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The development of Air Quality Indices using AOD-Retrieved Images during haze events in Peninsular Malaysia

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Abstract. Advances in satellite sensors provide new datasets to assist in the observation of air quality at urban and local scales. Quantitative Aerosol Optical Depth (AOD) and qualitative true colour image data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra satellite have been widely used to assess air quality. In this study, both 3 km and 10 km MODIS aerosol products were used to provide an overview of the state of fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}) during haze episodes over Peninsular Malaysia covering the period 21 to 26 June 2013. The result showed a high concentration of PM during the haze period based on ground-level data, with an average level of $PM_{2.5}$ (mean ± standard deviation) of 99.86 ± 23.99, 190.37 ± 105.59, and 205.191 ± 165.76 (μg/m^3) in Tanah Merah station, Cheras station, and Putrajaya station, respectively. Meanwhile, the PM_{10} in the Tanah Merah, Charas, and Putrajaya stations was 100.56 ± 28.17, 181.31 ± 83.70, and 197.99 ± 74.67, respectively. Overall, the results showed a correlation between monitoring station measurements and satellite data. Satellite remote sensing analysis of atmospheric aerosols remain a great method for estimating haze distribution and can be further used to monitor the atmospheric environment in Malaysia.

1. Introduction

The phenomenon of dust, smoke, vapour, and moisture accumulating in the atmosphere such that visibility is reduced is known as the haze. Haze is air mixed with suspended fine water droplets that hover close to the ground [1]. Haze is normally characterised by a lower than 80% relative humidity (RH) and less than 10 km visibility [2]. Haze contains particulate matter (PM) with a 2.5 mm aerodynamic diameter ($PM_{2.5}$) and high concentrations of air pollutants [3]. Hence, high concentrations of $PM_{2.5}$ and stagnant meteorological conditions usually denote haze conditions [4-6].

The pollution of the atmosphere and other meteorological factors cause haze to occur [7]. In general, two types of aerosols, when in excess, will form haze i.e. anthropogenic-based primary aerosol and gaseous aerosols that transform into particles [3]. Gaseous pollutants and particulate matter (PM) are the main components of haze, with the major component being $PM_{2.5}$. The main PM sources are the sea spray, volcanic emissions, forest fires, vehicles exhausts, road dust, windblown soil, and smokestacks. Once these pollutants scatter and absorb ambient particles, the visibility of the atmosphere reduces [8].

In 1991 and 1994, Peninsular Malaysia and East Malaysia (Sabah and Sarawak) recorded severe haze events. Only three years later (i.e. 1997), another severe event was recorded in September and October caused by neighbouring Indonesia, especially southern Sumatra and central Kalimantan, which conducted large-scale forest and plantation fires. Local open-burning activities, motor vehicle emissions, and industrial pollution further exacerbated the haze conditions. In the worst-case scenario, particles of concentrations of up to 500 $\mu g/m^3$ that can absorb into the human respiratory system were observed, further limiting visibility to less than 500 m [9]. Malaysia recorded further severe haze episodes in 1997, 2005, and 2015, with some exceeding the Malaysian Air Quality Guideline for PM_{10} concentration (150 $\mu g/m^3$ over a 24-h average period) [10].

Smoke from Sumatra and Kalimantan can travel far northward to Brunei, Sabah, Sarawak, Peninsular Malaysia, and Singapore, as it is facilitated by the June-to-August southerly atypical winds, which lend strength to summer monsoon winds at that time. Meanwhile, there is a continued rainfall deficit in the southern parts of Sumatra and Kalimantan from September to November, covering areas as far reaching as Borneo. At this critical time, southern Sumatra and Kalimantan see very active fires until El Niño matures [11].

Aerosol Optical Depth (AOD) data is obtained from satellite remote sensing of aerosol [12, 13]. AOD data indicate solar radiation attenuation on the ground because of aerosols. Researchers usually study pollutants in the atmosphere via airborne and satellite observations [14]. There have been extensive investigations into aerosols because of their absorption and scattering of solar radiation, which disrupts the radiative balance. Aerosols also make up an integral part of heterogeneous chemistry. Satellite remote sensing can be used to obtain important information about aerosol extinction. Nevertheless, since the spectral signatures of aerosols are lacking, it is difficult to retrieve aerosol extinction coefficients [15]. Recently, satellite- and surface-based AOD observations have been used to determine the reasons for the heavy haze episodes in Beijing [16].

Remote sensing techniques such as satellite and aircraft imagery supported with ground-based data offer some new opportunities for evaluating the distribution of air pollution and how it impacts a region or ecosystem. More accurate information about the health impact of air pollution could be gathered from the dust haze, which is also a better indicator of air quality [17, 18]. This study primarily aims to investigate the distribution of haze and the variation in PM in a haze episode in Peninsular Malaysia in 2013 using remote sensing products based on the trends of AOD (AOD, 550 nm).

2. Materials and method

2.1. Study area

Forty percent of Malaysia' landmass is attributed to Peninsular Malaysia, which also houses 80% of the country's economic activities and population. Various environmental problems have emerged in some large cities in Peninsular Malaysia due to the recent fast economic development notably in industrial and transportation activities. Haze has been observed to occur almost every year during the dry season (1983, 1984, 1994, 1997, 1998–2000, 2002, 2004–2006, 2009, and 2013). The origin has been traced back to Indonesia's forest fires, namely the smoke particles emitted by these fires, and local sources such as domestic open burning, fossil fuel burning, and motor vehicle emissions. Evidently, such prolonged and intense episodes adversely impact people's health and socio-economy [19].

Moreover, since climatic conditions change according to season, the distribution of atmospheric aerosols is heterogeneous. Peninsular Malaysia has a tropical climate, with ~80% humidity, a high annual rainfall of ~2500 mm, and temperatures ranging from 23 °C to 31 °C. Most States in Malaysia experience the driest period in the middle of the year (June and July). Indonesia (Sumatra and Kalimantan) normally conducts extensive forest and agriculture fires at this time of year. The biomass-burning aerosols from these fires are carried by south-westerly winds to Peninsular Malaysia. During the rainy season, however, rain washouts and wet depositions result in lower levels of aerosol [20].

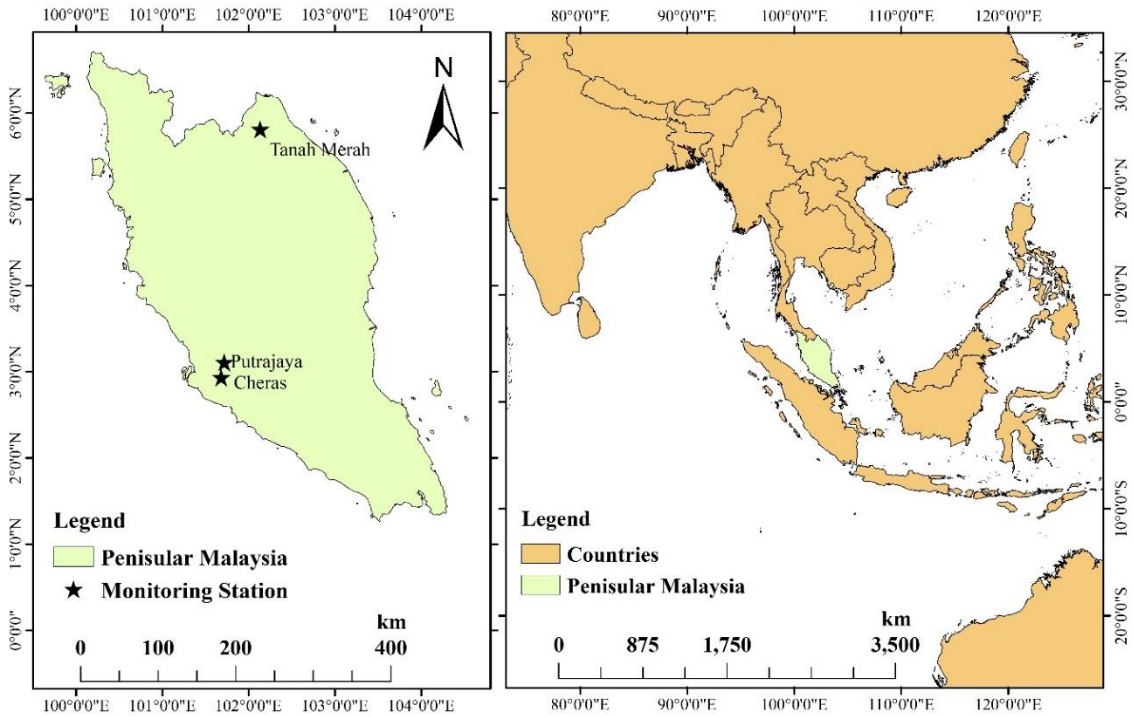

Figure 1. The location of air quality monitoring stations in Peninsular Malaysia

2.2. Collection of Data and MODIS pre-processing

This study used Terra MODIS-AOD data provided by NASA for Malaysia in 2013 (Collection 6; Level 2; 10 km and 3 km resolutions). The scanning capability of MODIS includes 36 spectral bands covering a 2330 km wide swath. The equatorial crossing time of Terra MODIS is 10.30 a.m. local time. Terra MODIS also provides almost complete global coverage every day. The (470, 550, and 660) nm spectral bands are used to compute the MODIS AOD over land [21, 22]. AOD retrievals are generated by an algorithm that produces a statistically robust product in 10 km × 10 km resolution and uses the MODIS spatial resolution of 250 m (660 nm band) and 500 m (470 nm and 550 nm bands). The NASA research team released AOD retrieved under a 3 km resolution as part of Collection 6 after a decade of producing AOD data via MODIS instrument with a 10 km spatial resolution [23]. MODIS True Colour Image, MODIS 10 km AOD, and 3 km AOD Products were used in this study on the same day to estimate haze events. MODIS aerosol products are available on the NASA website (https://ladsweb.modaps.eosdis.nasa.gov). The values of AOD extracted at 550 nm (MODIS parameter name: Optical_Depth_Land_and_Ocean, only the highest quality AOD (QAC flag = 3) were included overland for this parameter. MODIS was selected for its higher temporal resolution, frequency, and wider swath width coverage of Peninsular Malaysia.

2.3. Monitoring Data

Starting from 1996 until now, as part of the Malaysian Continuous Air Quality Monitoring (MCAQM) program, the Malaysian Department of Environment (DOE), through its concessionaire company, Alam Sekitar Malaysia (ASMA) Berhad, has been monitoring the PM_{10} levels at monitoring stations across

Malaysia [24]. The current research was conducted at three monitoring stations (Tanah Merah, Cheras, and Putrajaya) located throughout Peninsular Malaysia (Figure 1). The average daily $PM_{2.5}$ and PM_{10} mass concentrations for six days (21–26 June 2013) were obtained from DOE.

3. Results and discussion

3.1. Observations of PM and AOD

Figure 2 and Figure 3 provide the box plots of the $PM_{2.5}$ and PM_{10} concentrations (µg/m^3) over the period of study in the Tanah Merah, Putrajaya, and Cheras stations, respectively. Putrajaya and Cheras stations are the stations located in the Klang Valley area near Malaysia's capital city. Generally, the concentration of PM was higher in Putrajaya and Cheras and lower in Tanah Merah, possibly due to the variation in socio-economic activities, which are higher in Klang Valley, as it is the leading economic zone in Malaysia.

Table 1 presents the results of the 3-km and 10-km MODIS-AOD over Peninsular Malaysia for the period of 21–26 June 2013. As can be observed from Table 1, there is a difference in the number of pixels during the study period, where 24 June recorded a high number of pixels for 3 km and 10 km i.e. 4677 and 444 pixels, respectively. Meanwhile, a low number of pixels (375 pixels) was observed for 3 km MODIS-AOD on 25 June and 37 pixels were recorded on 21 June for the 10 km MODIS-AOD. High AOD values were observed on the two days (24 and 25 June), unlike other days, indicating that the study area was exposed to a high degree of haze during that period. Thus, naturally, the haze concentration was also expected to be higher in that area. Besides, Malaysia is also exposed to trans-boundary pollution caused by aerosols from biomass burning in neighbouring countries, particularly Indonesia. This haze is influenced by the south-westerly winds that transport the gases and particulate matter from the forest fires, especially from Sumatra between July and September (the dry season).

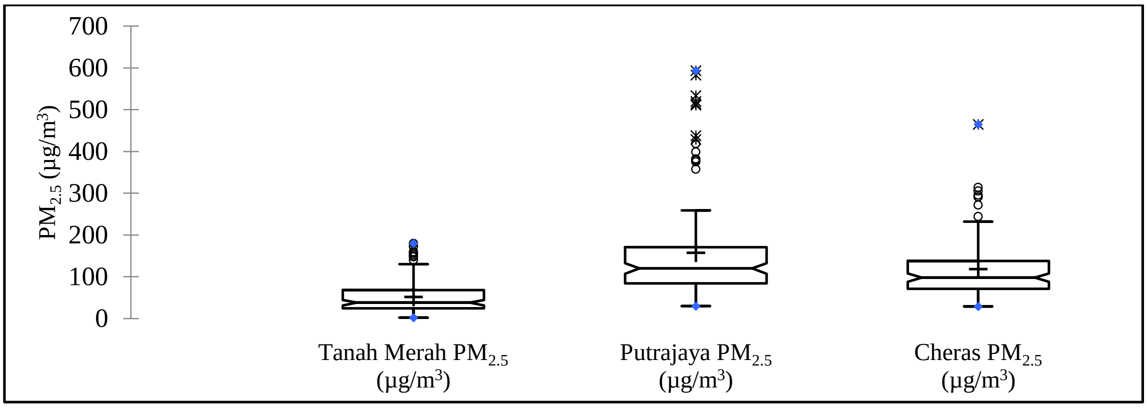

Figure 2. Box Plots of hourly $PM_{2.5}$ Concentrations (µg/m^3) from the three monitoring stations

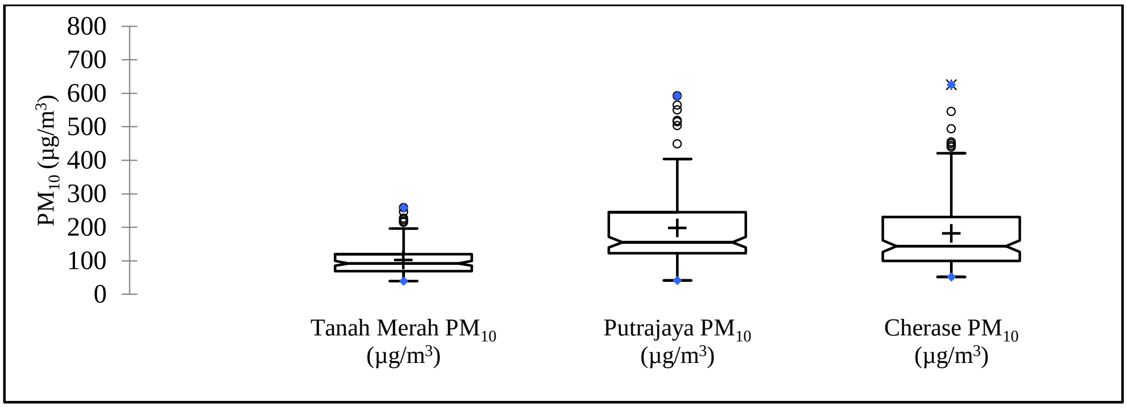

Figure 3. Box Plots of hourly PM_{10} Concentrations (µg/m³) from the three monitoring stations

Table 1. Summary Statistics of the MODIS (3 km and 10 km) Pixels over Peninsular Malaysia (21–26 June 2013)

Date	No. of observations		Min.		Max.		Mean		S.D.	
	3km	10km	3km	10km	3km	10km	3 km	10km	3km	10km
21-Jun-13	565	37	0.19	0.20	4.36	0.71	0.60	0.33	0.59	0.15
22-Jun-13	876	69	0.16	0.25	2.37	1.20	0.67	0.57	0.31	0.24
23-Jun-13	885	39	0.16	0.23	4.75	0.76	0.53	0.46	0.35	0.14
24-Jun-13	4677	444	0.22	0.25	5.00	4.94	1.71	1.51	0.92	0.90
25-Jun-13	372	101	0.83	1.12	4.98	4.58	1.92	1.43	1.02	0.65
26-Jun-13	587	109	0.29	0.34	1.79	2.09	0.70	0.58	0.25	0.28

3.2. Short-term variations of PM

Figures 4 and 5 show the PM concentration (µg/m³) measured by the Tanah Merah, Putrajaya, and Cheras stations over six days. In Figure 4, between 21 and 26 June 2013, the results showed a low PM concentration in Tanah Merah station. Putrajaya station saw a variation in $PM_{2.5}$ concentration, which increased on 22 June and 23 June that then declined afterward. In Cheras station, a high $PM_{2.5}$ concentration of more than 400 (µg/m³) was observed on June 23 and later dropped to a low concentration on June 26. The PM_{10} observation showed a very similar temporal pattern for all stations, with high concentrations observed on 23 June and 24 June for all stations.

The high PM concentrations in this period might be attributed to the haze carried by the forest fires, which brought most of the $PM_{2.5}$ and PM_{10} particles that had been transported over a long distance. Monitoring stations in South East Asia recorded high PM_{10} concentrations during the 1997 haze episode. Malaysia, specifically Klang Valley station, recorded the highest PM_{10} concentrations of up to 450 µg/m³, followed by southern Thailand (218 µg/m³) and Singapore (100 –150 µg/m³)

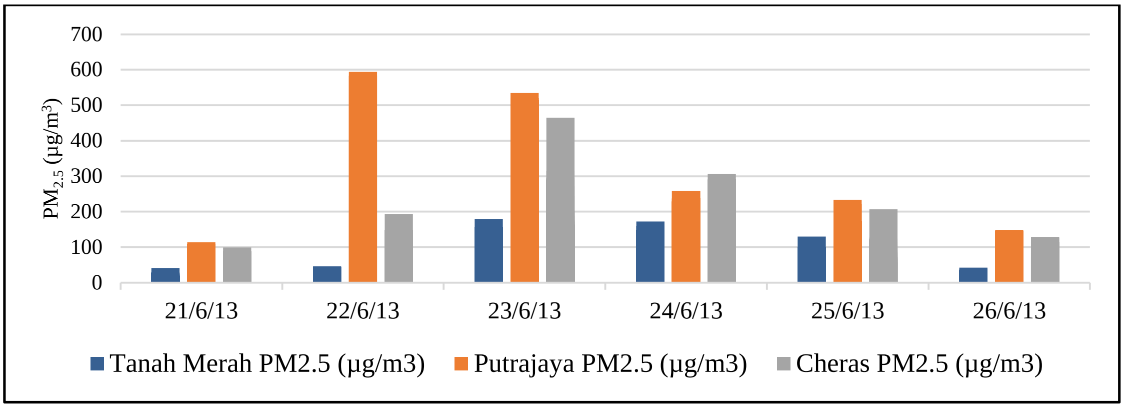

Figure 4. The daily variation in $PM_{2.5}$ ground levels over the stations from 21–26 June 2013

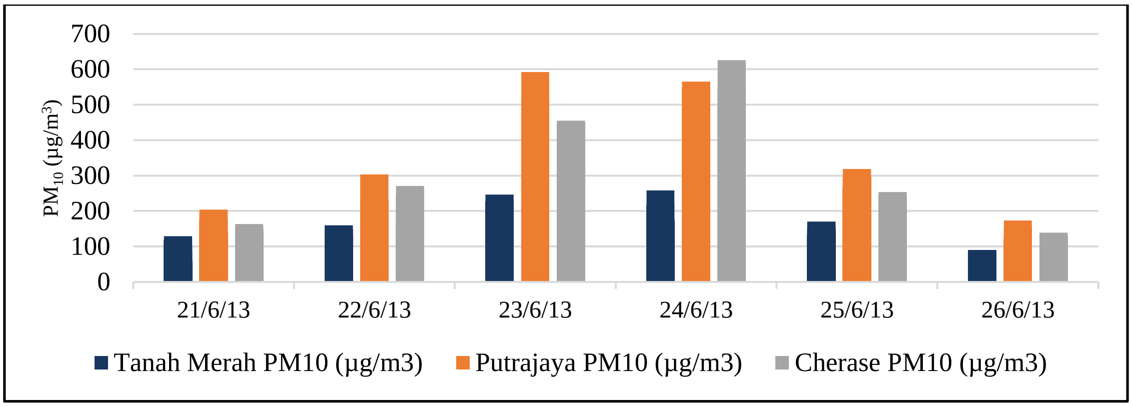

Figure 5. The daily variation of PM_{10} ground levels over the stations from 21–26 June 2013

3.3. Correlation between AOD and PM

The most important indicator of atmospheric pollution is arguably AOD (unitless). Changes in the atmospheric environment and the effect of radiative aerosol on the climate can be assessed via the determination of aerosol content, which is generally calculated using AOD. Table 2 shows a summary of the statistical daily average results. PM was recorded based on average hourly data and AOD was obtained as MODIS average spatial pixel data over Peninsular Malaysia over the period of study. Table 3 shows the correlation between the PM_{10}, $PM_{2.5}$, MODIS AOD 3km, and MODIS 10km variables for the study area. The correlation between PM_{10} and AOD 10km was (0.635), a little higher than AOD 3km (0.590), while the correlation between $PM_{2.5}$ and AOD 10km and $PM_{2.5}$ and AOD 3km was negative. These differences may be due to the local effect of meteorological and climate factors. For instance, the evaluation of particle mass can be influenced by increased relative humidity, because the particle size and its mass inflate dramatically when relative humidity is high [25, 26]. An important step in AOD retrieval is to use a proper cloud mask, as the process is done only during daytime and involves cloud-free pixels. The efficiency of the cloudy pixel removal process increases with smaller pixel size. That is, the correlation between PM (measured at ground level) and AOD (representing the column-integrated value) may depend on the vertical distribution of aerosols. Thus, correlating PM concentrations with MODIS-AOD may lead to significant errors.

Table 2. Statistical daily average results of PM_{10}, $PM_{2.5}$, AOD 3 km, and AOD 10 km for six days (21–26 June 2013)

Variable	Observations (Day)	Minimum	Maximum	Mean	S.D.
AOD 3km	6	0.535	1.924	1.023	0.622
AOD 10km	6	0.383	1.659	0.896	0.595
PM_{10} (μg/m^3)	6	95.026	253.847	159.963	61.089
$PM_{2.5}$ (μg/m^3)	6	69.774	247.431	148.472	79.539

Table 3. Correlation matrix for the AOD 3 km, AOD 10 km, PM_{10} and $PM_{2.5}$ variables for the study area, Peninsular Malaysia

Variable	3 km	10 km	PM_{10} (μg/m^3)	$PM_{2.5}$ (μg/m^3)
AOD 3km	1	0.988	0.590	-0.303
AOD 10km	0.988	1	0.635	-0.247
PM_{10} (μg/m^3)	0.590	0.635	1	0.349
$PM_{2.5}$ (μg/m^3)	-0.303	-0.247	0.349	1

p values were lower than 0.0001

3.4. Spatial evolution of AOD

Figures 6 to 9 show the (a) MODIS true colour image, (b) MODIS AOD 10 km and (c) MODIS AOD 3 km covering the whole of Peninsular Malaysia and coinciding with the six days of study in 2013. These images, due to their larger spatial coverage, enabled the researcher to detect the haze and cloud above the study area. The MODIS images were taken on 21 June (Figure 6), 22 June (Figure 7), 23 June (Figure 8), 24 June (Figure 9).

To compare between MODIS AOD 10 km (pixel size of 10 × 10 km at nadir) and MODIS AOD 3 km (pixel size of 3 × 3 km at nadir) ground AOD values were retrieved over the study area. The 10 km and 3 km pixels generally showed similar large-scale patterns in aerosol distribution, but the MODIS AOD 3 km seemed to cover the largest area of AOD retrieval compared to MODIS AOD 10 km based on the datasets for all the days. For instance, there were missing data in the South (Figure 8 (b)), while, in the same area, the missing data could be seen in the MODIS AOD 3 km (Figure 8 (c)).

Another case could be observed under normal weather conditions with a clear sky, where the MODIS (10 km and 3 km) showed a fine distribution of AOD (Figures 9 (a) and (b)). However, during cloudy days (white colour; Figure 6) or during high haze density (usually a grey colour; Figure 8 (a)), no AOD pixels were detected. It is difficult to explain this result, but it might be related to the sensitivity of MODIS in retrieving AOD at the area affected by cloud and high haze intensity. Some satellite-based AOD data could have been missed because of the effects of the cloud and a too-bright surface.

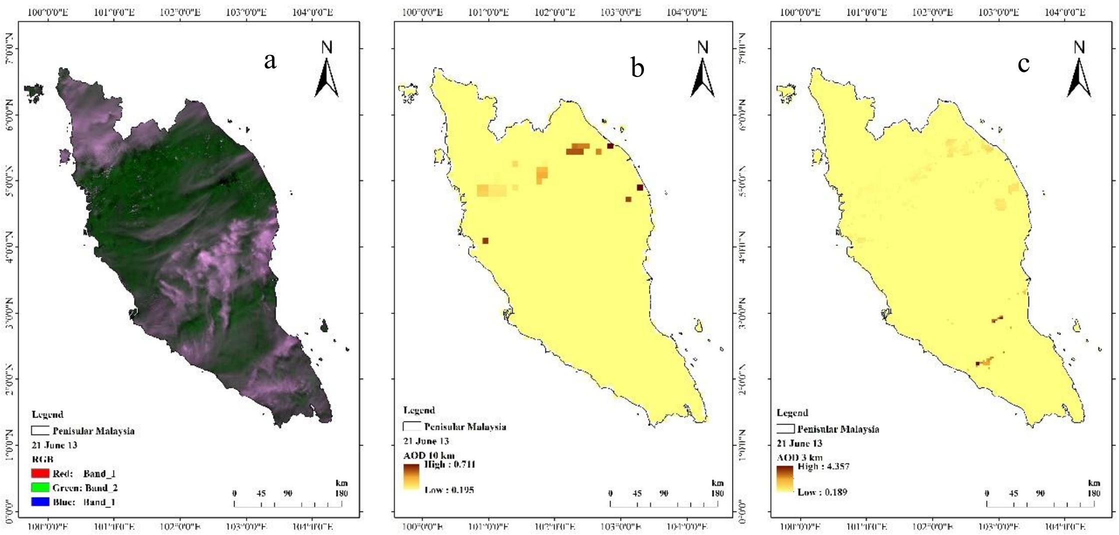

Figure 6. (a) True colour image (b) AOD retrieved from MODIS 10 km and (c) AOD retrieved from MODIS 3km on 21 June 2013

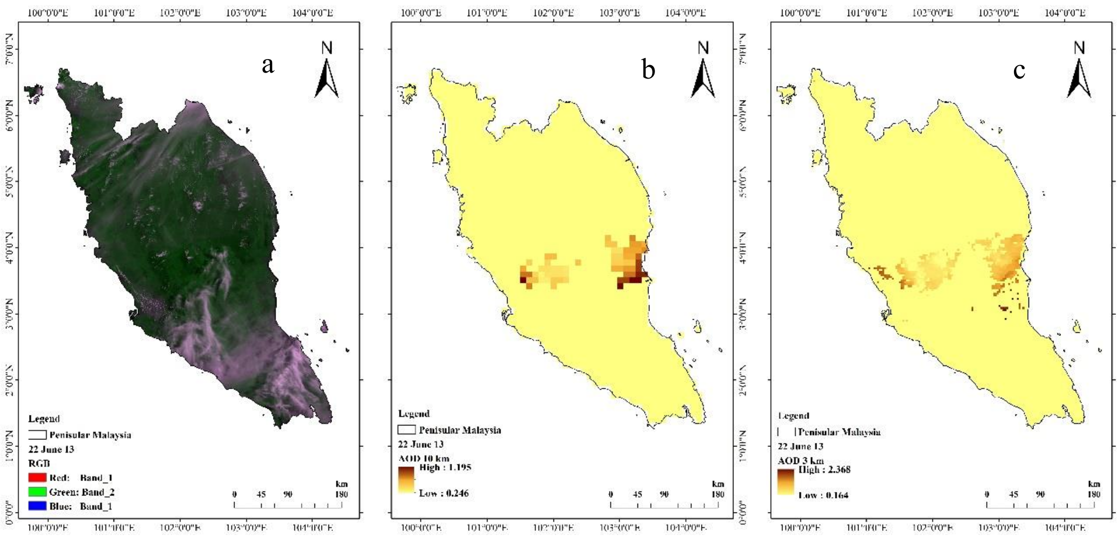

Figure 7. (a) True colour image (b) AOD retrieved from MODIS 10 km and (c) AOD retrieved from MODIS 3km on 22 June 2013

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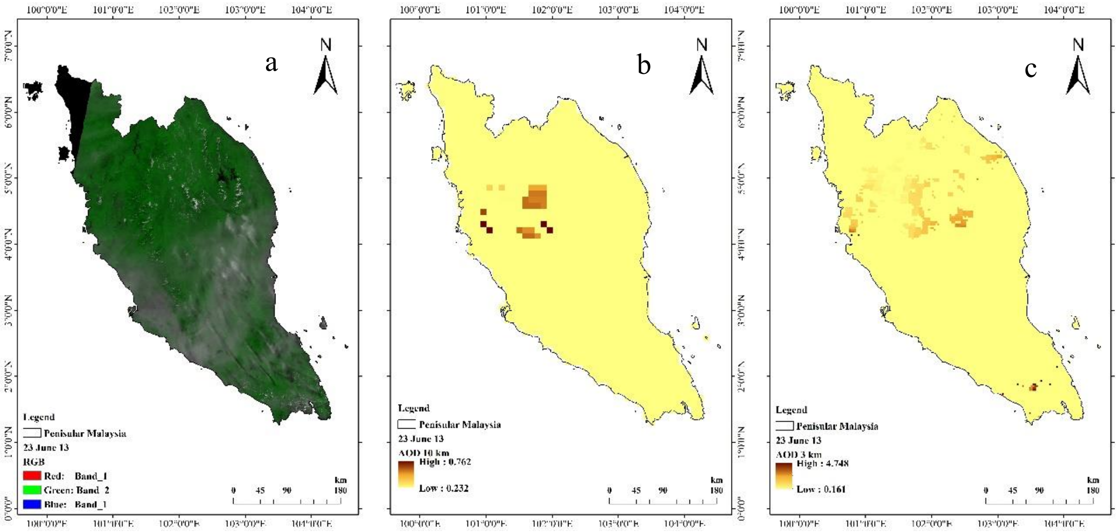

Figure 8. (a) True colour image (b) AOD retrieved from MODIS 10 km and (c) AOD retrieved from MODIS 3km on 23 June 2013

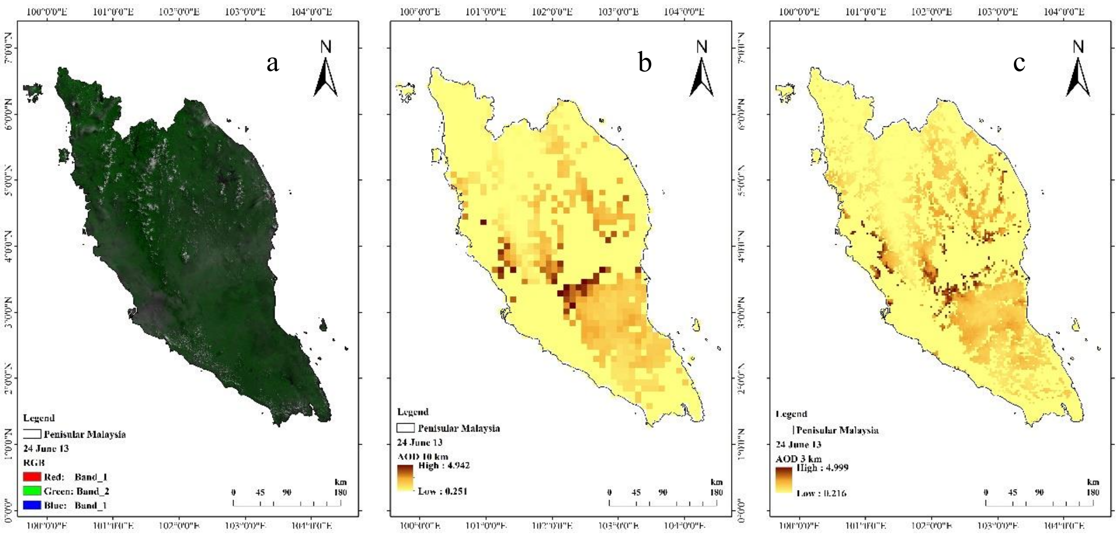

Figure 9. (a) True colour image (b) AOD retrieved from MODIS 10 km and (c) and AOD retrieved from MODIS 3km on 24 June 2013

4. Conclusion

This study was conducted from 21 to 26 June 2013, in which PM_{10} and $PM_{2.5}$ were intensively sampled. This study observed significantly high mass concentrations of most of the sampled PM_{10} and PM_2 over the study period. Furthermore, the results demonstrate that the AOD distribution maps, which were recovered from satellite information, could possibly bolster conditions for organisations to better investigate air quality. Additionally, MODIS-AOD is a good instrument for recognising the source of pollutants, which is hard to discover by only applying ground estimations. In addition, the information from satellite sensors can be utilised to obtain a better understanding of the haze phenomena. Besides, the findings of this study could improve upon the MODIS data usage for future atmospheric forecasts of haze problems.

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