ESTIMATION OF GROUND LEVEL PM2.5 CONCENTRATION USING AEROSOL OPTICAL THICKNESS FROM MODIS IMAGES IN PENINSULAR MALAYSIA

KHALED ALI AHMED BEN YOUSSEF

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KHALED ALI AHMED BEN YOUSSEF

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Chairman : Professor Ahmad Makmom, PhD
Faculty : Environmental Studies

Fine particulate matter is particulate matter lower in diameter than 2.5 µm ($PM_{2.5}$). It affects the public health, economic development, and the regional climate. Governments worldwide have been concerned about the levels of the $PM_{2.5}$ in the atmosphere and long ago began monitoring their levels continuously using air quality monitoring stations. The Malaysian government invested much in building ground monitoring stations. Most of these stations have been located in urban areas. In this context, use of remote sensing (RS) techniques and the geographic information system (GIS) in estimating the levels of the ambient $PM_{2.5}$ become more widespread. The Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical thickness (AOT) product of the Terra Satellite can be used to estimate the $PM_{2.5}$ levels with an accuracy that depends on the statistical relationship between $PM_{2.5}$ and AOT. This study aimed at estimating the $PM_{2.5}$ mass concentration in Peninsular Malaysia by linking the MODIS sensor data with the measured $PM_{2.5}$ concentrations and meteorological parameters in the year 2013. The first objective of this study was to validate MODIS-AOT retrievals with ground AERONET AOT data after extracting the AOT from MODIS images. The second objective of the study was to correlate the ground $PM_{2.5}$ levels with the validated MODIS AOT after identifying the spatial and temporal AOT distributions by using Multiple Linear Regression Analysis (MLRA) and Geographically-Weighted Regression models (GWRMs) for Peninsular Malaysia. The third objective of the study was to accurately evaluate the accuracy of estimates of the relationship between the $PM_{2.5}$ levels and the corresponding MODIS AOT data in different pixel size groups. The geographic domain of this study was Peninsular Malaysia, which has an area of about 131,598 km^2, covering 40% of the land area of Malaysia and hosting approximately 80% of its population and economic activities. The methodology of the study consisted of three stages. First, the values of AOT were extracted from MODIS images and the AOT retrievals were validated with ground AERONET- AOT data. Second, the MLRA and GWR modeling were attempted to

spatially and temporally correlate the reported ground $PM_{2.5}$ levels and meteorological data with the validated MODIS AOT data after identification of the spatial and temporal AOT distributions in Peninsular Malaysia in the year 2013. Subsequently, a comparison of strengths and weaknesses was held between the various generated models. Lastly, an assessment of the accuracy of $PM_{2.5}$ estimation has been conducted on the MODIS spatial models.

The results showed that the MODIS AOT retrievals have a good correlation with the ground observations derived from AERONET as indicated by the values of the coefficient of determination (R^2) for the linear regression models, which were 0.87 and 0.78 for the daily average and the hourly average (± 30 min) data, respectively. The map of distribution of AOT indicated that the AOT concentrated in the western coast of Peninsular Malaysia. Mostly, the spatial and temporal AOT values in the southwest monsoon were higher than in the northeast monsoon throughout the study period. The MLRA and GWRM both gave almost identical estimates of the $PM_{2.5}$ concentrations. The analysis outcomes revealed that the R^2 value for the hourly $PM_{2.5}$ regression model (0.66) was higher than that for the daily $PM_{2.5}$ (R^2 = 0.53). Comparison with the literature uncovers that results of estimation of $PM_{2.5}$ using AOT from MODIS for Peninsular Malaysia are similar to the results of other studies in other parts of the world. Furthermore, assessment of the accuracies of the hourly and daily estimates of $PM_{2.5}$ disclosed that the 5 x 5 pixel size model had the lowest values of the mean-squared error (MSE), root mean-squared error (RMSE), and relative root mean-squared error (rRMSE). The relatively low error values associated with the 5 x 5 pixel size model indicate the accuracy of this model in Peninsular Malaysia.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ANGGARAN KEPEKATAN $PM_{2.5}$ PARAS BUMI MENGGUNAKAN KETEBALAN OPTIK AEROSOL BERDASARKAN IMEJ DARIPADA MODIS DI SEMENANJUNG MALAYSIA

Oleh

KHALED ALI AHMED BEN YOUSSEF

Oktober 2019

Pengerusi : Profesor Ahmad Makmom, PhD
Fakulti : Pengajian Alam Sekitar

Zarah terampai halus adalah zarah terampai berdiameter kurang daripada 2.5 µm ($PM_{2.5}$). Ia memberi kesan kepada kesihatan awam, pembangunan ekonomi, dan iklim kawasan. Kerajaan-kerajaan dunia amat mementingkan tahap $PM_{2.5}$ dalam atmosfera dan telah mengawasi tahapnya secara berterusan melalui stesen pengawasan kualiti udara. Kerajaan Malaysia telah menyalurkan peruntukan yang tinggi untuk membina stesen pemantauan atas tanah ini. Kebanyakan stesen ini berada di kawasan bandar. Dalam konteks ini, penggunaan teknik penderiaan jauh (RS) dan Sistem Maklumat Geografi (GIS) untuk menganggar tahap ambien $PM_{2.5}$ semakin meluas. Produk Ketebalan Optik Aerosol (AOT) Spektroradiometer Pengimejan Resolusi Sederhana (MODIS) daripada Satelit Terra boleh digunakan untuk menganggar tahap $PM_{2.5}$ dengan ketepatan yang bergantung kepada hubungan statistik $PM_{2.5}$ dan AOT. Kajian ini bertujuan untuk menganggar kepekatan jisim $PM_{2.5}$ di Semenanjung Malaysia melalui hubungan diantara data sensor MODIS dengan kepekatan $PM_{2.5}$ yang telah diukur dan parameter meterologi bagi tahun 2013. Objektif pertama kajian adalah mengesahkan dapatan AOT-MODIS dengan data AOT AERONET selepas mengekstrak AOT daripada imej MODIS. Objektif kedua kajian adalah mengkorelasikan tahap $PM_{2.5}$ paras bumi dengan AOT-MODIS yang telah disahkan selepas mengenal pasti taburan ruangan dan masa AOT menggunakan Analisis Regresi Linear Berbilang (MLRA) dan Model Regresi berpemberat Geografi (GWRMs) untuk Semenanjung Malaysia. Objektif ketiga kajian adalah menilai ketepatan anggaran hubungan antara tahap $PM_{2.5}$ dan data AOT-MODIS yang berkaitan untuk kumpulan saiz piksel berbeza. Domain geografi kajian ini adalah Semenanjung Malaysia yang mempunyai kawasan seluas 131,598 km^2, merangkumi 40% kawasan tanah Malaysia dan kira-kira 80% populasi dan aktiviti ekonomi negara. Metodologi kajian terdiri daripada tiga fasa. Pertama, nilai AOT yang diesktrak daripada imej MODIS dan dapatan AOT disahkan dengan data AOT AERONET bumi. Kedua, pemodelan MLRA dan GWR dijalankan untuk membina korelasi ruangan dan masa antara tahap $PM_{2.5}$ paras bumi dan data meterologi yang dilaporkan

dengan data AOT-MODIS yang disahkan selepasa taburan ruangan dan masa AOT di Semenanjung Malaysia bagi tahun 2013 dikenal pasti. Selepas itu, kekuatan dan kelemahan model-model yang dibangunkan dibandingkan. Akhirnya, ketepatan model ruangan MODIS dalam mengaggar $PM_{2.5}$ dinilai.

Keputusan menunjukkan bahawa dapatan AOT-MODIS mempunyai korelasi baik dengan pemerhatian paras-bumi yang diambil daripada AERONET seperti yang ditunjukkan oleh nilai pekali penentuan (R^2) untuk model regresi linear iaitu 0.87 dan 0.78 untuk purata data harian dan purata data setiapjam (± 30 min) masing-masing. Peta taburan AOT menunjukkan bahawa AOT tertumpu di kawasan pinggir laut Barat Semenanjung Malaysia. Nilai ruangan dan masa AOT kebanyakannya lebih tinggi semasa musim Monsun Barat Daya berbanding Monsun Timur Laut sepanjang tempoh kajian. Kedua-dua MLRA dan GWRM memberikan anggaran kepekatan $PM_{2.5}$ yang hampir serupa. Keputusan analisis menunjukkan bahawa nilai R^2 untuk model regresi $PM_{2.5}$ setiap jam (0.66) adalah lebih tinggi daripada model regresi $PM_{2.5}$ data harian (R^2 = 0.53). Perbandingan dengan literatur menunjukkan bahawa keputusan anggaran PM2.5 menggunakan AOT daripada MODIS untuk Semenanjung Malaysia adalah lebih kurang sama dengan keputusan kajian yang dijalankan di kawasan-kawasan lain di dunia. Selain itu, penilaian ketepatan anggaran $PM_{2.5}$ harian dan setiap jam menunjukkan bahawa model saiz piksel 5 × 5 mempunyai ralat min kuasa dua (MSE) dan ralat min punca kuasa dua (rRMSE) yang paling rendah. Nilai ralat yang rendah yang dikaitkan dengan model piksel bersaiz 5 × 5 menunjukkan ketepatan model untuk Semenanjung Malaysia yang dibangunkan dalam kajian ini.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Ahmed Makmom Abdullah, PhD
Professor
Faculty of Environmental Studies
Universiti Putra Malaysia
(Chairman)

Helmi Zulhaidi Mohd Shafri, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Zulfa Hanan Asha'ari, PhD
Senior Lecturer
Faculty of Environmental Studies
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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Name and Matric No: Khaled Ali Ahmed Ben Youssef, GS37721

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Signature:	
Name of Chairman of Supervisory Committee:	Professor Dr. Ahmed Makmom Abdullah

Signature:	
Name of Member of Supervisory Committee:	Associate Professor Dr. Helmi Zulhaidi Mohd Shafri

Signature:	
Name of Member of Supervisory Committee:	Dr. Zulfa Hanan Asha'ari

TABLE OF CONTENTS

LISTS OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AERONET	Aerosol Robotic Network
AOD	Aerosol optical depth
AOT	Aerosol Optical Thickness
BHL	Boundary Layer Height
r	Correlation coefficient
R^2	Coefficient of determination
DB	Deep Blue
DEM	Digital Elevation Model
DT	Dark Target
EPA	Environmental Protection Agency
ESA	European Space Agency
GEOS-Chem	Goddard Earth Observing System Atmospheric Chemistry Transport
GIS	Geographic Information Systems
GWR	Geographically Weighted Regression
HDF	Hierarchical Data Format
LUTs	Look-up tables
MERIS	Medium Resolution Imaging Spectrometer
MISR	Multi-angle Imaging SpectroRadiometer
MLR	Multiple Linear Regression
MODIS	Moderate Resolution Imaging Spectro-radiometer
NASA	National Aeronautics and Space Administration
PM	Particulate Matter
PM_{10}	Particulate Matter (diameter <=10 µm)
$PM_{2.5}$	Particulate Matter (diameter <=2.5µm)

RH	Relatively humidity
RMSE	Root-Mean-Square Error
RS	Remote Sensing
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Evaluation of the air quality is a topical issue in atmospheric studies. Deterioration of local, regional, and globe air quality depends on the aerosol concentration in the atmosphere. The main pollutants of the air encircle particulate matter (PM), carbon monoxide, nitrogen oxides, sulphur oxides, and the ground level ozone. The Global Burden of Disease (GBD) project of the World Health Organization (WHO) ascribed more than 3.2 million premature deaths worldwide in 2010 to the ambient PM pollution. Moreover, in 2010, the ambient PM pollution ranked fourth in the list of health risk factors in East Asia (Gao et al., 2015). On the other hand, most of the countries in Asia have experienced fast economic development during the past decade. The increased urbanization, industrialization, and use of vehicles in cities in these countries, in addition to the trans-boundary haze pollution and the Asian dust phenomenon, have contributed to the rise in the concentrations of PM in Asian cities (Engel-Cox et al., 2004; Liu et al., 2017; Tahir et al., 2013).

In general, the coarse particles comprise alumino silicates and oxides of crystal elements and the principal sources of these particles encompass dust originating from the industry, roads, construction operations and material, agricultural activities, and construction. On other hand, the fine particulate matter ($PM_{2.5}$), also known as the respirable particulate material, is usually related to anthropogenic pollution (Mao et al., 2017). The $PM_{2.5}$ consists of varying amounts of nitrate, sulfate, and ammonium ions; water; organic compounds; elemental carbon, and small amounts of trace elements and soil dust. For comparison purposes, while the coarse-mode particles have an atmospheric half-life of minutes to hours, the half-life of $PM_{2.5}$ ranges from days to weeks. Furthermore, the $PM_{2.5}$ can travel hundreds to thousands of kilometers while the coarse particles can only travel one kilometer to tens of kilometers (Wilson and Suh, 1997).

The increase in the atmospheric levels of $PM_{2.5}$ has serious negative effects on the weather and contributes to climate change, besides negatively impacting public health and economic development. Effects of the $PM_{2.5}$ on climate change can be classified into direct and indirect effects. The direct effects include interactions of $PM_{2.5}$ with radiation, such as absorption and scattering of the solar radiation and terrestrial surface radiation, which influence temperature and the radiation budget balance (Wang, 2003; Xin et al., 2014). The indirect effects of $PM_{2.5}$ are mainly embodied in its influence on the density and chemical composition of the atmosphere, which, in turn, influence the climate. The indirect effects of $PM_{2.5}$ also include altering the characteristics of clouds, and even the precipitation, since the formation of clouds depends on the atmospheric composition and dynamics, among other factors (Yu et al., 2015).

Due to their very small sizes, the $PM_{2.5}$ can be deeply breathed and they find their way to the lungs from which they never go out (Sun et al., 2015). The WHO estimates that exposure to the outdoor air pollution in 2012 led to 3.7 million premature deaths (Ford and Heald, 2016). From a global perspective, Asia consists of countries with high population densities and a multitude of highly-polluted areas. For instance, it was reported that the levels of $PM_{2.5}$ in India are five times higher than the corresponding WHO standards (Figure 1.1).

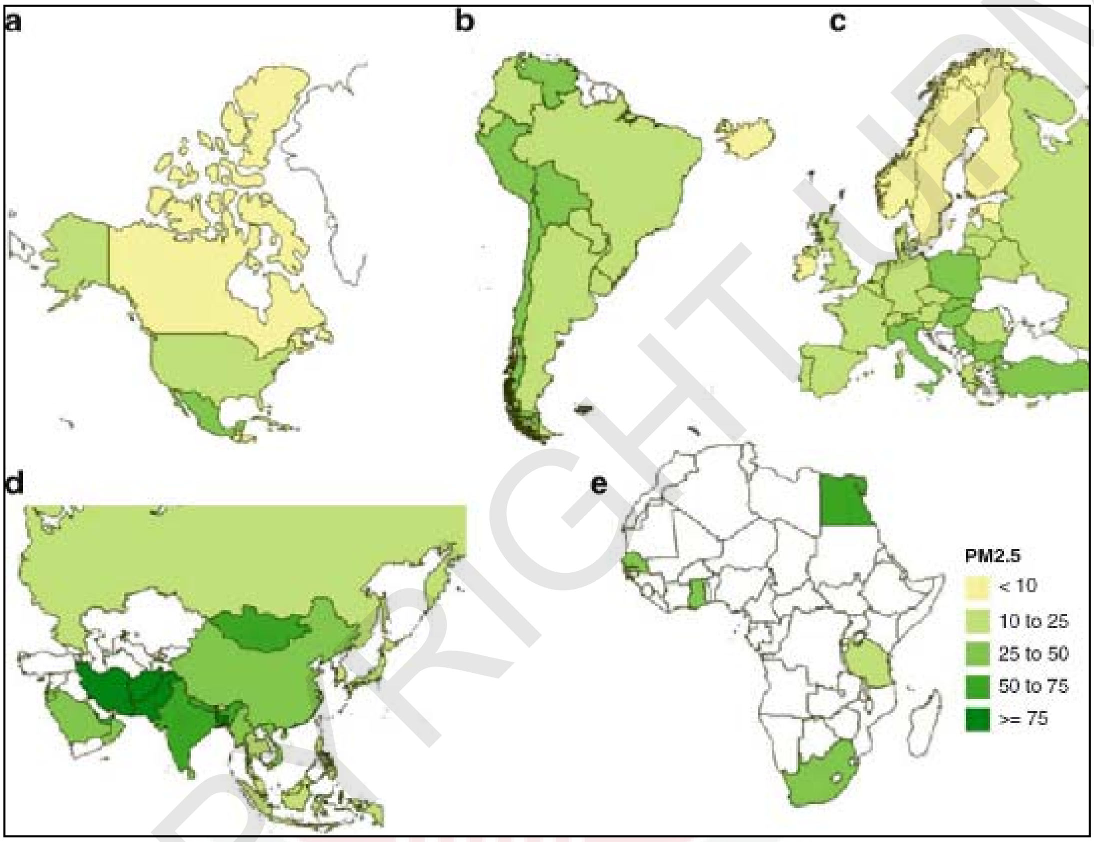

Figure 1.1 : Global Distribution of the $PM_{2.5}$ Concentration (µg/m^3) in Different Continents: (a) North America; (b) South America; (c) Europe; (d) Asia; and (e) Africa. Source: (Mukherjee and Agrawal, 2017)

Many epidemiological studies have shown that a rise in the risk of mortality from lung cancer and cardiovascular and respiratory diseases is associated with short-, and long-term exposure to $PM_{2.5}$, with the underlying presumption that causal relation exists between health outcomes and PM (Aurela et al., 2015; Changqing Lin et al., 2016; Wang et al., 2016). Besides its effect on human health and climate change, the $PM_{2.5}$ also results in economic losses. For example, the World Bank (2007) estimated the health cost of the urban PM pollution in China in 2003 at 157 billion Chinese Yuan by use of an adjusted human capital approach and at 520 billion Chinese Yuan by use of the value of the statistical life method (Kan et al., 2009). In Malaysia, the concentration of the $PM_{2.5}$ increases during the haze. As an example, the highest 24-h average $PM_{2.5}$ concentration was 136 µg/m^3 during the haze episode of 2015. For comparison purposes, the corresponding concentration during non-haze times ranges from 14.3 μg/m^3 to 24.5 μg/m^3 (Latif et al., 2018).

So far, only few studies have examined the health effects of aerosols in Malaysia. The few available studies mainly concentrated on the health impacts of the aerosols during the haze crisis of the year 1997. Those studies found evidence on positive relation between number of the cases of diseases like conjunctivitis, asthma, and the upper respiratory tract infections and the Air Pollution Index (API). The high health damage cost, which was estimated at approximately RM129 million, was associated with the long duration of the 1997 haze episode (Kanniah et al., 2016).

Complaints about air pollution, which have been raised since 13th century when coal was first used in London (Bell and Davis, 2001), urged and pushed governments and public organizations to pay more attention than before to air pollution and, in consequence, relevant policies and standards were formulated. In the Air Quality Guidelines of the WHO, the yearly and daily (24 h) standards for $PM_{2.5}$ were set at 10 μg/m^3 and 25 μg/m^3, respectively (Organization, 2006). This guideline is widely used by decision makers across the world as a reference for setting air quality management goals and standards (Consultation, 2018).

In general, the ground-based air quality monitoring data are considered as accurate measurements of air quality. However, they usually represent the PM concentrations in relatively small regions (Sorek-Hamer et al., 2013). In addition, the number of ground stations is often limited and those stations are quite often sparse and unbalanced. This makes continual spatial monitoring of air quality difficult (Hu et al., 2013). Apart from spatial coverage and resolution, temporal coverage of the ground-level PM monitoring stations, which depends on the operation period and functionality of the instruments, varies highly (Karimian et al., 2016). Further, construction and maintenance of the ground stations are costly and time-, and labor-consuming.

In other respects, and in view of the drawbacks of ground monitoring of PM over vast areas, the remote sensing (RS) technology is the most important alternative for continuous exploration of PM over large areas (Kumar et al., 2008). This technology has various advantages. First, the images derived from the satellites can provide general and thorough information on air quality anywhere in the world (Chu et al., 2003). Second, the satellites provide an opportunity for acquiring global air quality data. Hence, they make it possible to discover the sources of the urban air pollutants and even global transport of those pollutants (Gupta et al., 2006). Furthermore, the RS technology corresponds to a low cost alternative for air quality monitoring for the developing countries which suffer from severe air pollution and yet lack ground-level monitoring stations. In this respect, previous studies reported significant correlations between the ground-level $PM_{2.5}$ concentrations and the satellite-derived Aerosol Optical Thickness (AOT) values (Chu et al., 2003; Van Donkelaar et al., 2016; Wang, 2003).

Monitoring mass concentrations of the PM at the ground level in association with the AOD is a challenging task. Numerous studies have been carried out to investigate the AOD-PM relation. The satellite-estimated PM concentrations are particularly essential for regions lacking ground data (Karimian et al., 2016). Even though the AOT describes polarized measurement of PM with no information on its vertical distribution, it, nonetheless, remains a reasonable and effective proxy for $PM_{2.5}$ prediction. Within this context, it is worth noting that AOD and $PM_{2.5}$ represent measures of two differing atmospheric pollutants (Gupta et al., 2006). The $PM_{2.5}$ concentration expresses the 'point' mass concentrations of particles near the surface while the AOD denotes the total columnar optical properties over an 'area' that is related to the spatial resolution of the measuring instrument. Several AOD retrieval algorithms have offered differing AOD products by using other devices such as the Moderate Resolution Imaging Spectro-radiometer (MODIS).

Few satellite sensors are available for AOD observations, including AVHRR, Multi angle Imaging Spectro-Radiometer (MISR), MODIS, and TOMS. Of these, the MODIS, which is boarded on Aqua and Terra satellites, is the most frequently used satellite sensor. Additionally, the user can use the 10-km MODIS AOD products that are provided by the National Aeronautics and Space Administration (NASA), rather than retrieving the AOD from the satellite images themselves. This product has been provided in 2000. It is based on the Dark Target (DT) algorithm and the Deep Blue (DB) algorithm. Various statistical models are used, including the simple linear regression model (SLRM), the multiple linear regression model (MLRM), and the geographically-weighted regression model (GWRM) and the artificial neural network (ANN) algorithms (Reid et al., 2013; Song et al., 2014).

Air pollution in Malaysia originates from mobile and stationary sources of pollution, e.g., open-burning activities. The stationary sources include emissions of dust from quarries and urban construction works, incinerators, energy power plants, and the industries. The open sources result in local pollution and encircle vegetation burning and trans-boundary pollution, especially during forest fires in neighboring countries due, mainly, to peat combustion. The mobile sources, on the other hand, are more related to traffic emissions (Abdul Halim et al., 2018). The increasing population will affect more resource consumption and the release of more air pollutants. This means that health of many more people will be affected by air pollution. Thus, monitoring and regulating local pollutant emission will be a challenging task in the following years. In other respects, studying $PM_{2.5}$ concentrations and emissions may help in reducing the international disputes. For example, in Klang Valley in Malaysia, haze has caused the PM_{10} mass concentration to increase more than four times and the levels of the AOT to increase more than three times over their levels before the haze episode (Amanollahi et al., 2011).

Numerous studies have examined the AOT over Malaysia (Amanollahi et al., 2011; Jamil et al., 2011; Kanniah et al., 2016; Kanniah et al., 2014), but there is limited research to date on the relationship between AOT and ground $PM_{2.5}$ concentration, and on how to utilize this information in $PM_{2.5}$ exposure modelling. This study investigated the relationship between the $PM_{2.5}$ concentration and satellite-retrieved AOT using one-year (2013) data for Peninsular Malaysia.

Direct, though not perfect, correlation exists between the load of aerosol found in the atmosphere and AOD. Development of algorithms for retrieval of the MODIS-AOD irradiance observations turned out to be significant in the process of creating accurate estimates of the ground-level $PM_{2.5}$ concentrations (Lee et al., 2012). Other methods include the SLRMs of the relationship between AOD and measured $PM_{2.5}$, which has been developed for major cities worldwide to estimate the ground-level $PM_{2.5}$ concentrations with the aid of the satellite-derived MODIS-AOD (Evans et al., 2013; Martin, 2008). Though, light extinction around the total integrated atmospheric column is measured with MODIS whereas the aerosol amount is measured at the surface level only. Because of this, the correlation between these two variables is controlled by the vertical distribution of the aerosols and other meteorological parameters which influence the aerosol extinction coefficient like the mixing layer height, relative humidity (RH), and temperature (Li et al., 2009).

Even though satellite-based assessment of air quality is promising, it faces a number of challenges. Various factors can influence the relation between $PM_{2.5}$ and AOT. For instance, the satellite-derived parameter values provide columnar information about the ambient conditions while the $PM_{2.5}$ measurements represent the near-surface, dry mass concentrations. Moreover, the satellite data represent wide spatial areas and are prone to cloud interception (Zhang et al., 2005). But the daily data for the given area which these instruments provide at specific wavelengths make them great tools for assessment of pollutants in large areas.

Recent policy and research emphasis on the regional and intercontinental transport of varied air pollutants like $PM_{2.5}$ has spotlighted the need for additional sources of reliable data to augment the ground-based data for monitoring the air pollution, which, in effect, varies temporally and spatially. The satellite data can provide thorough information and visualization of the ground-based measurements of air quality and reliable data for air quality modelling. Numerous studies have examined the AOT over Malaysia (Amanollahi et al., 2011; Jamil et al., 2011; Kanniah et al., 2016; Kanniah et al., 2014). However, there is limited research thus far on the relationship between AOT and ground $PM_{2.5}$ levels in Malaysia, and on how to utilize this information in $PM_{2.5}$ exposure modelling. In response to this knowledge gap, this study investigated the relationships among the satellite-retrieved AOT values and the $PM_{2.5}$ mass concentrations using one-year data for Peninsular Malaysia.

Peninsular Malaysia lies in an area affected by high concentrations of $PM_{2.5}$ (Figure 1:1). Therefore, the present study focused on three issues: (i) characterizing the distribution of the MODIS pixels that cover the study area, taking into account seasonal variations; (ii) developing MLRMs of the relations among meteorological parameters and AOT data derived from the MODIS sensor at the local scale to estimate $PM_{2.5}$ concentration; and (iii) performing the analyses for individual pixels and array of pixel (1 x 1, 3 x 3, and 5 x 5 pixels) for thorough assessment of effectiveness of AOT in estimation of the concentrations of $PM_{2.5}$ at different spatial resolutions.

1.2 Problem Statement

Particulate matter is an aggregation of solid and liquid particulates with different sizes and compositions. It is particles in suspension in the atmosphere whose concentration tells much about the urban air quality. For decades, air quality and pollution has raised high public health concern all over the world (Van Donkelaar et al., 2010) due to the ever growing urban and industrial developments. In particular, East Asia is the major source of aerosols globally, where anthropogenic pollutant particles, besides dust and sea salt, are abundant (Dai et al., 2014; Kim et al., 2014). Aerosol studies received high attention in southeast Asia and in Malaysia perhaps due to the extensive local generation of aerosols in the region, mainly including emissions from factories, automobiles, and open burning, including burning of wood, fossil fuels, trash, and plant leaves), in addition to the substantial amounts of trans- boundary air pollutants (Kanniah et al., 2014).

Remote sensing (RS) is an effective tool in the Earth science in particular and the climate studies in general for understanding the impacts of aerosols in the air on human health and environmental safety. Indeed, it is the only observational tool available for many parts of the world, including Southeast Asia. Owing to that the satellites have sensors on geostationary and polar platforms, remote sensing does actually provide systematic data over vast areas with high frequency. Additionally, movement and functioning of the satellites is not affected by the political and administrative boundaries. As such, the data they provide constitute the backbone of models. The satellites provide voluminous data on many parameters of the land, ocean, and atmospheric systems (Reid et al., 2013). However, with proliferation of population and urbanization, there are growing concerns about the urban air quality, which led to emergence of numerous studies on urban air turbidity during the last few decade to identify its sources and quantify the emissions of urban pollutants to the air (Clerbaux et al., 2010). Therefore, use of satellite RS allows for the collection of global or regional data at high resolution on the spatial and temporal distributions of most pollutants and contributes to our understanding of the air quality and changes in it over time.

Many researchers attempted to estimate the ground levels of $PM_{2.5}$ using satellite-based AOT data (Wang, 2003). The AOT is the extinction coefficient of aerosols of the points accumulating in the vertical direction (Hoek et al., 2013; Tao et al., 2013). The AOD research started in the mid 1970s. In 2003, Wang (2003) initiated use of the MODIS AOD in prediction of the ground-level $PM_{2.5}$ concentrations by linear regression analysis (LRA). Liu et al. (2004) developed a Chemical Transport Model (CTM) and (Lee et al., 2011) employed MODIS AOD data to develop day-specific Mixed-Effect Model (MEM). In recent years, the levels of $PM_{2.5}$ were estimated using various types of satellite sensors that included the Multi-Angle Imaging Spectrometer (J. Li et al., 2015)); MODIS (Geng et al., 2015; Zheng et al., 2016)); Polarization of the Earth's Reflectance and Directionality (Léon et al., 2010); the Geostationary Operational Environment Satellite (Liu et al., 2009); the Cloud-Aerosol Lidar with Orthogonal Polarization (Toth et al., 2014); the Ozone Monitoring Instrument (J. Li et al., 2015); and the Sea-viewing Wide Field-of-view Sensor (Van Donkelaar et al., 2015a). Though studies of this sort are becoming more popular, their prediction results are in general unstable and varying from a region to another (Hu, 2009).

Peninsular Malaysia is an area with rapid development and population growth. Its weather is hot and humid with uniform temperatures throughout the year. Particulate matter (PM) is persistently creating an atmospheric problem in Malaysia, particularly since it has exceeded the standards of acceptable urban limits. For example, Jaafar et al. (2018) found that the concentrations of $PM_{2.5}$ in Malaysia far surpassed the USEPA air quality standard for $PM_{2.5}$ (a mean exposure rate of 35 $\mu g/m^3$ for 24 h) and the 2005 air quality guidelines of the WHO, that is, a mean exposure rate of 25 $\mu g/m^3$ for 24 h. The levels of $PM_{2.5}$ in the ambient air during the haze episodes are extremely high, ranging from 14.5 $\mu g/m^3$ to 160.9 $\mu g/m^3$. The highest $PM_{2.5}$ levels were reported in the third and fourth days of the haze episode, 146.2 $\mu g/m^3$ and 160.9 $\mu g/m^3$, respectively.

The PM has been categorized as one of the major air pollutants during the haze episodes. When its diameters fall within the respirable range, it can contribute to serious illness and, even, mortality because the fine particulates can enter the respiratory system easily through inhalation (Latif et al., 2018). The health effects of haze on the respiratory system and mortality and their effects on certain age groups were studied in Malaysia. For example, (Yaacob et al., 2016) conducted a study of the effect of haze on the peak expiratory flow rate (PEFR) of school children and found that there was a 15.0% reduction in the PEFR. Twenty two of the sample children had cough and headache. As well, mucus and throat symptoms were reported at high rates. Furthermore, Sahani et al. (2014) analyzed the health effects of haze in Klang Valley, Malaysia, from 2000 to 2007. Analysis uncovered that haze contributed a 19.0% increase in the respiratory mortalities and that there was a 41.4% growth in the delayed impacts of haze on the natural mortality of the children and a 66.0% growth in the respiratory mortalities of the adult females. In another example from Malaysia, Othman et al. (2014) reported that over the years of 2005, 2006, 2008, and 2009, there were 19 days on average of transboundary haze episodes during which the values of the API were equal to, or higher than, 76, that is, within the low to moderate air pollution hazard categories. On the average, every haze episode brought about an annual increase of 2.4% in the inpatient cases per 10,000 capita. Further, the study found that the marginal influence of haze on the inpatient rates was the highest for the children, followed by the young adults, the senior adults, and the infants.

Of all the constituents of the atmosphere, the aerosols stand as a highly-variable influential factor of solar radiation attenuation. It affects the climate, weather, and many weather-related phenomena and processes. In this context, the AOT is a spectral variable that reflects the amount of aerosols in a vertical column in the atmosphere from the viewpoint of their potential radiative effects. It is for this reason why having a suitable representation of the AOD is of paramount importance for successful irradiance modeling (Bright and Gueymard, 2019).

In assessing urban aerosol content, satellite RS is a conventional tool that helps in measurement and prediction of ground-level PM concentrations. The satellites have the ability to monitor vast space, especially those areas in which ground monitoring stations are lacking. Past studies in Malaysia concentrated on the use of satellite data for measuring and monitoring the levels of PM_{10}. Only few studies addressed the levels of $PM_{2.5}$ in Malaysia. Thus, the use of RS data to estimate the levels of $PM_{2.5}$ in Peninsular Malaysia provides information that was not provided by the majority of previous air pollution studies in the country, which focused on the levels of air pollution in only certain parts of the country.

1.3 Significance of the Research

Atmospheric aerosols are among the most critical classes of the atmospheric pollutants. Various published works confirm that particles with small sizes have serious effects on human health, increasing the cardiovascular and respiratory diseases and reducing the life expectancy. This study underscores the benefits of using RS and geographic information system (GIS) data integrated with quantitative methods for air pollution studies. It uses satellite-derived AOT data for Malaysia, which is the main parameter employed in assessment of air pollution, particularly for quantifying the relationship between satellite data and measurements of ground air pollution monitoring stations. The study was carried out for Peninsular Malaysia, which has an area of almost 131,598 km^2 and hosts the majority of the population and economic activity in Malaysia.

In this study, firstly, data on the ground-level AOT were used to validate the latest MODIS data (collection 6 (C6)) available for Malaysia, which correspond to the period January 2012 to December 2013. Secondly, the AOT data used were Terra satellite data based on the MODIS sensor. They were employed to estimate the levels of $PM_{2.5}$ in Peninsular Malaysia in the year 2013. To the researcher's best knowledge, this study is the first study that used data derived from MODIS sensor to estimate the mass concentrations of $PM_{2.5}$ in Peninsular Malaysia.

The ground-based measurements of $PM_{2.5}$ are limited in Peninsular Malaysia. Data from only seven stations and one year (2013) were available for the study area. An alternative way was to combine the two datasets (the Satellite AOT and ground $PM_{2.5}$ data) to provide more robust information about the temporal and spatial distribution of $PM_{2.5}$ in Malaysia. The findings of this research can benefit decision making regarding air quality forecasts. Additionally, this study is useful for highlighting the health risks associated with exposure to PM and, ultimately for promulgating effective control strategies to protect the public health.

1.4 Research Questions

Since the $PM_{2.5}$ mass is measured from the ground irrespective of cloud cover while satellite data only provide AOT information during cloud-free and favorable retrieval conditions, so the researcher addressed the following questions:

1. What is the relation between the satellite and ground aerosol optical thickness (AOT) values?
2. How was the spatiotemporal distribution of AOT in Peninsular Malaysia in 2013?
3. How can satellite data on AOT be employed to determine the distribution of the fine particulate matter ($PM_{2.5}$)?
4. Are there relations among AOT and the meteorological parameters of temperature (T), relative humidity (RH), wind speed (WS), and wind direction (WD)?
5. Does the different array of 10km pixels affect the accuracy of $PM_{2.5}$ estimation?

1.5 Research Objectives

The overall purpose of this study was to estimate the mass concentrations of the $PM_{2.5}$ at the ground level in Peninsular Malaysia and explore the relationship between MODIS AOT and ground $PM_{2.5}$ levels. This purpose could be achieved by meeting the following objectives:

1. To validate MODIS-AOT retrievals extracted from MODIS images with ground AERONET-AOT data.
2. To correlate the ground $PM_{2.5}$ levels with the concomitant validated MODIS AOT data by using MLR and GWR modeling after identification of the spatiotemporal AOT distribution in Peninsular Malaysia.
3. To evaluate the relationship between $PM_{2.5}$ level and MODIS AOT data under different array of pixels using accuracy assessment.

1.6 Study Scope and Limitations

This research processed sets of quantitative and qualitative data in the GIS environment in an effort to estimate the levels of $PM_{2.5}$ in Peninsular Malaysia in the year 2013. The temporal and spatial distributions of $PM_{2.5}$ in the study area were also determined. The study used the latest Collection 6 (C6) of the AOT data that were obtained at the wavelength of 550 nm from the MODIS instrument aboard the Terra spacecraft, which travels across the equator from north to south in the morning. The MODIS sensor was selected because it provides daily data and the images it takes cover the entire study region. The hourly and daily ground concentrations of $PM_{2.5}$ ($\mu g/m^3$) were obtained from seven stations in Peninsular Malaysia.

Validation of the satellite data against ground measurements is challenging due to a number of reasons like different measured variables, lack of coinciding measurements, and problems in integration due to differences between the satellites readings and the point-based measurements of the ground instruments. Thus, validation of the reliability and accuracy of the AOT data derived from MODIS at the wavelength of 550 nm is required and is achieved by comparisons with independent data. In this context, the current study employed AERONET Level 2 AOT data as independent data for comparison purposes. Four-year historic data were used in the validation.

The period of study was between 2012 to 2015 in Peninsular Malaysia, there was only one AERONET station in the study area (USM_Penang; Peninsular Malaysia; Start running in November 2011), during that period the $PM_{2.5}$ data was limited, the researcher choose the year 2013 for estimate $PM_{2.5}$ because in that both the number of stations and the measured $PM_{2.5}$ data is relatively more obtainable. Effort has been made by the researcher to acquire $PM_{2.5}$ data in 2015 using handheld device (APECJ651), but due limited nature of that data it cannot be compared to the vast study area. However, after the period of study, the Department of Environment Malaysia has expanded the number of $PM_{2.5}$ monitoring stations over Malaysia (http://apims.doe.gov.my/public_v2/announcement.html). Additionally, the team of MODIS in 2015 developed a new spatial resolution MODIS Level-2 AOT with the spatial resolution 3 × 3 km^2 at nadir. Therefore, a study of this nature can be an opening for future research particularly regarding the test and constrains in the implementation of a new models for the estimation of $PM_{2.5}$ especially in the local scope considering the high resolution of the sensor (3 × 3 km^2).

The use of satellites for acquisition of surface data is an economical and reliable practice because satellite data can be obtained at low cost. So, local financial limitations will not be an obstacle to acquisition of such data. Thus, as a source of data for aerosol studies, satellites are the best option for less-developed nations, especially since the budgets for installation and maintenance of continuous air quality monitoring stations (CAQMS) is a significant constraint. However, one of the main limitations of AOT is that it is affected by clouds. Hence, it is missing when there is/was cloud coverage, which is the reason why quite often AOT data are missing at the point station in most MODIS pixels. Another limitation to this study is that some important covariates, e.g., planetary boundary layer (PBL) height and land use information, were missing. A widespread series of biomass burning events associated with forest fires, particularly in Sumatra and Kalimantan, Indonesia, caused a thick, smoky haze over a large portion of Southeast Asia. A huge amount of PM from this biomass burning was transported to Peninsular Malaysia. So, the concentrations of PM will be higher during hazy days than during non-haze days.

1.7 Organization of the Thesis

This thesis is organized in five chapters as follows:

Chapter 1 introduces to this study. It discusses sources and impacts of $PM_{2.5}$ and presents the objectives and significance of the study. Chapter 2 reviews the trends and present status of $PM_{2.5}$ and the implications of its levels on the population and the climate. As well, in this chapter, the researcher reviewed the measuring techniques in order to identify the most suitable of which to be adopted in this study. Chapter 3 outlines the research methodology, including the experimental design and structure, and the techniques used for determination of the $PM_{2.5}$ concentrations. Chapter 4 presents and discusses the research results. Chapter 5, then, lists the conclusions drawn from the research findings and gives recommendations for future research.

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