ESTIMATING PARTICULATE MATTER USING SATELLITE BASED AEROSOL OPTICAL DEPTH AND METEOROLOGICAL PARAMETERS IN MALAYSIA

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All challenging work needs self-efforts as well as support from who were close to our heart. Therefore, I would like to dedicate my thesis to my family

Fahmin (Abe G),Faris, Fakhri (Li),Fariha (Tik), Faiz (ieh), Farhana (Ana), Natasha (Kak Tasha), Fatin (Kak Tyn), Hafizah (Kak Fizah), 3D

especially

UMI (*Nooraini Awang*) & **PAPA** (*Kamarul Zaman Ibrahim*)

“You are every reasons, hope and dream I have ever had”

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ABSTRACT

The insufficient number of ground-based stations for measuring Particulate Matter less than 10μm (PM_{10}), especially in the developing countries hinders PM_{10} monitoring at a regional scale. The present study aims to develop empirical models for PM_{10} estimates from space over Malaysia using Aerosol Optical Depth (AOD_{550}) retrieval from Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectrometer/Advanced Along-Track Scanner Radiometer (MERIS/AATSR) synergy algorithm and meteorological data that include surface temperature, relative humidity and atmospheric stability from 2007-2011. Accuracy of meteorological parameters that have been used in the estimation of PM_{10} are examined. The estimated relative humidity and surface temperature using satellite data agree well with ground data where coefficient of determination (R^2) = 0.78 and 0.49 and Root Mean Square Error (RMSE) = 5.14% and 2.68°C for relative humidity and surface temperature respectively. Multiple Linear Regressions (MLR) and Artificial Neural Network (ANN) techniques are utilized to develop the empirical models. The models were developed using PM_{10} data measured at 29 stations over Malaysia. Result of the research reveals that the ANN using MODIS AOD_{550} provide higher accuracy with R^2 = 0.71 and RMSE = 11.61μgm^{-3} compared to the MLR method where R^2 = 0.66 and RMSE = 12.39μgm^{-3} or models that use MERIS/AATSR AOD data. Stepwise regression analysis performed on the MLR method reveals that the MODIS AOD_{550} is the most important parameter for PM_{10} predictions where R^2 = 0.59 and RMSE = 13.61μgm^{-3}. However, the inclusion of the meteorological parameters in the MLR increases the accuracy of the PM_{10} estimations. The significance of the meteorological parameters in prediction of PM_{10} concentrations is in the order of (i) atmospheric stability, (ii) relative humidity and (iii) surface temperature. The estimated PM_{10} concentrations are validated against another 16 stations dataset of measured PM_{10} with the ANN model to result in higher accuracy (R^2= 0.58, RMSE = 10.16μgm^{-3}) compared to the MLR technique (R^2 = 0.56, RMSE = 10.58μgm^{-3}). The higher accuracy that has been attained in PM_{10} estimations from space allows (i) to map the PM_{10} distribution at large spatial and temporal scales and (ii) permits for future estimates of $PM_{2.5}$ concentrations from space for monitoring of the Environmental Performance Index (EPI).

ABSTRAK

Jumlah stesen darat yang tidak mencukupi untuk mengukur jirim zarahan yang bernilai kurang daripada 10µm (PM_{10}), khususnya di negara-negara membangun telah menghalang pemantauan PM_{10} pada skala serantau. Tujuan kajian ini ialah untuk membangunkan model empirikal bagi PM_{10} berdasarkan anggaran dari ruang angkasa Malaysia dengan menggunakan kedalaman optik aerosol (AOD_{550}) yang didapati daripada spektroradiometer pengimejan resolusi sederhana (MODIS), algoritma sinergi spektrometer pengimejan resolusi sederhana/radiometer pengimbasan sepanjang-trek tinggi (MERIS/AATSR) dan data meteorologi termasuk suhu permukaan, kelembapan relatif dan kestabilan atmosfera dari tahun 2007 hingga 2011. Ketepatan pembolehubah meteorologi yang digunakan dalam penganggaran nilai PM_{10} telah diperiksa. Anggaran nilai kelembapan relatif dan suhu permukaan dari data satelit adalah bersamaan dengan data tanah dimana pekali penentuan (R^2) =0.78 dan 0.49, serta ralat min punca kuasa dua (RMSE) = 5.14% dan 2.68°C bagi nilai kelembapan relatif dan suhu permukaan. Bagi membangunkan model empirikal, teknik regresi linear berganda (MLR) dan teknik buatan rangkaian neural (ANN) telah diguna pakai. Model ini telah dibangunkan menggunakan data dari PM_{10} yang dicerap di 29 buah stesen di seluruh Malaysia. Hasil kajian mendapati ANN yang menggunakan AOD_{550} dari MODIS telah memberikan nilai ketetapan yang lebih tinggi dimana R^2=0.71 dan RMSE = 11.61μgm^{-3} berbanding teknik MLR yang memberi nilai R^2= 0.66 dan RMSE = 12.39μgm^{-3} atau model yang menggunakan data AOD_{550} dari MERIS/AATSR. Analisis regresi berperingkat yang dilakukan ke atas teknik MLR menunjukkan bahawa AOD_{550} dari MODIS adalah pembolehubah yang paling penting bagi menganggar nilai PM_{10} dimana R^2=0.59 and RMSE=13.61μgm^{3}.Walau bagaimanapun, penambahan pembolehubah meteorologi dalam MLR mampu meningkatkan lagi ketepatan anggaran PM_{10}. Kepentingan pembolehubah meteorologi dalam ramalan kepekatan PM_{10} adalah mengikut turutan berikut (i) kestabilan atmosfera, (ii) kelembapan relatif dan (iii) suhu permukaan. Anggaran kepekatan PM_{10} telah disahkan terhadap set data daripada 16 stesen lain yang mencerap PM_{10} dengan ANN untuk menghasilkan nilai ketepatan yang lebih tinggi (R^2= 0.58, RMSE =10.16μgm^{-3}) berbanding teknik MLR (R^2 = 0.56 dan RMSE = 10.58μgm^{-3}). Penambahbaikan ketepatan ketara yang telah dicapai dalam penganggaran PM_{10} membolehkan (i) taburan PM_{10} dipetakan pada skala ruang dan masa yang besar dan (ii) membolehkan anggaran kepekatan $PM_{2.5}$ dibuat pada masa hadapan dari angkasa untuk tujuan pemantauan indeks prestasi alam sekitar (EPI).

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LIST OF ABBREVIATIONS

AE	Ångström Exponent
AERONET	AErosol RObotic NETwork
AI	Aerosol Index
AIRS	Atmospheric Infrared Sounder
ANN	artificial neural network
AOD	aerosol optical depth
AOD_{550}	aerosol optical depth at 550nm
API	Air Pollution Index
ASMA	Alam Sekitar Malaysia Sdn Bhd
ATSR	Along Track Scanner Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BAM1020	Beta Attenuation Monitor
BLH	Boundary Layer Height
CAICE	Center for aerosol Impacts on climate and the environment
CAQM	Continuous Air Quality Monitoring
CCN	cloud condensation nuclei
CTM	chemical transport models
DEM	Digital Elevation Model
DOE	Department of Environment
DRAGON	Distributed Regional Aerosol Gridded Observation Networks
DTA	Differential Textual Analysis
ENVISAT	Environmental Satellite
EPA	Environmental Protection Agency
EPI	Environmental Performance Index
FMF	fine-mode fraction
FR	Full Resolution
GAW	Global Atmosphere Watch
GDE	Guide to the Demonstration of Equivalence
GEOS CTM	Goddard Earth Observing System Chemical Transport Model
GEOS-CHEM	Goddard Earth Observing System-Chemistry
GOME	Global Ozone Monitoring Experiment
GWR	Geographical Weighted Regression
HPBL	Height of Planetary Boundary Layer
HVAS	High Volume Air Sampler
HVPM10S	High Volume PM_{10} Sampler
IN	ice nuclei

IPCC	Intergovernmental Panel on Climate Change
LOTOS-EUROS	Long Term Ozone Simulation-EURopean Operational Smog
LUR	Land Use Regression
LUT	Look Up Table
MAAP	Multi Angle Absorption Photometer
MAIAC	Multi Angle Implementation of Atmospheric Correction
MAQM	Manual Air Quality Monitoring
MBE	Mean Bias Error
MERIS	Medium Resolution Imaging Spectrometer
MERIS/AATSR	Medium Resolution Imaging Spectrometer/Advanced Track Scanner Radiometer
METMalaysia	Malaysian Meteorological Department
MISR	Multiangle Imaging Spectroradiometer
MLP	Multi-Layer Perceptron
MLR	Multiple linear regressions
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NIR	Near Infrared
NPP	National Polar-orbiting Partnership
OLCI	Ocean and Land Colour Instrument
OMI	Ozone Monitoring Instrument
PFR	Precision Filter Radiometer
PM	Particulate Matter
$PM_{0.1}$	Particulate Matter less than 0.1µm
PM_{10}	Particulate Matter less than 10µm
$PM_{2.5}$	Particulate Matter less than 2.5µm
POLDER	Polarization and Directionality of the Earth's Reflectance
RH	Relative Humidity
RMSE	Root Mean Square Error
RR	Reduce Resolution
RSE	Relative Standard Error
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SEA	Southeast Asia
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SLSTR	Sea and Land Surface Temperature Radiometer
SRTM	Shuttle Radar Topography Mission
TEOM	Tapered Elemental Oscillating Microbalance
TOA	Top of Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TSP	total suspended particles
UNEP	United Nations Environment Programme

USM	Universiti Sains Malaysia
UV	Ultra Violet
VIIRS	Visible Infrared Imager Radiometer Suite
VIS	Visible
WMO	World Meteorological Organisation

LIST OF SYMBOLS

CO	Carbon Monoxide
NO_2	Nitrogen dioxide
O_3	Tropospheric Ozone
R_{eff}	Effective radius of aerosol size
SO_2	Sulphur dioxide
R^2	Coefficient of determination
α	Angstrom Exponent
λ	wavelength
e	vapour pressure
e_s	saturation vapour pressure
T_a	Surface air temperature
P_a	Air pressure
Q	Specify humidity
PW	Perceptible water vapour
T_{obs}	Observed transmittance
ρ^*	Apparent reflectance
W	Mean water vapour
H	elevation
N	Total number of data point
m	Measured
e	estimated
K	Kelvin

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Air pollution is a serious environmental problem in Southeast Asian countries such as Malaysia, which aims to become an industrial nation by 2020. Malaysia is ranked 171th of 180 nations for air quality (EPI, 2016). Major sources of Malaysian are air pollutants from open biomass burning, motor vehicles and industry (Afroz *et al.*, 2003; Hyer *et al.*, 2013; Alias *et al.*, 2014). Biomass-burning aerosols from wildfires in Indonesia are also transported to Malaysia during the dry season and the southwest monsoon (Kanniah *et al.*, 2014a; Khan *et al.*, 2015). Malaysia lies in the main pathway of the Southeast Asian pollution outflow (Lawrence and Lelieveld, 2010; Reid *et al.*, 2013; Wang *et al.*, 2013), which contributes significantly to local aerosol and pollutant emissions. Air pollution levels in Malaysia are expressed via the Air Pollution Index (API), calculated using surface concentrations of carbon monoxide (CO), tropospheric ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and Particulate Matter less than 10 μm (PM_{10}) (Awang *et al.*, 2000; Dominick *et al.*, 2012).

PM_{10} is an important component of air-pollution monitoring networks because it causes respiratory problems (Balakrishnan *et al.*, 2002; Pope *et al.*, 2011; Trang and Tripathi, 2014). The inhalation of PM_{10} and $PM_{2.5}$ can cause cardiovascular diseases (Dominici *et al*, 2006), birth defects and premature deaths (Ballester *et al.*, 2010). PM_{10} is an aerosol particle that effects the climate by absorbing and scattering incoming solar radiation (Ramanathan and Carmichael, 2008). Effects vary depending on the type of particles (i.e. dust, soot or anthropogenic pollution), and the particles optical and chemical properties.

In Malaysia, the most widely measured air-quality parameter is PM_{10}. The PM_{10} monitoring network is rather sparse, accounting for 75 stations across Malaysia with a coverage area of 330,290 km^2. These limited stations provide insufficient data to describe spatial variations in PM_{10}. In most of developing countries, installing more air quality monitoring stations is limited due to insufficient finances. PM_{10} estimates for space are considered necessary for the continuous monitoring of large spatial extents and for providing air quality warnings.

1.2 Problem Statement

After vigorous study, the connection between PM_{10} and increases in morbidity and mortality was discovered (Woodruff *et al.*, 2006). Remote satellite sensing is increasingly available for PM_{10} studies over large spatial domains. Remote-sensing retrieval of Aerosol Optical Depth (AOD) from multiple satellite sensors, such as the Multiangle Imaging Spectroradiometer (MISR) (Liu *et al.*, 2007; Van Donkelaar *et al.*, 2010; Dey *et al.*, 2012; Sotoudeheian and Arhami, 2014), Spinning Enhanced Visible and Infrared Imager (SEVIRI) (Emili *et al.*, 2010), Moderate Resolution Imaging Spectroradiometer (MODIS) (Gupta *et al.*, 2006; van Donkelaar *et al.*, 2010; Jamil *et al.*, 2011; Nordio *et al.*, 2013; Yap and Hashim, 2013; Chitranshi *et al.*, 2014), Medium Resolution Imaging Spectrometer (MERIS) (Kaskaoutis *et al.*, 2010; Kanniah *et al.*, 2014b; Beloconi *et al.*, 2016), Landsat (Nadzri *et al.*, 2010; Nguyen and Tran, 2014) and Visible Infrared Imager Radiometer Suite (VIIRS) on board of Suomi National Polar-orbiting Partnership (NPP) are used to estimate PM_{10} and $PM_{2.5}$ from space.

Among the available remote-sensing data, MODIS AOD was found to have high retrieval accuracy over land (i.e. ±0.05*AOD under clear skies and ±0.15*AOD under moderately cloud-contaminated atmospheres), as well as daily global coverage (Remer *et al.*, 2008). Validation of MODIS AOD retrieved from both Terra and Aqua satellites showed a high correlation (R^2 = 0.9) with AERONET AODs worldwide (Levy *et al.*, 2010) and (R^2 = 0.55) over Malaysia (Kanniah *et al.*, 2014a). MODIS AOD with 10 km resolution generalizes AOD information spatially, but its archive of available data and its high correlation with ground based AOD makes it popular for estimating PM_{10}. MODIS AOD_{550} data was used in this study to map PM_{10} for Malaysia.

Several studies have used satellite AOD via simple linear regressions for PM estimations from space, resulting in estimated correlation coefficients of around 0.52 to 0.77 and measured PM_{10} concentrations (Gupta and Christopher, 2008; Schaap *et al.*, 2009). According to Gupta and Christopher (2009a, b), AOD alone is poor predictor of PM, since AOD corresponds to total columnar aerosol, whereas PM refers to particle concentration at the surface. The correlation between PM and AOD depends on the vertical distribution of aerosols and several meteorological factors (Chitranshi *et al.*, 2014; Sinha *et al.*, 2015).

Incorporating meteorological parameters such as ambient Relative Humidity (RH), fractional cloud cover and mixing layer height improves PM predictions (Gupta and Christopher, 2009b; Benas *et al.*, 2013b; Chitranshi *et al.*, 2014). RH influences the hygroscopic growth of particles (Benas *et al.*, 2013b), while strong wind speeds affect PM dispersion (Xiao *et al.*, 2011) or contribute to additional emissions over arid terrains (Rashki *et al.*, 2012). The inclusion of surface temperature in PM estimates significantly improves results (Benas *et al.*, 2013b; Chitranshi *et al.*, 2014) because temperature modulates the photochemical reactions and plays a major role in boundary-layer dynamics that control PM concentrations near the surface via dilution and/or the trapping of pollutants (Dumka *et al.*, 2015). The atmospheric stability index and Boundary Layer Height (BLH) index have been used as surrogates for atmospheric stability, resulting in more accurate estimates of PM since the vertical aerosol variability can be determined

(Rohen *et al.*, 2010; Emili *et al.*, 2010). No previous studies have estimated PM_{10} for the entire Malaysia region. Yap and Hashim. (2013) provided PM_{10} estimates for Peninsular Malaysia, however their model only considers AOD. In this study surface temperature, RH and atmospheric stability are integrated with MODIS derived AOD to provide a more representative estimate of AOD for Peninsular Malaysia, Sabah and Sarawak.

An overview of the literature (e.g. Hoff and Christopher, 2009) shows that various techniques, such as simple linear regressions (Wang and Christopher, 2003; Engel-Cox *et al.*, 2004), multiple linear regressions (Gupta and Christopher, 2009a; Kanniah *et al.*, 2014b; Chitranshi *et al.*, 2014), nonlinear regressions (Benas *et al.*, 2013b; Sotoudeheian and Arhami, 2014), mixed effects models (Kloog *et al.*, 2012; Nordio *et al.*, 2013; Yap and Hashim, 2013; Hu *et al.*, 2014; Xie *et al.*, 2015; Beloconi *et al.*, 2016), statistical and chemical transport models (Van Donkelaar *et al.*, 2010), as well as complex nonlinear regressions, such as artificial neural networks (ANN) (Gupta and Christopher, 2009b ;Kanniah *et al.*, 2014b) have been employed for PM monitoring from space at the local, regional and global level. These advanced statistical techniques significantly improve the prediction capability of simple AOD-PM relationships that were initially used for PM estimation from space. The continuous improvement of databases, methods and techniques for PM monitoring from space justifies the importance of these studies for air-pollution mitigation efforts and human health in developing countries (Snider *et al.*, 2016).

Yap and Hashim (2013) attempted to estimate PM_{10} over Malaysia via a mixed-effects model which took into consideration the monthly variability of the coefficients (i.e. slope and intercept) in association with MODIS-AOD and PM_{10}. The model provided greater predictive accuracy relative to linear regression models. To improve the accuracy of PM_{10} estimates, this study integrates atmospheric/meteorological parameters with advanced statistical methods such multiple linear regressions (MLR) and ANN for the PM_{10} monitoring from space for Malaysia for the first time. The seasonality of the spatial distribution of PM_{10} is provided at a 10 x 10 km spatial resolution from 2007 to 2011 and is checked against potential sources of aerosols and pollutants. Results are useful for air quality, meteorological and health studies as well as for the calculation of the Environmental Performance Index (EPI) over Malaysia.

1.3 Aim and Objectives

The aim of this study is to estimate PM_{10} using the AOD provided by MODIS, MERIS/AATSR satellite sensors. This study has the following research objectives:

1) To assess the accuracy of AOD product from MODIS and MERIS/AATSR satellite sensors using AOD retrieved by AERONET stations.
2) To develop empirical models to estimate PM_{10} concentration in Malaysia based on MODIS AOD, MERIS/AATSR AOD, surface temperature, atmospheric stability and relative humidity.
3) To validate the estimated PM_{10} with PM_{10} measured using ground based measurements.

1.4 Scope

This study focuses on PM_{10} estimation using AOD derived from MODIS and MERIS/AATSR synergy algorithms. AOD data is a basic parameter used to determine aerosol concentration from throughout the entire atmosphere. Synergistic AOD is a combination of MERIS and AATSR instruments that improve the characterization of aerosol properties and surface reflectance compared to AOD retrieved using a single instrument (North *et al.*, 2009). The AOD data estimated by these sensors covers 2007 to 2011 due to data being available for both of the sensors used in this study (MODIS and MERIS/AATSR). AOD meteorological parameters such as relative humidity, air surface temperature, and atmospheric stability data were obtained from MODIS sensors. PM_{10} data was obtained from the Department of Environment (DOE) using 45 stations throughout Malaysia (Figure 1.1). These stations have long-term data availability.

Multiple Linear Regression (MLR) and Artificial Neural Network techniques (ANN) were used in estimating PM_{10} in Malaysia. Stepwise techniques were used for multiple linear regression because it can access the performance of each variable. Multi-Layer Perceptron (MLP) was used for ANN and consists of interconnected neurons that simplify nonlinear mapping between each set of inputs. This study covers the entire Malaysia area, including Sabah and Sarawak.

1.5 Study Region

Southeast Asia (SEA) has the most complicated aerosol system in the world with complex meteorological data, a heterogeneous land surface, high biological productivity, and various atmospheric pollutants (Reid *et al.*, 2013). Malaysia is a developing country in SEA that is undergoing rapid growth in industry and transportation as well as increasing air pollution and PM_{10} concentrations (Afroz *et al.*, 2003; Jamil *et al.*, 2011). Regional meteorology in Malaysia is characterized by four seasons, dry season (June-September), wet season (November-March) and two inter-monsoon seasons (April-May and October, respectively). Each season is examined separately due to differences in aerosol loading and aerosol characteristics. During the dry season, south-westerly winds blow from Indonesia (Sumatra and Kalimantan) carrying biomass-burning aerosols from extensive forest and agricultural fires (Abas *et al.*, 2004). The dry season also sees high international demand for agricultural products like palm oil, sugar and rice (Reid *et al.*, 2013). The land surface of Malaysia experiences rapid changes due to deforestation and agricultural production. Low level of aerosol loading are recorded for the rainy season due to a wet deposition and rain washout. Winds are mostly from the northeastern directions traversing the South China Sea. During the two transition seasons, a wind shift occurs. Monsoonal behaviour together with complex tropical wave phenomena, rough topography and heterogeneous land surface makes atmospheric studies over this region very challenging.

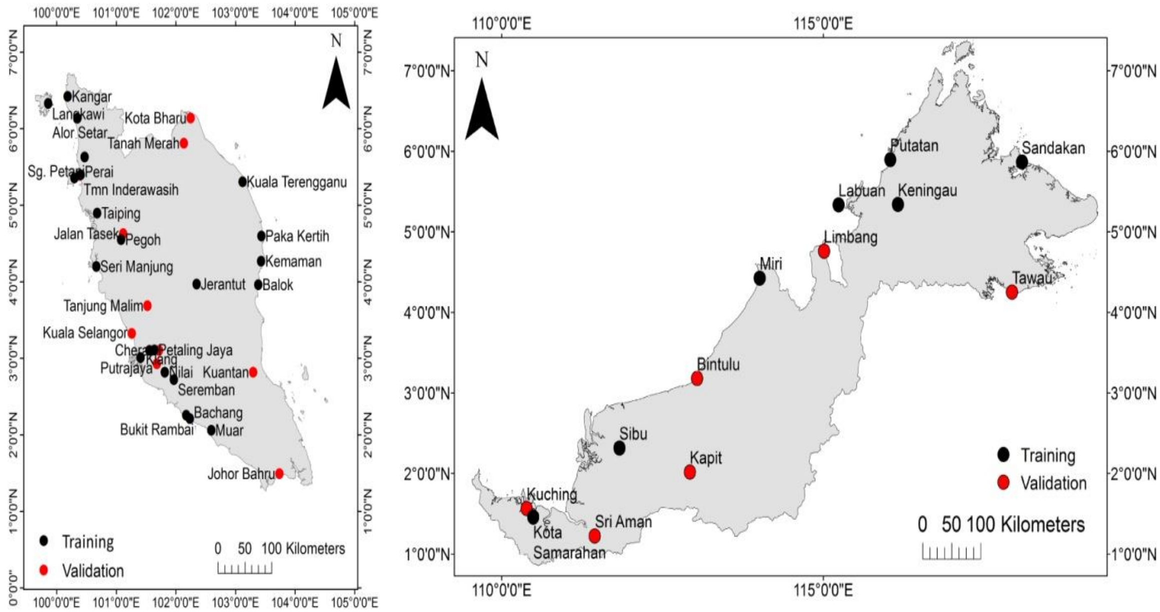

Figure 1.1: Locations of the 45 PM_{10} monitoring stations that were used for training (black dots) and validating (red dots) the empirical models developed in this study.

1.6 Significance of the Study

The results of this study (maps of PM_{10}) are useful for pinpointing PM_{10} concentrations in different seasons (dry seasons, wet seasons, inter-monsoon (April-May) and inter-monsoon (October)). This information can be used as an indicator for air pollution.

This study provides important parameters for the effects of PM_{10} on health and climate. PM_{10} estimations in this study are useful for calculating the Environmental Performance Index (EPI) of Malaysia. Currently the global EPI is computed using PM2.5 and MODIS AOD at 10km spatial resolution (Van Donkelaar *et al.*, 2010). This index needs to be refined to represent local variations.

1.7 Thesis Organization

This thesis consists of five chapters. Chapter 1 is an introductory chapter highlighting research gaps in PM_{10} monitoring in Malaysia. Chapter 2 provides previous studies on PM_{10}. Chapter 3 describes the methods that used to achieve the research objectives. Chapter 4 presents and discusses the main outputs of this study. Chapter 5 concludes this thesis and provides recommendations for further study.

The next section provides a literature review for aerosols (i.e. PM and AOD), methods for aerosol measurements, remote sensing for atmospheric aerosols and modelling/estimating PM using AOD measured by remote sensors.

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