INVESTIGATING AEROSOL PROPERTIES IN PENINSULAR MALAYSIA VIA THE SYNERGY OF SATELLITE REMOTE SENSING AND GROUND-BASED MEASUREMENTS

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To my beloved mother and father

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ABSTRACT

Atmospheric aerosols play an important role in climate change and air quality. Aerosol studies that are related to their spatio-temporal variation and trends are useful in order to understand their roles and impacts on solar radiation and clouds. The main objectives of this study are to validate the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Depth (AOD) products, analyse the spatio-temporal evolution and trend of AOD from Terra and Aqua MODIS sensors, to identify aerosol types and their origin, and to investigate the effects of aerosol on solar radiation. The Terra MODIS AOD was found to correlate significantly with Aerosol Robotic Network (AERONET) AOD with $R^2 = 0.86$.The spatial pattern of MODIS AOD in Peninsular Malaysia shows highest AOD values at western stations whereas the lowest AOD values were recorded at Cameron highlands. The AOD trend over a period of 10 years shows a neutral-to-declining trend, while that from Aqua exhibits an increasing trend. AERONET AODs exhibit either insignificant diurnal variation or higher values during afternoon, while their short-term availability does not allow for trend analysis. Moreover, the Particulate Matter below 10 micron (PM_{10}) concentrations exhibits a general positive trend over the examined locations suggesting increase in aerosols near the ground. The identification of sources and destination of aerosols revealing that aerosols during the dry season are mainly originated from the west and southwest, while in the wet season they are mostly associated with the northeast monsoon winds from the South China Sea. Four types of aerosols were identified and the AOD was found negatively correlated with solar radiation with low R^2 but statistically significant.

ABSTRAK

Aerosol di atmosfera memainkan peranan penting dalam perubahan iklim dan kualiti udara. Kajian aerosol yang berkaitan dengan variasi ruang dengan waktu serta tren adalah amat berguna bagi memahami peranan dan kesan aerosol terhadap sinaran suria dan awan. Objektif utama kajian ini adalah untuk mengesahkan produk Kedalaman Optik Aerosol (AOD) dari penderia Spektroradiometer Pengimejan Resolusi Sederhana (MODIS) pada satelit Terra, menganalisis evolusi ruang dengan waktu dan trend AOD daripada penderia MODIS pada satelit Terra dan Aqua, mengenal pasti jenis dan asal usul aerosol, serta meninjau kesan aerosol terhadap sinaran suria. AOD dari penderia MODIS pada satelit Terra didapati berhubung kait rapat dengan AOD dari Rangkaian Robot Aerosol (AERONET) dengan R^2 = 0.86. Corak ruang MODIS AOD di Semenanjung Malaysia menunjukkan bahawa AOD tertinggi telah direkodkan di stesen-stesen yang terletak di pantai Barat manakala nilai AOD terendah tercatat di Tanah Tinggi Cameron. Tren AOD sepanjang sepuluh tahun menunjukkan tren neutral ke menurun, sedangkan Aqua memaparkan tren meningkat. AOD dari stesen AERONET menunjukkan sama ada variasi harian kecil atau nilai yang lebih tinggi pada waktu petang. Analisis tren terhadap ketersediaan jangka pendek AOD pula tidak dapat ditinjau. Tambahan pula, kepekatan Partikulat di bawah 10 mikron (PM_{10}) memperlihatkan satu tren positif umum di lokasi kajian, yang membayangkan peningkatan dalam aerosol yang berhampiran dengan muka bumi. Pengenalpastian sumber dan destinasi mendedahkan bahawa kebanyakan aerosol di musim kering berasal dari barat dan barat daya, manakala pada musim hujan, kebanyakannya berkaitan dengan monsun timur laur dari Laut China Selatan. Empat jenis aerosol telah dikenal pasti di Semenanjung Malaysia. Didapati AOD berhubung kait secara negatif dengan sinaran suria dengan R^2 yang rendah, tetapi mempunyai kepentingan.

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AD-Net	Asian Dust Network
AERONET	Aerosol Robotic Network
AOD	Aerosol Optical Depth
API	Air Pollution Index
ASMA	Alam Sekitar Sdn Bhd
AVHRR	Advanced Very High Resolution Radiometer
BAER	Bremen Aerosol Retrieval
CAQM	Continuous Air Quality Monitoring
CCN	Cloud Condensation Nuclei
CIRES	Cooperative Institute for Research in Environmental Sciences
DDV	Dark Dense Vegetation
DOE	Department of Environment
EARLINET	European Aerosol Research Lidar Network
EDAS	Eta Data Assimilation System
EQA	Environment Quality Act
ESA	European Space Agency
FMF	Fine Mode Fraction
GDAS	Global Data Assimilation System
GMD	Global Monitoring Division
GOME	Global Ozone Monitoring Experiment
HVAS	High Volume Air Sampler
HYSPLIT	Hybrid Single Particle Lagrangian Intergrated Trajectory
IMPROVE	Interagency Monitoring of PROtected Visual Environment
IPCC	Intergovernmental Panel on Climate Change

ISIN	Integrated Sinusoidal projection
LUT	Look-Up Table
MAN	Maritime Aerosol Network
MAQG	Ambient Air Quality Guidelines
MAQM	Manual Air Quality Monitoring
MERIS	Medium Resolution Imaging Spectrometer
MFRSR	Multifilter Rotating Shadowband radiometer
MISR	Multi-angle Imaging Spectro Radiometer
MMD	Malaysia Meteorological Department
MODIS	Moderate resolution Imaging Spectrometer
MPLNET	Micro Pulse Lidar Network
NAM	North America Mesoscale model
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Differential Vegetation Index
NGM	Nested grid Model
NIR	Near-Infrared
NOAA	National Oceanic and Atmospheric Administration
OMI	Ozone Monitoring Instrument
PM	Particulate Matter
POLDER	Polarization and Directionality of the Earth's Reflectance
REALM	Regional East Atmospheric Lidar Mesonet
RF	Radiative Forcing
SCIAMACHY	Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY
SDA	Spectral De-Convolution Algorithm
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SPM	suspended particulate matter
TOA	Top-of-Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TSP	Total Suspended Particulate
TSP	total suspended particulates

UV	Ultraviolet

CHAPTER 1

INTRODUCTION

1.1 Background

Atmospheric aerosols are suspended particles in the air that are originated either from natural (dust, volcanoes eruption, or sea salt) or anthropogenic sources (industrial activities) (Lee and Kim, 2010). Aerosols usually have diameter ranged from a few nanometres to tens of micrometers. Aerosols have become the main issue in climate change, air quality and public health due to their tremendous impact on radiative forcing (NASA Facts, 2005). Aerosols are still one of the large uncertainties in earth's climate system by virtue of their high spatio-temporal variability and various optical properties (IPCC, 2007). Aerosols may induce significant changes on global climate by its characteristics of scattering and absorbing incident solar radiation, which this impact is known as the direct radiative effect of aerosols. Furthermore, aerosols can render harmful impact to human being by reducing air quality which causes health effects (i.e. eye and lung disease) and poor visibility (Reid et al., 2013). The effects of aerosol are dependent on its optical and physical characteristics and aspects that are usually being examined under this subject are optical depth, size distribution, and single scattering albedo and etc (NASA Facts, 2005; Kahn et al., 2009). Therefore, aerosol properties are crucial aspects to be weighted in order to understand the influence of aerosols on radiation and climate.

Aerosol optical depth (AOD) is a basic optical parameter which is related to atmospheric load and used to understand the effect of aerosols on radiative transfer in the Earth's atmosphere (IPCC, 2007). Detailed knowledge of the optical properties is important to clarify the mechanisms of aerosol radiative forcing. Refined aerosol models also useful to improve the accuracy of satellite retrieval algorithms that rely on assumptions of the aerosol properties of different aerosol types (King et al. 1999).

Southeast Asia was listed as one of the most vulnerable regions of the world to climate change by the 2007 IPCC Report on Impacts, Adaption and Vulnerability (IPCC, 2007). Southeast Asia is having a complex aerosol system in the world. The atmospheric observation, analysis and prediction over this region are a challenging task due to the topographic geography (heterogeneous land surface), meteorological and hydrological complexity (Reid et al., 2013). Population growth, rapid urbanization and development of Southeast Asia countries (including Malaysia) can be linked to the high aerosol concentrations. Increment of aerosol concentration or poor air quality in Malaysia is mainly contributed by sources from automobiles emissions, industry activities and biomass burning (including fossil fuel and forest). Large number of motor vehicles (i.e. personal cars, public vehicles and motorcycles) in high population area has produced high emissions of air pollutants and it is the major source of air pollution in Malaysia (Afroz et al. 2003). Furthermore, the haze period which is usually happened in the dry season (June to September) is another main air quality issue in Malaysia. It is due to the injection of suspended ash particles from large scale forest fire in Sumatera and Kalimantan which is transported by the south-westerly winds.

As mentioned before, aerosol brings impact on human health. Infectious or chronic disease is prone to happen when human is exposed to polluted air. Within a short period, high level of air pollution may block sunlight from entering the earth and this may affect the photosynthesis process and agriculture production (Chameides et al., 1999). However, the possible long term health effects caused by air pollution are still unknown and difficult to detect. Various studies have linked human health issue to the 1997 forest fire in Indonesia (Brauer and Jamal, 1998; Awang et al., 2000; Nasir et al., 2000). Brauer and Jamal (1998) found that cases of asthma, acute respiratory infection and conjunctivitis increased significantly during August to September of 1997 at some major hospitals in Kuala Lumpur, Malaysia.

However, the number of cases was found to have decreased followed by the declining of air pollutant concentration after September. This phenomenon indicated that high levels of air pollutant, especially the Particulate Matter (PM_{10}), were harmful to human health (Awang et al., 2000).

1.2 Problem statement

The study of aerosol is important to Malaysia but only a few studies have been carried out especially for large spatial extent and on continuous basis due to the limited availability of aerosol data. Aerosol distribution and air quality of Malaysia are analyzed mostly based on Particulate Matter less than 10 micron (PM_{10}) data that are obtained using ground based instruments such as high volume air sampler which is managed by a private company known as Alam Sekitar Sdn Bhd (ASMA) and Malaysia Meteorological Department (MMD). A total of 52 and 22 air quality monitoring stations have been setup and operated nationwide by ASMA and MMD respectively. Several studies have been conducted using these data to study the health impact of fine mode particles (Jamil et al., 2011; Awang et al., 2000), variation of PM_{10} concentration (Juneng et al., 2009) and relationship between PM_{10} and meteorological variables (Azmi et al., 2010; Juneng et al., 2011).

PM_{10} are taken with high temporal frequency but they do not cover large areas. A total of 51 continuous air quality monitoring stations and 19 manual air quality monitoring stations were installed by ASMA while total of 22 air quality monitoring stations were installed by MMD to cover the entire country. Moreover, PM_{10} values which are usually used in various studies (i.e. health and meteorology) are referred to particles that mostly suspended within the boundary layer (~1.5 – 2km of the lower troposphere) and only represent the surface/subsurface aerosol concentration. These data are not suitable to be used to study the spatial and temporal variability of columnar aerosols. The characteristics of columnar aerosols are also important to be studied as the flow of aerosols can occur from the higher troposphere or even stratosphere to low troposphere. The characteristics, size and effect of aerosols may alter due to their transportation. In this context, satellite remote sensing can be the alternative approach or tool to measure aerosols and study the spatial distribution of aerosol properties over large spatial scales. Various satellite sensors such as Advanced Very High Resolution Radiometer (AVHRR), Total Ozone Mapping Spectrometer (TOMS), MODerate resolution Imaging Spectrometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and etc (discussed in chapter 2) have been used in aerosol studies regarding to aerosol concentration, distribution, types, their effects on climate, health and hydrological cycle (Kokhanovsky et al., 2007, 2009, 2010).

MODIS is one of the satellite sensors which is widely used in aerosol studies due to its long term aerosol data availability (since February 2000), high accuracy of Aerosol Optical Depth (AOD) retrieval (i.e. ± 0.05 AOD under clear sky and ± 0.15 under moderately contaminated atmosphere) (Remer et al., 2008), and twice daily coverage. MODIS aerosol products were used in many aerosol studies namely radiation and climate (e.g. IPCC, 2001; Yu et al., 2006), and air quality (e.g. Chu et al., 2003; Al-Saadi et al., 2005). In addition, MODIS aerosol products (Aerosol optical depth) have also been used to describe aerosol pattern over various geographical area (Prasad and Singh, 2007; Kosmopoulos et al., 2008; Song et al., 2008; Alam et al., 2011; Kanniah and Yaso, 2010; Marey et al., 2011; Kittaka et al., 2011). Meanwhile, aerosol size related products such as fine-mode fraction and Ångstrom Exponent have also been used to discriminate different types of aerosols (Barnaba and Gobbi, 2004; Kaskaoutis et al., 2007, 2012; Kim et al., 2007; Santese et al., 2007; Deng et al., 2012).

1.3 Objectives of the study

Study of aerosols is meaningful and critical due to its close relationship with issues of climate and human health. In this context, this study is undertaken to study the aerosol properties and distribution over Peninsular Malaysia. Specifically, the objectives of this study are as follows:

i. To validate MODIS AOD with Aerosol Robotic Network (AERONET) AOD.
ii. To analyze the spatial and temporal evolution of AOD in Peninsular Malaysia.
iii. To investigate the transport pathways of AOD to Peninsular Malaysia.
iv. To study the aerosol types in Peninsular Malaysia.
v. To investigate the effect of AOD on solar radiation.

1.4 Scope of the study

In order to achieve the aim and objectives of this study, this study is limited to Peninsular Malaysia (which is located around 1° 30’ N - 7° N and 100° E - 105° E). Both MODIS Terra and Aqua level 2 aerosol products (MOD04 and MYD04) were used in this study. Moreover, AERONET level 2 aerosol products covering USM Penang, Tahir (Peninsular Malaysia), Kuching Sarawak, Singapore and Songkhla (Thailand) were used to validate Terra MODIS AOD. The validation of Aqua MODIS AOD was excluded in this study because the number of valid points from Aqua MODIS sensor is not sufficient (only 12 valid points) for validation purposes. The MODIS Fine Mode Fraction (FMF) was used to classify the types of aerosols. The Particulate Matter (PM_{10}) data was used to analyze the temporal evolution of aerosols on the ground and then compared with the MODIS AOD.

1.5 Significance of the study

Aerosols bring various impacts on several aspects, for instance, climate and human health. Assessment and /or validation of satellite aerosol products (i.e. MODIS Terra data) over the study area (Peninsular Malaysia) can make sure that the quality of the products is satisfactory for further analysis of aerosol properties in this region. The influence of aerosols always depends on their properties (i.e. concentration, size distribution, types, lifetime and etc.). The aerosol properties are also related to local and regional events such as biomass burning, volcanic eruptions and urban process. Therefore, understanding aerosol properties and distribution as well as their relationship with local and regional events and/or meteorological parameters (i.e. solar radiation) is important. The analysis of spatial-temporal variation and trends in atmospheric aerosols in this study could be useful to regional and global climate change assessment. In addition, the mitigation of aerosol's effect by related parties will need this information as well. Furthermore, the study of transport pathways of aerosols to Malaysia is good to identify aerosol sources and estimate the anthropogenic contribution. This information is important to air pollution control and mitigation in major cities of Malaysia.

1.6 Thesis organization

There are five chapters in this thesis. Chapter 1 of the thesis provides the background, problem statement, objectives and significance of this study, while chapter 2 provides description of aerosols and a review of previous studies on the optical and physical properties of aerosol using satellite-based and/or ground-based data. Chapter 3 describes datasets and analysis methods used to achieve the objectives of the study. Chapter 4 exhibits the main results and discussion whereas chapter 5 presents the conclusion of this study.

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