016).

This paper aims to evaluate the aerosol optical thickness over Malaysia by analyzing and visualizing data from multiple satellite sources and ground measurement stations.

MATERIALS AND METHODS

Remote sensing techniques have attracted a lot of attention in the past few years. The installation of ground-based aerosol measuring stations (e.g., IMPROVE, AERONET, and EPA routine sites), and the launch of satellite remote sensing instruments (e.g., Multi-angle Imaging Spectroradiometer (MISR), and the Moderate Resolution Imaging Spectroradiometer (MODIS)) have improved our view and understanding of aerosols near the surface of the earth and its atmosphere (Di Girolamo et al., 2004; Kaufman et al., 1997). The aerosol characteristics retrieved from the MODIS sensor were obtained from seven (0.47-2.13 mm) out of 36 channels of the sensor (Chu et al., 2002; Jung et al., 2018).

The data produced by the MISR sensor is obtainable on a day-to-day basis with 17.6 × 17.6 km resolution. The MISR device obtains daytime data, which covers global areas, but its frequency depends on latitude. The interval of coverage fluctuates from 2 to 9 days in response to the intersection of their tracks poleward and their separation while moving toward the equator (Bruegge et al., 2004; Martonchik et al., 1998).

The Sea-WiFS sensor is used principally for the regular data generation of the world's ocean color and bio-optical properties. Moreover, SeaWiFS has eight spectral bands centered between 412 and 865 nm. The spatial resolution is approximately 4.5 km at nadir with a swath width of 1,502 km (±45.0°) at the equator (Wang et al., 2005).

The Aerosol Robotic Network (AERONET) is the most widely used surface measurement tool for quantifying the total column of aerosol optical characteristics. The relationship between the size and absorption of the aerosols allow for the determination of major aerosol types (Giles et al., 2012). Although the ground stations are limited in terms of spatial coverage (Qu et al., 2016), they are still useful for confirming aerosol products based on the type of satellite (Asmat et al., 2017).

Study Area

Malaysia is a Southeast Asian country located between 2.3167°N and 111.5500°E (Figure 1). The spatial extent of the study area is about 329,758 km^2 occupying the Malaysian Peninsula, which is bordered by the Asian landmass in the southern part, and the States of Sabah and Sarawak in the north-western coastal of Borneo Island. Malaysia's two separate regions are separated from each another by about 531 km (Semire et al., 2012).

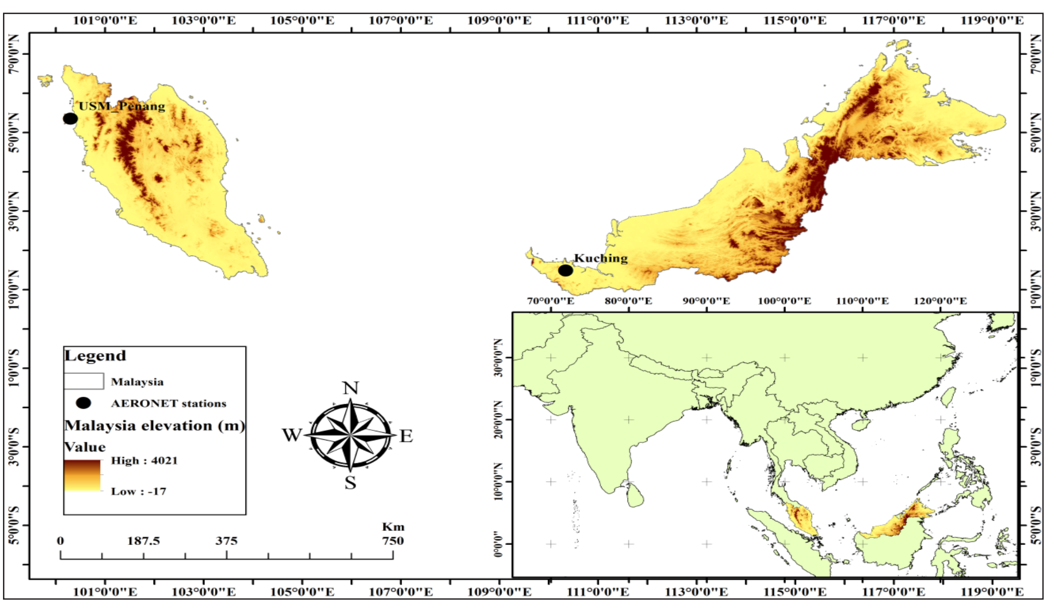


Figure 1. Study area and AERONET station location

Data and Methodology

Data Set. This study utilizes aerosol optical thickness (AOT) data from AERONET and satellites (Table 1). The data was sourced via a Giovanni online data system (Ganguly, 2016). The data was specifically retrieved from the archives of a NASA-operated Giovanni portal (http://disc.sci.gsfc.nasa.gov/giovanni). The Monthly AOT has a wavelength of 550 nm. The MODIS (Terra and Aqua satellites) (Jung et al., 2018) and SeaWiFS-derived AOT is based on a spatial resolution of 1° × 1° (Wang et al., 2005). Meanwhile, MISR is set at a spatial resolution of 0.5° × 0.5° at 555 nm (Bruegge et al., 2004). This study used different sensors to compare between different AOT values. This is essential for establishing a long-term database for atmospheric studies and will assist in improving the accuracy of results obtained using a single sensor (Prasad & Singh, 2007). From the spatial dimensions, the MISR and MODIS AOT retrieval abilities for South-East Asia was found acceptable (Xiao et al., 2009).

The data from AERONET ground-based stations are made available at three different levels; Level 1.0 (unscreened), Level 1.5 (cloud screened), and Level 2.0 (quality assured) (Holben et al., 1998). The data can be obtained from the AERONET website (http://aeronet.gsfc.nasa.gov/). AERONET is a well-established network with over 700 stations and provides standardized high quality aerosol measurements. The network is extensively used for different aerosol-related studies including satellite retrieval and validation (Cheng et al., 2012).

In Malaysia, at the moment, there are only two functional AERONET stations: Universiti Sains Malaysia (USM) Penang and Kuching stations (Figure 1). The AERONET stations use a Cimel sun photometer to measure aerosol and radiation parameters (Kanniah et al., 2016).

The most accurate way to retrieve and verify satellite remote sensing AOT data is by taking measurements using a sun photometer. The commonly used sun photometer makes a measurement every 15 min during the day in a number of wavelengths (Holben et al., 1998; Ichoku et al., 2002).

The spatial-averaged MODIS AODs are compared with the temporal-averaged sun photometer. AERONET level 2.0 AOD data are the most used data for validating the MODIS aerosol product (He et al., 2010), as it is reliable. The MODIS and SeaWiFS sensors retrieve AOT at 550-nm wavelength while MISR does so at 555 nm. This does not comply with AERONET wavelengths (348, 388, 440, 500, 675, 878, 1020, and 1648 nm). Because AERONET does not make measurements at 550 nm, the AERONET data was interpolated to 550 nm using the standard Ångström exponent, α, as defined in Equation (1).

$$\alpha = ln\ (\tau1/\tau2)/ln(\lambda1/\lambda2) \qquad (1)$$

Where, τ1 and τ2 are the AOT data at wavelengths λ1 (500 nm) and λ2 (675 nm), respectively. These values are the nearest available pair of bounding wavelengths from AERONET (Sayer et al., 2013).

$$\alpha = ln\ (\tau 500nm/\tau 675nm)/ln(675nm/500nm)$$

To validate the result from the MODIS sensor, the sun photometer in AERONET ground stations is used to interpolate to a common wavelength of 550 nm, where Equation (2) is applied:

$$\tau 550\ \ = exp\ [ln(\tau 500nm) - ln(550nm/500nm)\alpha] \qquad (2)$$

The data used (Table 1) are the Version-2 direct sun algorithm Level 2 quality assured and cloud screened (Li et al., 2015). The product is available at http://aeronet.gsfc.nasa.gov/new_web/index.html

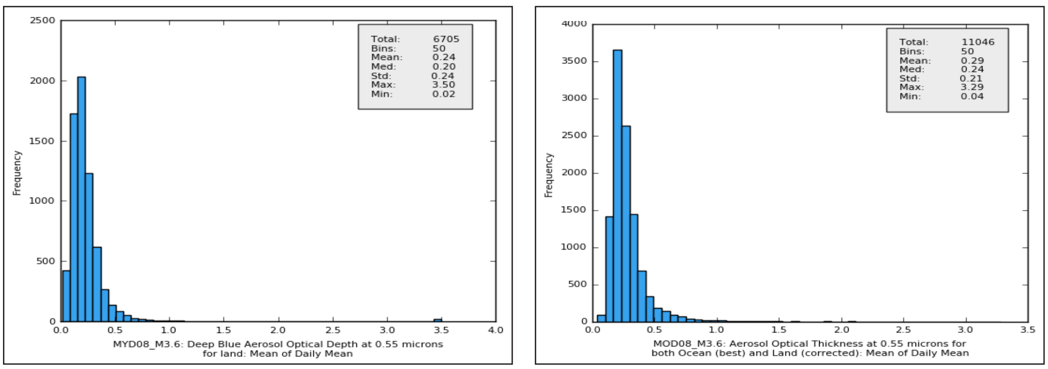
Table 1
Data sets used in the study

Satellite sensor	Special resolution	Spectral band (nm)	Data source
Satellite data			
MODIS Terra MODIS Aqua SeaWiFS	1° × 1°	550	https://giovanni.gsfc.nasa.gov/giovanni/
MISR	0.5° × 0.5°	555	
Ground data			
AERONET	Spectral band of 550 nm		http://aeronet.gsfc.nasa.gov/new_web/index.html

RESULTS AND DISCUSSIONS

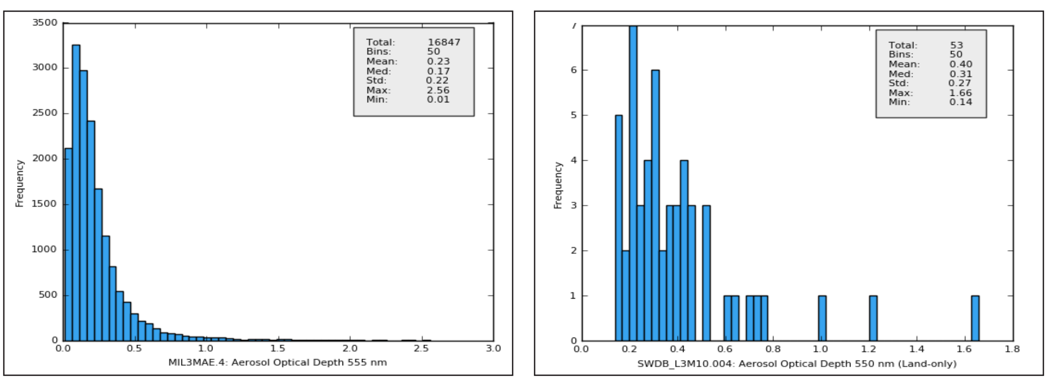
Descriptive Statistics of AOT over Malaysia Based on Satellite Remote Sensors

The spatiotemporal variabilities of aerosol optical thickness over Malaysia was assessed using information acquired from the NASA-operated GIOVANNI portal (https://giovanni.gsfc.nasa.gov/giovanni/) and AERONET ground stations. Figure 2 shows the monthly mean AOT (unitless) average results obtained from MODIS Aqua (0.24) (Figure 2 (a)), MODIS Terra (0.29) (Figure 2 (b)), and MISR (0.23) (Figure 3 (a)) from the period 2002 to 2017. The monthly mean for SeaWiFS is 0.4 from the period 1997 to 2010. The distribution of AOT skewed right—apparent in MODIS Aqua (Figure 2 (a)), MODIS Terra (Figure 2 (b)) and MISR (Figure 3 (a)). Meanwhile, for SeaWiFS, there seemed to be outliers in the AOT data to the far right, indicating values of more than 1.0 (Figure 3 (b)). The disparity in AOT values between the sensors could possibly be due to differences in platforms. This may be attributed to the large aerosol load, the complex aerosol mixtures, and the variations in climatic conditions such as precipitation, temperature, and wind pattern (Habib et al., 2018).



(a) (b)

Figure 2. Histogram of AOD at 550 nm for: (a) MODIS Aqua and (b) MODIS Terra from 2002 to 2017 (https://C.gsfc.nasa.gov/giovanni/)



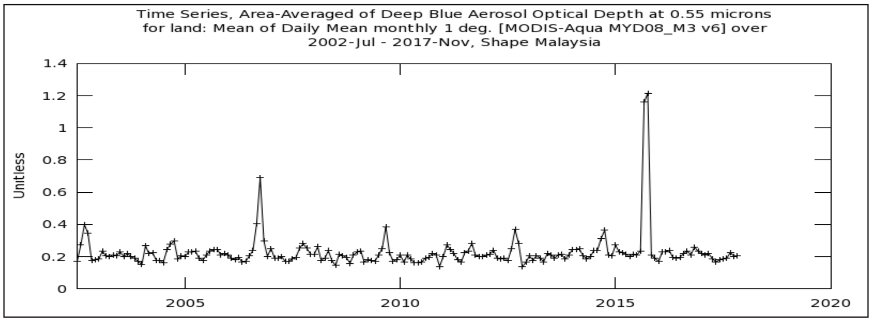
(a) (b)

Figure 3. Histogram of AOD at 550 nm for: (a) MISR at 555 nm from 2002 to 2017 and (b) SeaWiFS from 1997 to 2010 (https://giovanni.gsfc.nasa.gov/giovanni/)

Temporal Distribution of AOT

The combined columnar aerosol disappearance is comparable to the aerosol optical thickness. This information can be harnessed to understand the spatiotemporal disparities of aerosols and their effect on radiative transfer over Malaysia (Kanniah et al., 2016).

Figure 4 compares the long-term AOT temporal variability of four sensors. The monthly temporal variation of AOT for all sensors over different years was strongly similar. In general, the AOT value of the time series in all figures showed similar seasonal patterns for all sensors. Malaysia experienced two peak periods of AOT values from 2005–2007 and 2015–2016 for all the sensors. This finding is consistent with that of a previous study, which suggested that the results are due to Malaysia being exposed to haze in 2005 and 2006 (Othman et al., 2014).



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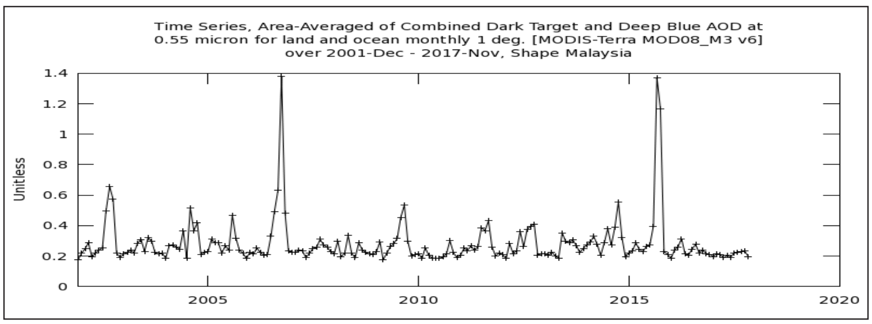

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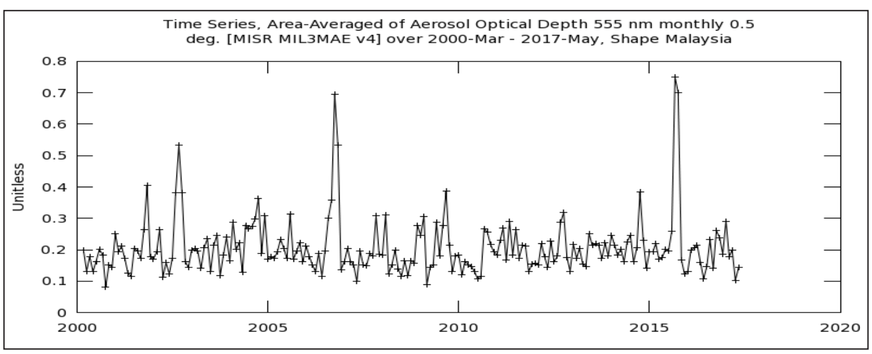

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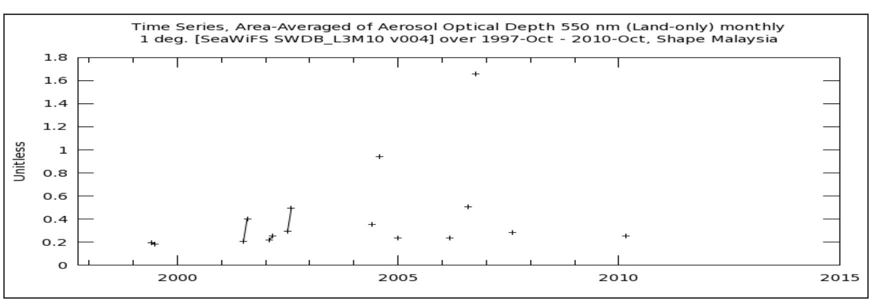
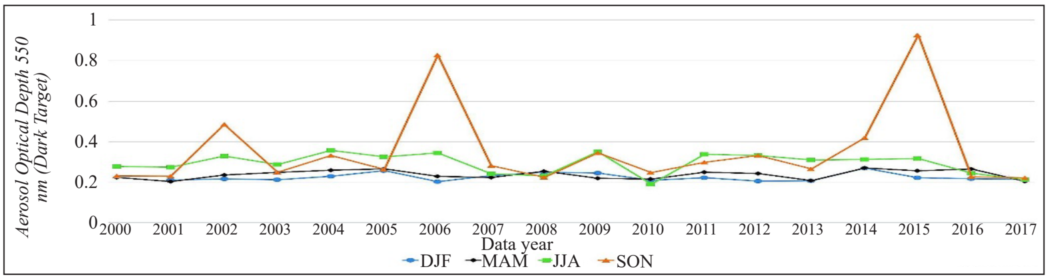


(d)

Figure 4. Monthly 1-degree time series area averaged of aerosol optical depth for: (a) MODIS Aqua Jun. 2002–Nov. 2017; (b) MODIS Terra Dec. 2001–Nov. 2017; (c) MISR Mar. 2000–May 2017; (d) and SeaWiFS from 1997 to 2010 (https://giovanni.gsfc.nasa.gov/giovanni/)

Seasonal Distribution of AOT

Recent advances in remote sensing at the time of this study has allowed for the retrieval of temporal seasonal distribution of AOT data from MODIS Terra (Figure 5 (a)), MODIS Aqua (Figure 5 (b)), MISR (Figure 5 (c)), and SeaWIFS (Figure 5 (d)). The main



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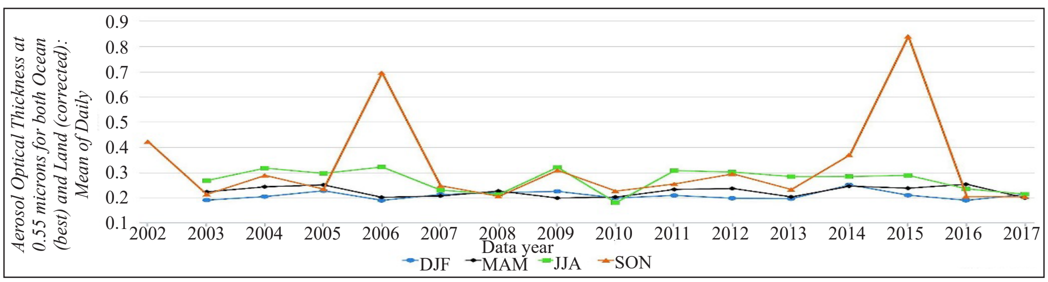

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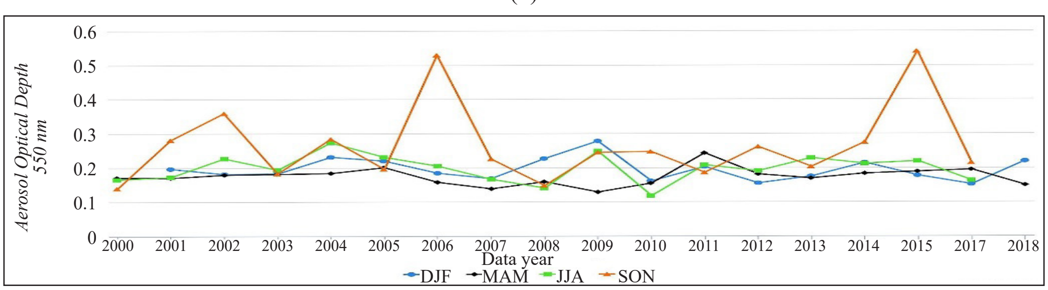

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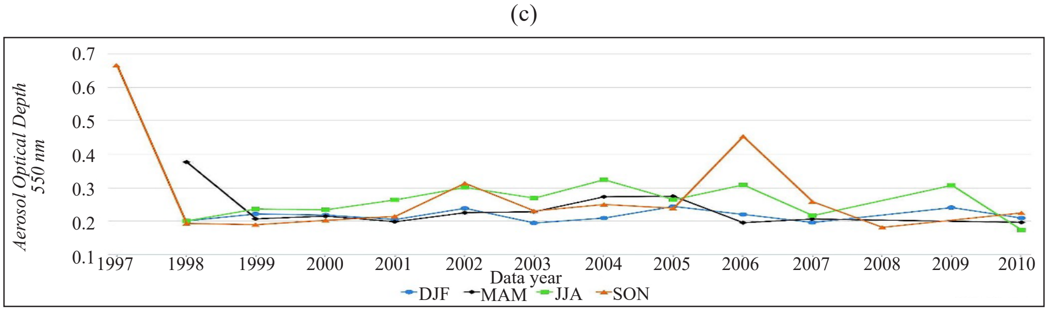


(d)

Figure 5. Seasonal time series for: (a) MODIS Terra; (b) MODIS Aqua; and (c) MISR for the period 2000–2017; as well as (d) SeaWiFS for the period 1997–2010. The months are denoted as December, January, and February (DJF), March, April, and May (MAM), June, July, and August (JJA), and September, October, and November (https://giovanni.gsfc.nasa.gov/giovanni/)

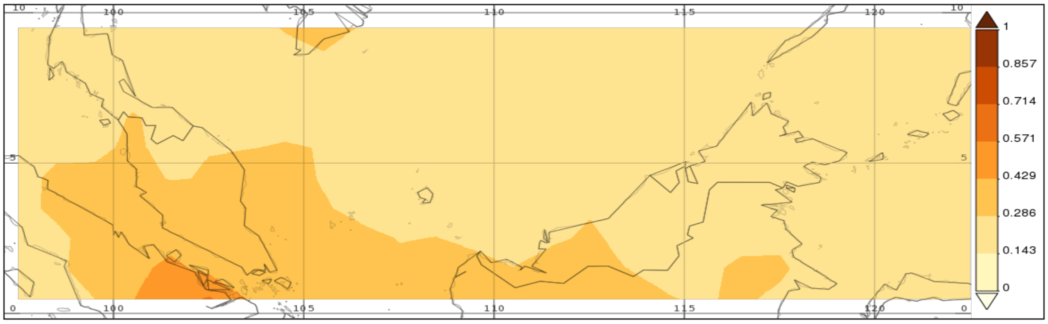
significance of these techniques is their effectiveness in detecting and comparing the averages of different seasons and AOT datasets. The results of this study show a higher value of AOT in September, October, and November (Southwest season) for all sensors. A possible explanation for this might be the regular phenomenon of Southeast Asian smog or air pollution incidents since the 1980s (Sahani et al., 2014). A substantial amount of particulate matter is released in the air from biomass burning, which moves with the help of south-westerly winds (between June and September) to Malaysia. Vehicular exhaust and burning of biomass, both locally and/or at the inter-boundary level, have consequently led to haze dispersal to Peninsula Malaysia and to Sabah and Sarawak (Sahani et al., 2014).

Tsai et al. (2011) used MODIS-derived AOD products for air quality monitoring; they found that haze layer height had larger impacts on correlation than boundary layer height, owing to an abundance of aerosols above the boundary layer. Additionally, Salinas et al. (2013) found that the temporal variability of AOD and fine-mode AOD indicated elevated levels of aerosol loading, where there were similarly high values of the Angstrom exponent number consistent with the presence of fine mode particulates. Nevertheless, these results suggest that data obtained using MODIS and SeaWiFS sensors provides more information on AOT that would be helpful in assessing the impact of haze and in predicting particulate matter in the area.

Spatial Distribution of AOT over Malaysia Area

Due to their extensive spatial coverage, satellite observations have been widely used to estimate AOT distribution. The data from the NASA-operated GIOVANNI portal (https://giovanni.gsfc.nasa.gov/giovanni/) is used to average the spatial distribution of AOT from MODIS Aqua (Figure 6 (a)), MODIS Terra (Figure 6 (b)), MISR (Figure 6 (c)), and SeaWiFS (Figure 6 (d)) over the area of Malaysia between 2005 and 2007. From these figures, it can be seen that there is slightly more satellite sensor data for Western Malaysia than its Eastern part. For example, the MODIS Terra data in Figure 6 (b) shows a clear trend of increasing AOT in Peninsular Malaysia. Kanniah et al. (2014) reported that the western sites in Peninsular Malaysia had the highest AOD 550 values from Terra MODIS, associated with densely populated, industrialized, and polluted areas. Highly populated areas have high vehicular traffic (Sahani et al., 2014). These results reflect the findings of Latif et al. (2014), who reported that urbanized areas in Peninsular Malaysia had high concentrations of aerosol.

Therefore, this result indicates that satellite sensors can account for spatial variability and long-range transportation of air pollution, and thus provide coverage of local and global distribution of aerosols.



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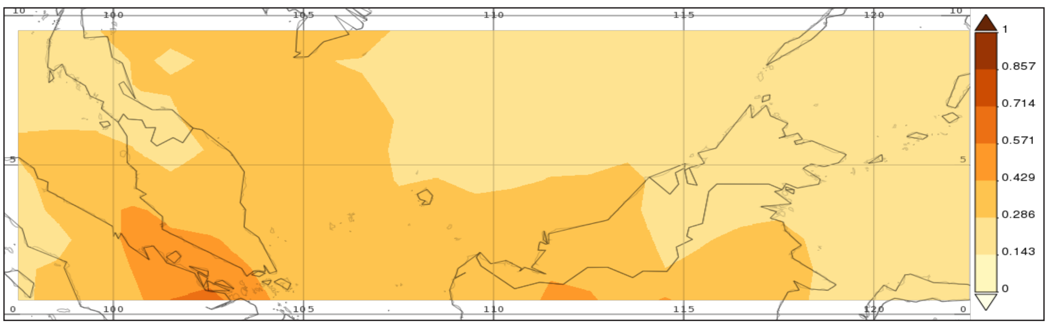

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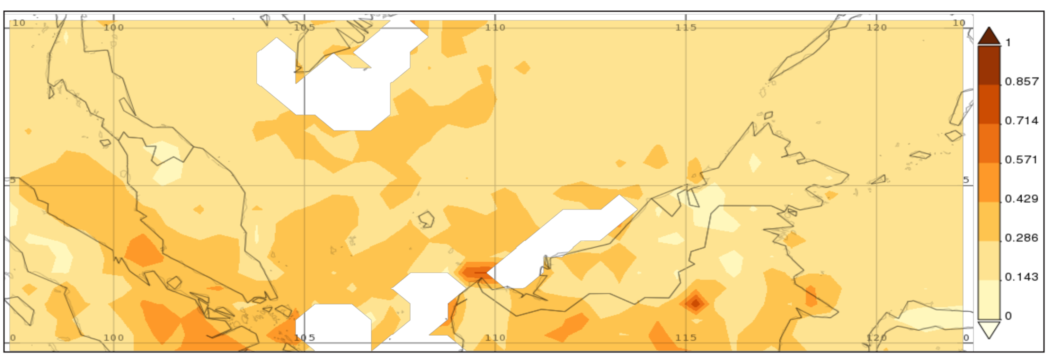

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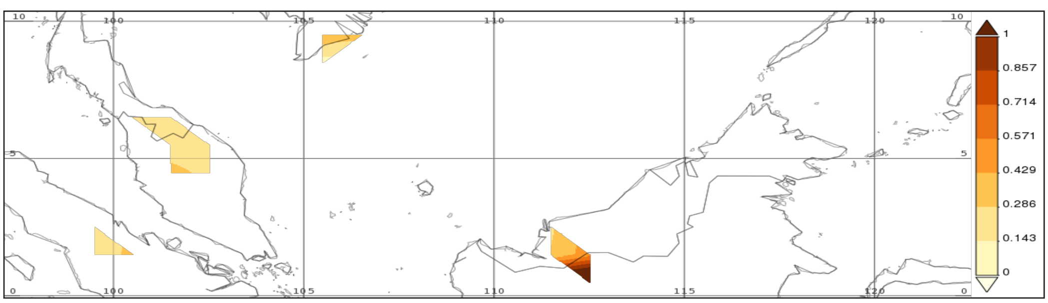

(d)

Figure 6. Spatial distribution of AOT retrieved from: (a) MODIS Aqua (550 nm); (b) MODIS Terra (550 nm); (c) MISR (555 nm); and (d) SeaWiFS (550 nm) over the area of Malaysia between 2005 and 2007 (https://giovanni.gsfc.nasa.gov/giovanni/)

Distribution of Ground-Measurement AOT

Figure 7 shows the frequency of ground measurement distribution of AOT from 2005 to 2007 for two AERONET stations in Malaysia. The AOT value in the two datasets is mostly less than 0.5, although the mean for USM station (0.66) is higher than that of Kuching station (0.27). There are similarities between the distribution of AOT in ground-based AERONET stations (Figure 7(a) & (b)) and the data distribution from satellite sensors (Figure 2 & Figure 3). The former data is skewed right, where these results support previous research that suggests that AERONET could be adopted to calibrate satellite AOT (Grosso & Paronis, 2012; Jiang et al., 2007).

The time series of AOT values from the ground from 2011 to 2018 are shown in Figure 8 and Figure 9, for the Kuching and USM stations, respectively. The AERONET data suggests a fair degree of diversity in aerosol properties in Malaysia. From the charts, it can be seen that the highest AOTs were observed in September 2015. A comparison of the findings with the seasonal time series is shown in Figures 5 (a), (b), and (c). These results are in keeping with previous studies, which suggest that the monthly concentration of major air pollutants were higher between June and September during the southwest monsoon. This is a result of air movement that transports these pollutants across the Malaysian border from Sumatra, Indonesia. Bushfires are primarily the major factor for the high density of particulate matter in the atmosphere in this area (Latif et al., 2014). However, more research on this topic needs to be done to understand the connection between satellite AOT and ground AOT measurements.

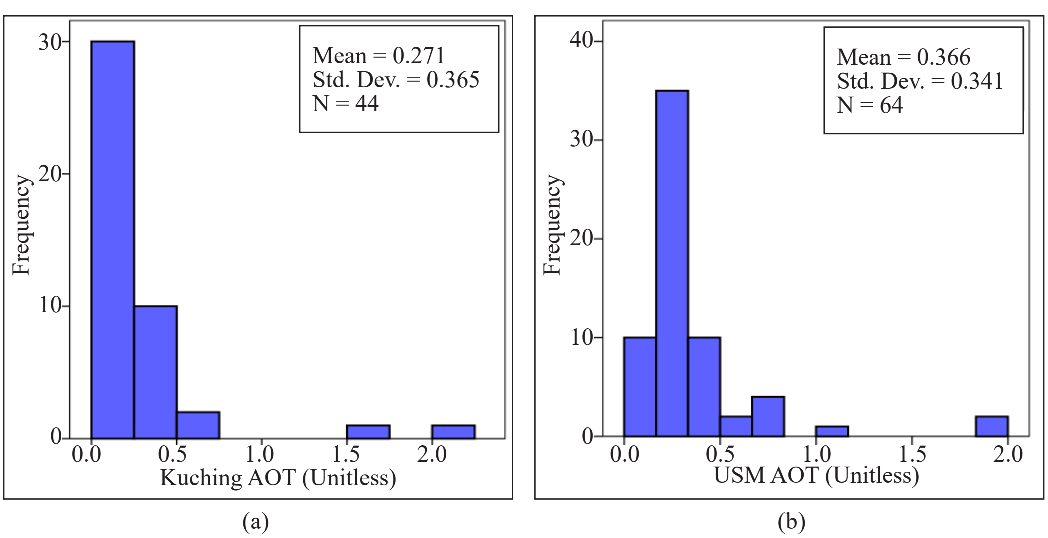

Figure 7. Histogram and description of Monthly mean AOT variability retrieved from: (a) AERONET Kuching; and (b) AERONET USM from 2011 to 2017

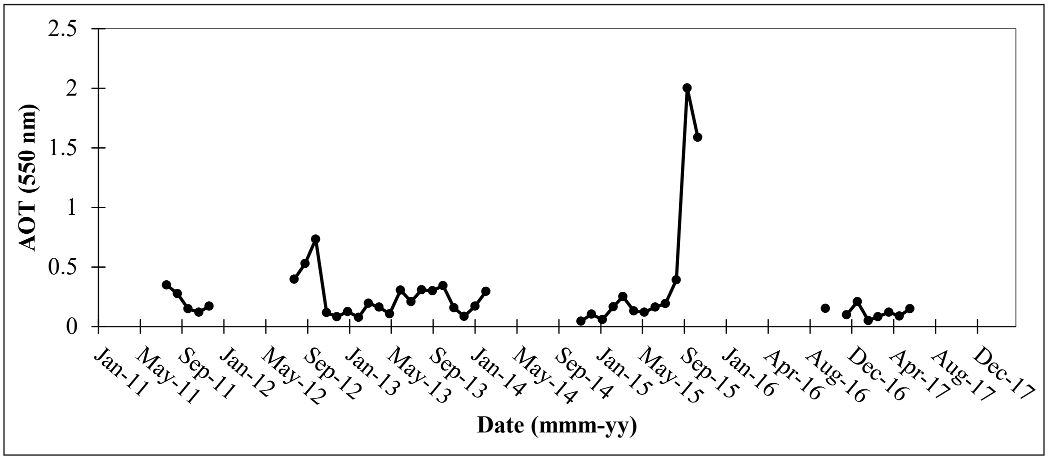

Figure 8. Monthly variation of AOD (550 nm) from 2011–2018 over KUCHING station

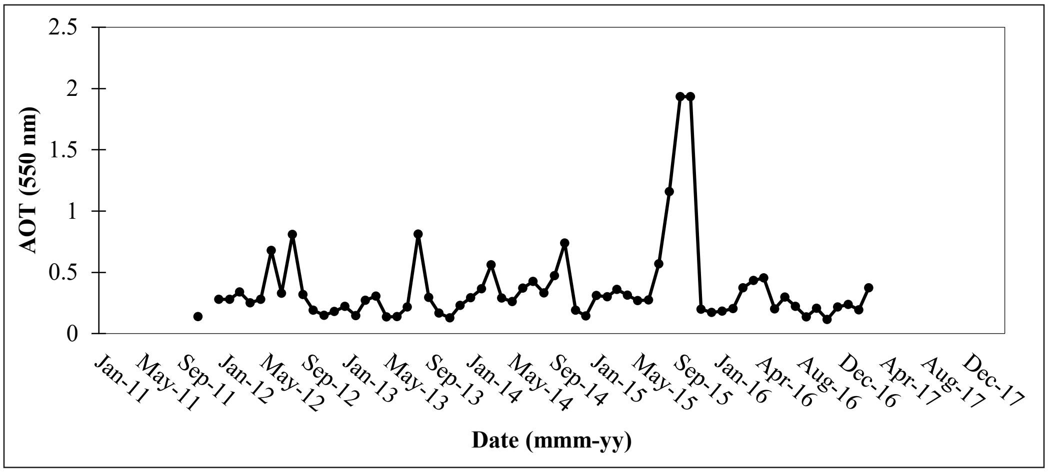

Figure 9. Monthly variation of AOD (550 nm) from 2011–2018 over USM station

CONCLUSIONS

SeaWiFS, MODIS (Terra and Aqua), and MISR aerosol measurements were used to evaluate the changeability of aerosol optical thickness over different areas of Malaysia. Both past (SeaWiFS) data and present (MODIS and MISR) data displayed an increase in AOT value between 2005 and 2007. For recent sensor data, all comparisons yielded very similar results between 2014 and 2016. The MISR data showed slightly lower AOT values than those obtained from MODIS. Nevertheless, the satellite sensor data showed very good temporal correlation, explaining the variability of AOT measured from ground AERONET data. Despite the limitation of surface observation stations, they still helped in validating the satellite data. This paper also highlighted the importance of satellite sensors in air quality monitoring in Malaysia. Future studies need to emphasize on comparing satellite and ground-based observation stations in Malaysia to better understand aerosols and their optical properties.

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