

Preliminary analysis of the spatial and temporal patterns of aerosols and their impact on climate in Malaysia using MODIS satellite data

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ABSTRACT:

Research on atmospheric aerosols has become an important component in atmospheric studies due to its tremendous implications to radiation budget, climate change, hydrological and carbon cycles. Several recent studies have analysed the spatio-temporal patterns of aerosols and their relationship with meteorological conditions which is essential to quantify regional and global climate changes. However, such analysis have been lacking in Malaysia although this region receives considerable amount of air pollutants from local sources and neighbouring countries. Therefore, an attempt has been undertaken in this study to analyse the spatial and temporal patterns of aerosols in Peninsular Malaysia and explore the link between aerosols and meteorological variables. More specifically the monthly periodicities in atmospheric aerosols have been analysed using aerosol optical depth (AOD) product (level 2 data) from Moderate Resolution Imaging Spectro-radiometer (MODIS) satellite data covering years 2000-2009. Subsequently the AOD has been associated with meteorological variables (surface measurements) of daily minimum and maximum temperature, solar radiation, and relative humidity. Preliminary results of this study show that AOD is relatively higher in the dry season months (September and October). Spreading and intensifying fire locations in Indonesia contributed to a further increase in the AOD. Predominating south-west wind directions transported the aerosols to the north-east (Peninsular Malaysia) and caused subsequently high pollution levels. Association between AOD and climate show no significant correlation. This could be due to the monthly resolution of climate data used. Results presented in this study will be useful to understand how and to what extent human perturbations such as anthropogenic aerosol emissions serve as an agent of climate change.

1. Introduction

Aerosols are liquid or solid particles suspended in the air, with sizes (diameters) ranging from a few nanometers to a few tens of micrometers (Kahn et al., 2009). The concentration of aerosols in the atmosphere is measured using indices such as aerosol optical depth (AOD). AOD is defined as the aerosol attenuation of direct beam through a vertical column of the atmosphere (Power, 2003). AOD values typically range between 0 and 5 with values exceeding 1 usually indicates heavy pollution (Engel-Cox et al., 2004). Anthropogenic fossil fuel combustion and biomass burning are two major sources of aerosols in the atmosphere (Seinfeld and Pandis 1998) that are concentrated in the immediate vicinity, and downwind of sources (Textor et al., 2006).

Aerosols exert a variety of impacts on the environment and human health. Directly they interact strongly with solar and terrestrial radiation by scattering and absorbing sunlight. Scattering of sunlight by atmospheric aerosols can reduce the amount of solar radiation reaching the Earth's surface and thereby affecting the carbon cycle (IPCC, 2007). The indirect effects of aerosols on climate include promotion of cloud condensation nuclei (CCN) that can affect cloud microphysics and cloud reflection of sunlight to the space and delay the onset of precipitation (Ramanathan et al., 2001; Kaufman and Koren, 2006). Aerosols (especially particulate matters that are tiny i.e <10 microns in diameter) have also been shown to affect pulmonary function and other aspects of human health (in Afroz et al., 2003).

Research on atmospheric aerosols has become critical in the global climate change and carbon cycle studies due to its tremendous implications to the global radiation budget, increasing surface albedo, cloud formation and precipitation and spread of plant and human diseases (IPCC, 2007). According to Rind et al. (2009) major researches are urgently needed in the following three areas of aerosols:

- (i) Impact of aerosols on climate and reduce the uncertainty on the impacts
- (ii) Spatial and temporal variation of aerosols amounts and properties for evaluating aerosols effects on climate and
- (iii) Effects of aerosols on global water cycle

One of the greatest challenges in studying aerosols and their impacts are their spatial and temporal variations in terms of their concentration, particle size, composition, and origin. Studying the spatial and temporal patterns of aerosols are important to monitor the sources and sinks of specific aerosol types, to serve as inputs for climate modelling and to detect anthropogenic climate change (Kaufman and Tanre' 1998).

Studying and/or monitoring aerosols loading in the vertical column of the atmosphere (AOD) over large spatial and various temporal scale is important because AOD constitutes the main parameter to assess the aerosol radiative forcing and its impact on climate (Kaufman et al., 1997). Both insitu and satellite based remote sensing techniques have been developed to estimate AOD. Insitu measurements are undertaken by networks such as AERONET, Atmospheric Radiation Measurement (ARM), NOAA's national surface radiation budget (SURFRAD) and other networks with multfilter

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rotating shadowband radiometer (MFRSR) and lidar (see review by Li et al., 2009). These networks provide high temporal frequency data (point based), but limited in terms of the spatial coverage. However, characterizing the heterogeneities of aerosols over a regional or global scale and at multi temporal scale is only feasible through satellite remote sensing. Many satellite sensors have been developed to provide continuous AOD data in recent years. Among others are Total Ozone Mapping Spectrometer (TOMS), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectroradiometer (MERIS), Ozone Monitoring Instrument (OMI), Multi-angle Imaging Spectroradiometer (MISR), and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) (see review by Li et al., 2009). Among the sensors, MODIS is of particular interest because, not only it provides data from early 2000, but also this sensor employs much robust cloud screening technique and on board calibration techniques thus providing AOD with greater accuracy, i.e., $0.03 \pm 0.05\tau$ (Remer et al., 2008). In addition to AOD, MODIS also provides other aerosol size parameters such as effective radius and fine-mode fraction of AOD which are used to study different types of aerosols.

The satellite-derived, aerosol optical properties have been applied to various research areas in atmospheric studies. More particularly, a number of studies have been published in recent years analysing the spatial and temporal patterns of aerosols over USA, Europe and in the tropical regions and oceans (Kosmopoulos et al., 2008; Song et al., 2008; Schaap et al., 2009; Huang et al., 2010; Zha et al., 2010). Such studies are however, have been lacking in Malaysia although this region is subjected to local sources of air pollution (emission from motor vehicles, fossil fuel burning industries and open burning and forest fires) and receives considerable amount of air pollutants through forest fire from neighbouring countries during monsoon seasons. Data and studies have shown that the level of air pollution is increasing in some large cities in Malaysia at an unacceptable levels set by the national ambient air quality standards (Afroz et al., 2003). Yet, data on air pollution (insitu) and case studies are not so widespread in this region (Afroz et al., 2003). Thus, an attempt has been undertaken in this study to utilise MODIS AOD to analyse the patterns of AOD and their relationship with climate in this region. The knowledge of aerosol distribution, the inter-annual variability of their concentrations, and descriptions of their impact on climate are needed to fully understand the influence of aerosols on Malaysia's climate and also carbon cycle. Thus, an attempt has been taken in this study to:

- (i) describe the patterns of AOD (spatial and temporal) over Peninsular Malaysia
- (ii) link AOD to climate parameters i.e. solar radiation, temperature and relative humidity

2. Study Area

Peninsular Malaysia shares a land border with Thailand in the north, Singapore to the south and Sumatra island to the west. Its area is 131,598 kilometres² and accounts for the majority of Malaysia's population and economy. The air quality in Malaysia is generally moderate to good and it is one of the least polluted countries in Asia (Afroz et al., 2003). However, recent rapid development has contributed to increased pollution especially in large cities. The three major sources of air

pollution in Malaysia are motor vehicles, industry and domestic fossil fuel burning and open burning sources (DOE, 2010). Besides these local sources, Malaysia also receives significant amount of biomass burning aerosols from neighbouring countries particularly Indonesia. Gases and particulate matter originating from Indonesian forest fires especially from Sumatera have been transported in the dry season months (between July and September) by south westerly winds. The haze episodes in Southeast Asia in 1983, 1984, 1994, 1997, 1998-2000, 2002, 2004-2006 and the most recent one in 2009 affected Malaysia with significant health risks and economic lost (Tangang et al., 2010).

The tropical climate of Malaysia can influence the spatial and temporal variability of aerosols. Peninsular Malaysia is characterized by quite high but uniform temperatures (between 23° and 31° C), high humidity, and high rainfall (~ 2500 mm annually) (MMS, 2010). There are spatial and seasonal variations in rainfall, with the heaviest rainfall from October to January. Spatially, more rainfall is received in the eastern coastal region (>3000 mm per year whilst, the northwestern and southwestern regions receiving the least rainfall (MMS, 2010). As a result, usually high aerosols are expected during June-August period when the seasonal rainfall is low, relatively warmer temperature and southwesterly winds that facilitates the advection of aerosols from Sumatera and Kalimantan northward to Singapore and Peninsular Malaysia (Tangang et al., 2010). On the other hand, periods from October-January will record lower levels of atmospheric aerosols due to heavy rainfall that washes away aerosols from the atmosphere.

Since particulate matters from forest fire can affect human health, most of the studies conducted in Malaysia were focused on the health impacts of aerosols (Awang et al., 2000 and Nasir et al., 2000 in Afroz et al., 2003). Although the impact of aerosols is severe on human health and the economy of the country, data on air pollution/aerosols are still not enough (Afroz et al., 2003). Alternatively, satellite remote sensing can provide aerosols data at sufficient spatial (10 km) and temporal (twice daily) coverage for this region to study phenomena such as patterns of aerosols and their impact on climate. The details of satellite data used in the current study are detailed in the following section.

3. Data and Analysis

MODIS AOD product Collection 5 covering 10 year period (2000 to 2009) was used in this study to analyse the spatial and temporal patterns of aerosols and their impact on climate in Peninsular Malaysia. Collection 5 of the MODIS AOD product is the latest version of MODIS aerosol retrieval algorithm that utilizes robust cloud screening and on board calibration techniques (Levy et al., 2007). The MODIS aerosol data are retrieved twice daily; in the morning from MODIS on Terra platform and in the afternoon (on Aqua platform) at 10 x 10 km spatial resolution (Kaufman et al., 1997). Seven channels between 0.47 and 2.13 μm (calibrated and geolocated reflectance level 1B data) are used to retrieve aerosol properties (in Li et al., 2009). This data are known as level 2 data and represent the first level of MODIS aerosol retrieval. Over vegetated land, three visible channels are used to retrieve AOD with high accuracy of $0.05 \pm 0.2\tau$ (Levy et al., 2007). The new Collection 5 AOD data also eliminates the systematic overestimation of AOD for low aerosol loadings and underestimation of high loadings which existed in previous collections (in Li et al., 2009). Collection 5 also expands

MODIS AOD coverage to bright desert surfaces by using the deep blue retrieval algorithm (in Li et al., 2009).

MODIS daily AOD level 2 data were downloaded from the NASA website (<http://modis.gsfc.nasa.gov>) covering Peninsular Malaysia region. Level 2 AOD data were used in this study due to their moderate spatial resolution of 10 km and these data have been validated elsewhere using ground data and showed acceptable accuracy (Engel-Cox et al., 2004; Lau et al., 2003) and have been used to study aerosols patterns, climatology and heart diseases (Lau et al., 2003; Engel-Cox et al., 2004; Kaskaoutis et al., 2007; Hu, 2009).

A total of 2049 daily images were downloaded from 2000 to 2009. This number however, represents only ~56% of total images. Heavy cloud cover in this region could be the main reason for the poor retrieval of AOD data. The downloaded data were then reprojected from ISIN to WGS 84 projection system. The daily data were then averaged to monthly resolution to match them with climate data.

Climate data covering monthly solar radiation, temperature and relative humidity were obtained from the Malaysian Meteorological Services for 11 stations around Peninsular Malaysia (Figure 1). These stations cover north (Alor Star, Bayan Lepas and Ipoh), south (Senai and Kluang), west (Subang, Petaling Jaya and KLIA Sepang), east (Kota Bharu and Kuantan) and highland areas (Cameron Highland) in Malaysia. AOD values were extracted for a single pixel at these meteorological stations by making an assumption that the footprint of the meteorological station was approximately 10 km². Based on our analysis, from 2049 available images, AOD values are not available for all dates. This again could be due to local variations in cloud cover at these locations.

MODIS AOD data were analysed using various statistical techniques to describe both the spatial and temporal patterns. Climate data (solar radiation, temperature and relative humidity) were correlated with AOD on a monthly basis using simple regression analysis (see section 4.3).

4. Results and discussion

4.1 Spatial pattern of AOD

There was a distinct spatial variability of aerosols in Peninsular Malaysia, as indicated by the monthly averaged AOD values (averaged between 2000 and 2009) (Figure 2). Areas in the central west coast of Peninsular Malaysia Petaling Jaya and Subang- Figure 1) recorded higher AOD values (between 0.34 ± 0.04 and 0.39 ± 0.04) (average \pm Standard Error) than other locations (Figure 2). Kluang (south) and Ipoh (north) also showed average AOD values of more than 0.30 (Figure 2). These values are comparable to some polluted cities in the world such as Athens in Greece that had average AOD values (6 years average) of 0.35 (data derived from MODIS Collection 5, level 2 AOD product-Kaskaoutis et al., 2007). These locations particularly Petaling Jaya represents highly urbanised and industrialised areas with high density of population. Anthropogenic activities particularly release of fossil fuel combustion from factories and motor vehicles can contribute to the high concentration of aerosols in these areas. Aerosols content in the air is usually close to the source of aerosols (Koelemeijer et al., 2006). Survey conducted by the Department of Environment, Malaysia, 1996 (in Afroz et al., 2003) shows

that 82 % of the more than three million tones of air pollutants were released by motor vehicles. The rest, about 9% is contributed by power stations and 5% released by the industrial sector. Moreover, findings by Hashim et al., (2004) and Shaharuddin and Noorazuan (2005) show that haze from forest fire in Sumatra, Indonesia reaches western part of Peninsular Malaysia more than the east coast.

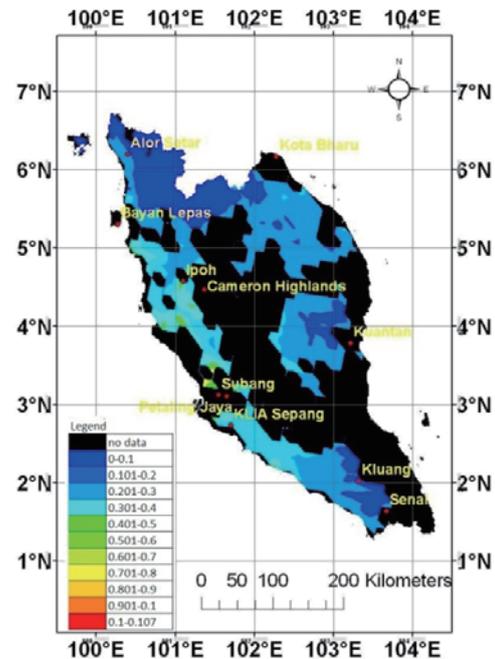


Figure 1. Location of 11 meteorological stations that were used to study the variation in the spatial and temporal pattern of aerosols in Peninsular Malaysia. Data were overlaid on AOD (Level 2) product of MODIS dated 20 June 2009.

Among the eleven locations analysed in this study, Cameron Highland (a hill station located at 1545 m above mean sea level) recorded the lowest average AOD values of (0.11 ± 0.01) . This place is far from any industrial or urban centres, thus minimal local production of aerosol.

4.2 Temporal pattern of AOD

There was a strong temporal variability of aerosols between 2000 and 2009, as indicated by the monthly AOD values (Figure 3). Generally, the AOD is higher in the dry months especially in October with an average AOD of 0.56 ± 0.16 (averaged across all eleven stations). This is followed by September with an average AOD of 0.43 ± 0.06 . These values are significantly different from the values recorded in other months ($F_{9,435} = 4.20$, $p < 0.001$). Relatively higher AOD values in September and October months are not only related to local sources of aerosols as mentioned in section 4.1, but also contributed by aerosols released from burning of palm oil plantations in Riau and other Sumatra provinces. During this time of the year, generally the southwest monsoon greatly influence the cross equatorial transport of aerosols from Sumatra and Kalimantan to Peninsular Malaysia (Tanggang et al., 2010). Meanwhile, the lowest AOD was recorded in the rainy season months of November to January (AOD values between 0.15 ± 0.02 and 0.22 ± 0.03). The low AOD values in the wet season corresponded with monsoonal rainfall which

likely scavenged aerosols from the atmosphere through wet deposition processes (Tanggang et al., 2010). This pattern is observed for all sites considered in this study except for Cameron Highland where the monthly variation is small as this location is not affected tremendously by any source of pollution (data not shown).

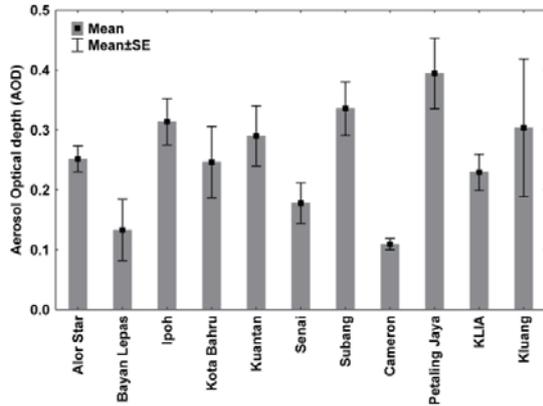


Figure 2. The spatial variation in monthly aerosol optical depth in Peninsular Malaysia from 2000 to 2009. Error bars show \pm SE from monthly average values.

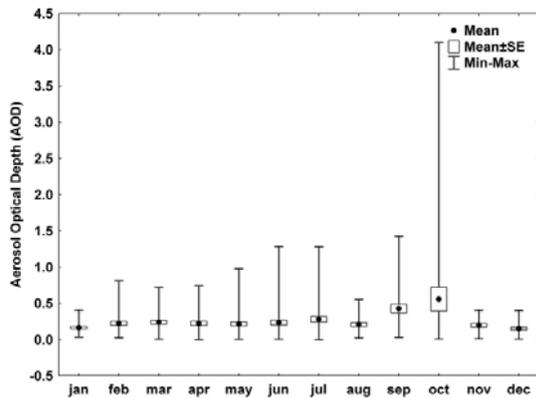


Figure 3. The temporal variation in monthly aerosol optical depth values in Peninsular Malaysia from 2000 to 2009. The mid point in each of the boxes is the means, the boxes are \pm SE and the whiskers are the minimum and maximum values.

Inter-annual variation in AOD showed that the year 2006 had a higher aerosol concentration in the atmosphere than other years with AOD value of 0.46 ± 0.12 and this was followed by year 2004 and 2002 with AOD of 0.33 ± 0.04 (Figure 4). The large value in 2006 is linked to the El-Nino event that made the pollution/haze problem worse than during non El- Nino years. During El-Nino event, changes in the Pacific sea surface temperature and low pressure centre causes increased subsidence and atmospheric stability that suppresses precipitation for months (Tanggang et al., 2010). During this time fires in Kalimantan that were on peatland produced great amounts of aerosols. Reduced rainfall can also prolong the atmospheric residence time of aerosols and restrict their concentration to the lower troposphere because the upward air motions over Indonesia were suppressed by the strong ENSO event (Tanggang et al., 2010). The only transport of aerosols is via advection i.e. south-west winds. The Air Pollution Index (obtained using fine particles $<10 \mu\text{m}$ and several gases) showed high values close to 200 in October which is an unhealthy level in most big cities in Malaysia (The Star, 2006).

This value is comparable to AOD derived from MODIS (this study) in 2006 which showed higher value of 2.2 ± 0.72 in October compared to September or November which was 0.82 and 0.31 respectively. The occurrence of haze in 2002 and 2004 were only moderate compared to 2006 (ADB and CAI-Asia, 2006).

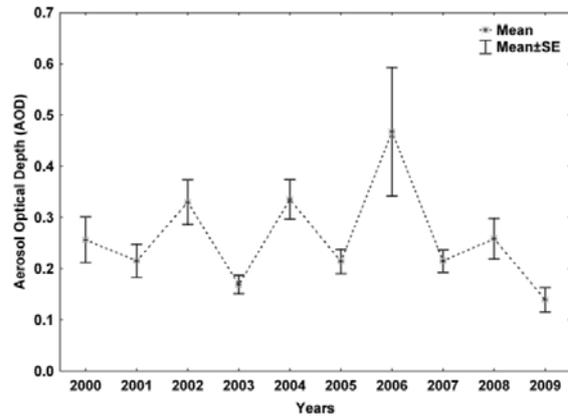


Figure 4. The yearly average values (2000 to 2009) of aerosol optical depth from 11 locations in Peninsular Malaysia. Error bars show \pm SE from yearly average values.

Quantifying the inter-annual variation in aerosols is important in assessing the influence of aerosols on climatic variation. The magnitude of inter-annual variability in AOD from 2000 to 2009 was analysed in this study using Coefficient of Variation (CV; calculated as standard deviation/mean). Large inter-annual variations were found for Kluang, Kota Bahru and Petaling Jaya (CV of 105, 97 and 64% respectively), whereas AOD in Cameron Highlands and Alor Star were less variable ($\sim 32\%$). Other stations/cities had intermediate variation with CV, ranging between 40 and 49%. The reason for the large inter-annual variation is associated with the severe haze occurred in southeast Asia in 2006. According to reports by “The Star Online” newspaper (07 October, 2006), the worst affected area in Peninsular Malaysia was Johor Bahru with API (Air Pollution Index) readings exceeded 150 during first week of October 2006. Similarly, east Malaysia and Klang Valley also were seriously affected by haze from Indonesia that were brought to these regions by southwest winds.

4.3 Influence of AOD on climate

Aerosols have been shown to cause reduction in total solar radiation at the surface (Stanhill and Cohan, 2001; Kanniah et al. 2010) and reduce the surface temperature (Huang et al., 2006). In this study, the effects of aerosols on the component of total surface irradiance and temperature were examined. The data indicate that there was no significant relationship between AOD and solar radiation measured at the surface for any of the stations studied. Similar pattern was also obtained for monthly minimum and maximum temperature except for one station (Alor Star) where the minimum temperature showed a positive correlation with AOD although the strength of the relationship is weak ($r^2 = 0.13$ at $p < 0.005$). The reason for the poor relationship between AOD and climatic parameters may be due to the datasets used in this study. The time of satellite AOD acquisition was between 11 am to 1 pm whereas climate data represent averaged values for the whole day/month. This problem will be overcome in the future when high temporal resolution climatic data are obtained from the Malaysian

Meteorological

Services.

5. Summary and future works

This study described the aerosol environment for Peninsular Malaysia and identified both local and trans-boundary emission and transport as the main source of aerosols in this region. Variations in the spatial and temporal patterns of aerosols were also linked to the local sources and aerosols transported from Indonesia to Malaysia via monsoonal winds. This study is however can be enhanced in the future by considering the following:

- (i) Analysing the size of particles (i.e. fine mode particles product from MODIS) could provide information on various types of aerosols (urban, industrial, maritime and dust) present in this atmosphere. More specific information about different types of aerosols will facilitate the analysis of their impacts on earth radiation budget and cloud microphysical properties.
- (ii) Trajectory analysis will help to identify the source of aerosols and their transport to Peninsular Malaysia. This can be done using trajectory models such as HYSPLIT.
- (iii) As mentioned in section 4.3 high temporal resolution climate data that match satellite AOD data will be purchased from MMS (although it is costly) to perform the relationship between AOD and climate in Malaysia.

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