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AEROSOLS TREND AND CHARACTERISTICS ON EAST COAST OF PENINSULAR MALAYSIA BY INTEGRATING REMOTE SENSING AND IN-SITU DATA

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By

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October 2016

Chairman : Zulfa Hanan Ashaari, PhD
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The study of atmospheric aerosol is becoming more important due to its various adverse effects on human beings, the environment and the Earth's climate. The issue of atmospheric aerosol is a great concern to Malaysia because of the rapid development and urbanization and the regional haze occurrence. There are a number of issues concerning aerosol monitoring in Malaysia because of the weaknesses of ground-based aerosol monitoring. This study aims to apply remote sensing in conjunction with ground-based data of aerosol as solutions to the weaknesses. The correlation between remote sensing and ground-based aerosol data has been found to range from 0.014 to 0.739. Furthermore, the spatial and temporal variability of aerosol is determined. Two different patterns of monthly aerosol concentrations are identified and influenced by rainfall and monsoonal seasons. Source apportionment analysis reveals urban/industrial aerosol type as the most abundant aerosol type. It is followed by aerosols from biomass burning, maritime environment and mineral sources/dust. The Principal Component Analysis (PCA) reveals only one underlying spatial pattern in aerosol concentration which explains 62.23% of the data variability. The influence of meteorological factors, based on the multiple linear regression model is significant and able to explain 7.7% of the variation of the aerosol. This study shows that remote sensing is very useful in aerosol monitoring, especially when used in conjunction with ground-based data.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

TREND DAN CIRI-CIRI AEROSOL DI PANTAI TIMUR SEMENANJUNG MALAYSIA MELALUI INTEGRASI DATA PENDERIAAN JAUH DAN *IN-SITU*

Oleh

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Kajian tentang aerosol atmosfera adalah sangat penting disebabkan oleh pelbagai kesan aerosol terhadap manusia, alam sekitar dan iklim bumi. Bagi negara Malaysia, isu aerosol atmosfera adalah topik yang sentiasa membimbangkan disebabkan oleh pembangunan pesat dan juga fenomena jerebu.Terdapat beberapa kelemahan yang boleh dikaitkan dengan pemantauan aerosol di Malaysia. Kajian ini bertujuan untuk menggunakan teknologi remote sensing bersama-sama data aerosol yang diperoleh di peringkat permukaan, untuk menyelesaikan kelemahan-kelemahan tersebut. Kajian mendapati bahawa julat korelasi antara data dari pemantauan remote sensing dan peringkat permukaan adalah dari 0.014 kepada 0.739. Selain itu juga, dua trend spatial dan temporal telah dikenalpasti. Ia dipengaruhi oleh hujan dan angin monsun. Analisis bagi mengkategorikan jenis aerosol mendapati bahawa aerosol jenis bandar/industri sebagai jenis aerosol yang paling kerap, diikuti oleh jenis aerosol dari pembakaran biomass, kawasan maritime dan sumber mineral/habuk. Analisis komponen utama (PCA) mendapati bahawa hanya satu trend spatial yang boleh menerangkan 62.23% dari perubahan data aerosol. Pengaruh faktor meteorologi juga dikaji dengan menggunakan analisis regresi linear berganda (MLR) dan model MLR berjaya menerangkan 7.7% perubahan data aerosol. Kajian ini membuktikan bahawa penggunaan remote sensing bersama-sama data dari pemantauan peringkat permukaan adalah sangat berguna dalam pemantauan aerosol.

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I certify that a Thesis Examination Committee has met on 26 October 2016 to conduct the final examination of Mohd Muzammil bin Salahuddin on his thesis entitled "Aerosols Trend and Characteristics on East Coast of Peninsular Malaysia by Integrating Remote Sensing and *In-Situ* Data" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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Signature : ____________________
Name of Member of Supervisory Committee: : Dr Ahmad Makmom Abdullah

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

PM	Particulate matter
µm	Micrometer
MEQR	Malaysia Environmental Quality Report
API	Air Pollution Index
DOE	Department of Environment Malaysia
MMD	Malaysia Meteorological Department
CAQM	Continuous air quality monitoring
RMAQG	Recommended Malaysian Air Quality Guideline
AOD	Aerosol optical depth
MODIS	Moderate-resolution imaging spectroradiometer
TOMS	Total ozone mapping satellite
SPOT	Satellite Pour l'Observation de la Terre
AERONET	Aerosol robotic network
AD	Asian dust
FMF	Fine mode fraction
km	Kilometer
NO_2	Nitrogen oxide
CO	Carbon monoxide
SO_2	Sulphur dioxide
PCA	Principal component analysis
WHO	World Health Organization
MAQI	Malaysian Air Quality Index
MSS	Multispectral scanner
EOS	Earth observing system
AVHRR	Advanced Very High Resolution Radiometer
SAM	Stratospheric Aerosol Measurement
OMI	Ozone Monitoring Instrument
CFC	Chlorofluorocarbon
I	Light intensity
λ	Wavelength
AAI	Absorbing aerosol index
NCEP	National Center for Environmental Prediction
NCAR	National Center for Atmospheric Research
CERES	Clouds and Earth's Radiant Energy System
HYSPLIT	Hybrid single particle lagrangian intergrated trajectory
PFM	Protoflight Model
CZCS	Coastal zone color scanner
LST	Local standard time
CTE	Coefficient of thermal expansion
MLR	Multiple linear regression

CHAPTER 1

INTRODUCTION

This chapter will provide an introduction to the main issues addressed in this study, as well as brief descriptions of global and local aerosol scenarios. The significances of the outcome of study are also postulated based on the results from previous studies. Moreover, the most important aspect of the study, the objectives, are also stated as solutions to the issues of aerosol monitoring in Malaysia.

1.1 The importance of aerosol studies

The study of atmospheric aerosol is becoming more important each day due to its various effects on human beings and also to the environment. By definition, aerosols near the ground is known as the atmospheric particulate matter(PM) (Pope et al., 1995). Particulate matters smaller than 10 μm can cause and worsen respiratory and cardiovascular diseases by entering human lungs via respiration (Franck, Odeh, Wiedensohler, Wehner, & Herbarth, 2011; Sardar, Fine, & Sioutas, 2005). If the diameter of the particles is more than 10 μm (PM_{10}), they will not be able to enter human body through respiration due to the morphology of human's nose. If the diameter of the particles is between 2.5 μm and 10 μm, they can enter the upper respiratory tract. Nevertheless, some of them will be filtered by the nose, thus are less harmful to human health relatively. On the other hand, particles with diameter less than 2.5 μm (PM2.5), can be inhaled into the body as they can evade from being filtered by human's nose. The relative sizes of the particles in comparison with human hair are shown in Figure 1. Hence, these particles devastating effects to human health such as asthma, bronchitis and cardiovascular diseases. As these particles are able to enter the human bloodstream, the particles' interaction with dissolved metal and gases in blood can cause detrimental effect to the human body (Fang & Chang, 2010; Pope et al., 1995; J. Wang & Christopher, 2003).

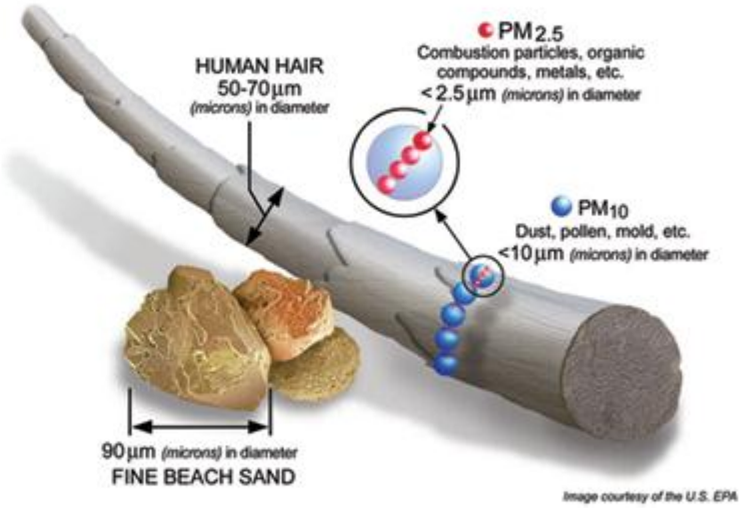

Figure 1: Size of pollutant particles compared to human hair
(Source : US EPA)

1.2 Global atmospheric aerosol

The aerosol particles in the atmosphere are important in the atmospheric radiative budget due to their ability to absorb and scatter the solar and terrestrial radiation (Davison, Roberts, Arnold, & Colvile, 2004; Feng & Christopher, 2013). It is also evident that acid deposition due to the atmospheric aerosol transportation influences the river and ocean chemistry (Sundarambal, Balasubramanian, Tkalich, & He, 2010). Due to local emissions and transboundary transport from regional sources, a significant amount of additional sources of new nitrogen and phosphorus have been found in the aquatic ecosystems (He et al., 2011). Besides, aerosol particle radiative impacts photochemical rates in plants (Tang et al., 2003) and have been found to contaminate food (Srinivas, Ramakrishna Rao, & Suresh Kumar, 2009). In addition, aerosol indirectly impacts the ocean photochemistry due to the radiation perturbation in the atmosphere and can be seen in the coral record (Risk, Sherwood, Heikoop, & Llewellyn, 2003).

Most of the aerosols originate from the natural sources, including mineral dust from the desert, soil dust, sea salt particles, volcanic ashes and forest fire smoke (Chin, Kahn, & Schwartz, 2009). Approximately half of the elements found in the atmospheric aerosol exist in near-crustal proportions and probably originate from the desert (Rahn, Borys, Shaw, Schutz, & Jaenicke, 1979). The atmospheric dust is also the main source of iron deposition to the ocean. Iron is an important micronutrient for phytoplankton in the ocean, which is part of the natural carbon cycle due to its photosynthesis process. In many open-ocean regions, the atmospheric mineral aerosols are the main provider of the new iron (Sarthou et al., 2003).

The global mineral dust emission caused by wind driven erosion of dry areas range between 1000 and 3000 Tg yr^{-1}. This represents approximately half of the annual particle emission at the global scale, making desert areas one of the main sources of the atmospheric aerosol. The global dust belt is named because of the location of the major dust source which extends from the west coast of North Africa, through the Middle East, into Central Asia and covers the Sahara, the deserts of the Arabian Peninsula and of Oman, Caspian Sea and Aral Sea regions in Central Asia, and Gobi and the Taklamakan in China (Formenti et al., 2011). Once the particles are in the atmosphere, the mineral dust are transported to all over the world influencing the global climate and environment (Rahn et al., 1979; Szykman & Mintz, 2003; F. Tsai, Chen, Liu, Lin, & Tu, 2008; Uno et al., 2011).

1.3 Atmospheric aerosol in Malaysia

Atmospheric aerosol in Malaysia is affected mainly by local and transboundary emissions. There are three major sources of air pollution in Malaysia, namely mobile sources, stationary sources and open burning sources. Emissions from motor vehicles (mobile sources) accounts for more than 70% of the total emissions in the urban areas (Afroz, Hassan, & Ibrahim, 2003; Awang et al., 2000). Stationary sources contributed to 20-25% of the air pollution, and open burning and forest fires are responsible to approximately 3-5% of the total air pollution (Juneng, Latif, & Tangang, 2011). Particulate Matter with an aerodynamic diameter of less than 10 µm (PM10) is considered a significant pollutant and is included in the computation of Malaysian Air Pollution Index (Afroz et al., 2003). The total suspended particulate matter is the main contributor of pollution with its concentration at few locations exceeding the Recommended Malaysia Air Quality Guideline. Two peaks are reported in the diurnal pattern of aerosol concentration in the observation during the study period of 1984-1985, in which one was in the morning hours and the other one was during late evening (Awang et al., 2000).

Apart from the local sources of anthropogenic aerosol, Malaysia is also exposed to the trans-boundary air pollutants produced by the Southeast Asia biomass burning. These contributes to high load of aerosol and pollution especially during the dry season from June to September (Juneng et al., 2011). Since 1980, six major episodes of haze periods were recorded in Malaysia. The major haze occurred in April 1983, August 1990, June 1991, October 1991, August to October 1994, and July to October 1997 (Awang et al., 2000). In a more recent incident, forest fires in Sumatra and Borneo in September and October 2006 caused the daily mean concentrations of PM_{10} to increase to 150 µg m^{-3} at multiple locations in Singapore and Malaysia over several days (Hyer & Chew, 2010). In the Malaysia Environmental Quality Report (MEQR) 2013 (Department of Environment Malaysia, 2014a), Malaysia was recorded to be hit by short periods of severe haze episodes in June 2013. Muar District in Johor recorded the highest Air Pollution Index (API) reading of more than 500. It is also critical to note that there exist significant crustal and marine sources of aerosol in the coastal areas (Tahir, Suratman, Fong, Hamzah, & Latif, 2013)

1.4 Aerosol monitoring in Malaysia

In Malaysia data of aerosol (PM_{10} concentration) is recorded by ground stations located across the country (**Figure 2**). The ground stations are part of the monitoring network which is managed by the Malaysian Department of Enviroment (DOE) through its concessionaire company known as Alam Sekitar Malaysia Sdn Bhd (ASMA) and Malaysia Meteorological Department (MMD). DOE and MMD currently manage 51 and 22 monitoring stations respectively nationwide (Kanniah, Lim, Kaskaoutis, & Cracknell, 2014; F. Tangang, Latif, & Juneng, 2009). The continuous air quality monitoring (CAQM) stations of DOE are categorized into four types of stations, namely Industrial, Urban, Sub-urban and Background. The categorization indicates the type of area that the CAQM station is located in. PM_{10} concentration is measured at all type of stations. The CAQM data will be continuously collected automatically every hour during the monitoring period. The CAQM is complemented by the manual air quality monitoring stations (High Volume Sampler) located at 19 different sites. Other parameters like Total suspended particulates (TSP) and heavy metals concentrations such as lead mercury, sodium, iron, copper are measured once every six days. These data are collected monthly by ASMA.

1.5 Problem statement

Aerosol studies in Malaysia is important because of the exposure of Malaysia to the local anthropogenic aerosol producing activities such as the use of automobiles, industrial and open burning activities, and the regional transboundary air pollutants (Juneng et al., 2011; Kanniah et al., 2014; F. Tangang et al., 2009). Local aerosol consists of several key pollutants such as particulate matter, carbon monoxides and sulphates. In 2013, it was estimated that the combined air pollutant emission load amassed to 1,874,836 metric tonnes of carbon monoxide CO, 858,048 metric tonnes of nitrogen oxides (NO_2), 198,920 metric tonnes of sulphur dioxide (SO_2) and 24,006 metric tonnes of PM (Department of Environment Malaysia, 2014a). The air quality slightly deteriorated compared to the previous year mainly due to the serious haze event which occurred in 2013.

Aerosol data in Malaysia (PM_{10} concentration) is generally recorded by ground stations located across the country (Department of Environment Malaysia, 2014a). The ground-based monitoring stations offer continuous high frequency high quality data but lack in the spatial coverage required to derive a good synoptic spatial pattern. Besides the basis of aerosol detection used by ground stations are surface based, meaning that any variability of columnar aerosol in the atmosphere is not taken into consideration in the measurements (Kanniah et al., 2014).

The east coast of Peninsular Malaysia is rarely the focus of aerosol studies in Malaysia as most of the aerosol studies usually focusses on the urban areas of Klang Valley, or the entire state of Malaysia in general (Amanollahi, Abdullah, Ramli, & Pirasteh, 2011; Amanollahi, Abdullah, Saeid, Ramli, & Prinaz, 2011; Azmi, Latif, Ismail, Juneng, &

Jemain, 2010; Jaafar et al., 2014; Juneng et al., 2011; Norela, Saidah, & Mahmud, 2013). Understandably, the east coast of Peninsula Malaysia has relatively lower significance, in terms of the magnitude of pollution and the amount of economic activities in the area, in comparison to stations from the southwestern region of Peninsula Malaysia (Selangor and Kuala Lumpur). Nevertheless, due to the rapid development of the urban areas and industrial activities in the east coast of Peninsula Malaysia in recent years, the aerosol concentration has became increasingly affected by the athropogenic activities, as well as the by the biomass burning and forest fires events in the region (Tahir et al., 2013). Thus a separate study, focusing on the aerosol pattern only in the east coast of Peninsula Malaysia is necessary.

Studies on source apportionment of aerosols (PM_{10}) in Malaysia is scarce (Tahir et al., 2013) and at the moment (2016), fine mode aerosol ($PM_{2.5}$) is not yet included in the aerosol monitoring by the DOE and in the Recommended Malaysian Air Quality Guideline (RMAQG). Fine particles ($PM_{2.5}$) cause relatively more harm to human, than the course particles (PM_{10}) and hence it is crucial that the measurement of fine particles is included in the aerosol monitoring in Malaysia.

To date there is no scientific paper that discusses the possibility of Malaysia being affected by the Asian Dust (AD) event (Kanniah et al., 2014). Realistically the effects of AD event towards Malaysia may not be as significant as compated to Japan, Korea and Taiwan due to the geographical distance. However, the AD event may be significant to affect the environment around Malaysia, such as the iron deposits for phytoplanktons into the South China Sea. A study (Tahir et al., 2013) showed that 32% and 34% of total variance in the principal component analysis of the particulate compostion, are attributed to the soil being the source. Furthermore, It was found that 17-40% of the aerosol are dust aerosols (Kanniah et al., 2014). Both reports confirms the presence of dust aerosols without confirming their source. Thus the application of remote sensing product which could help in determining the aerosol type is needed (Kanniah et al., 2014; Kaskaoutis, Kosmopoulos, Kambezidis, & Nastos, 2007; Kosmopoulos, Kaskaoutis, Nastos, & Kambezidis, 2008).

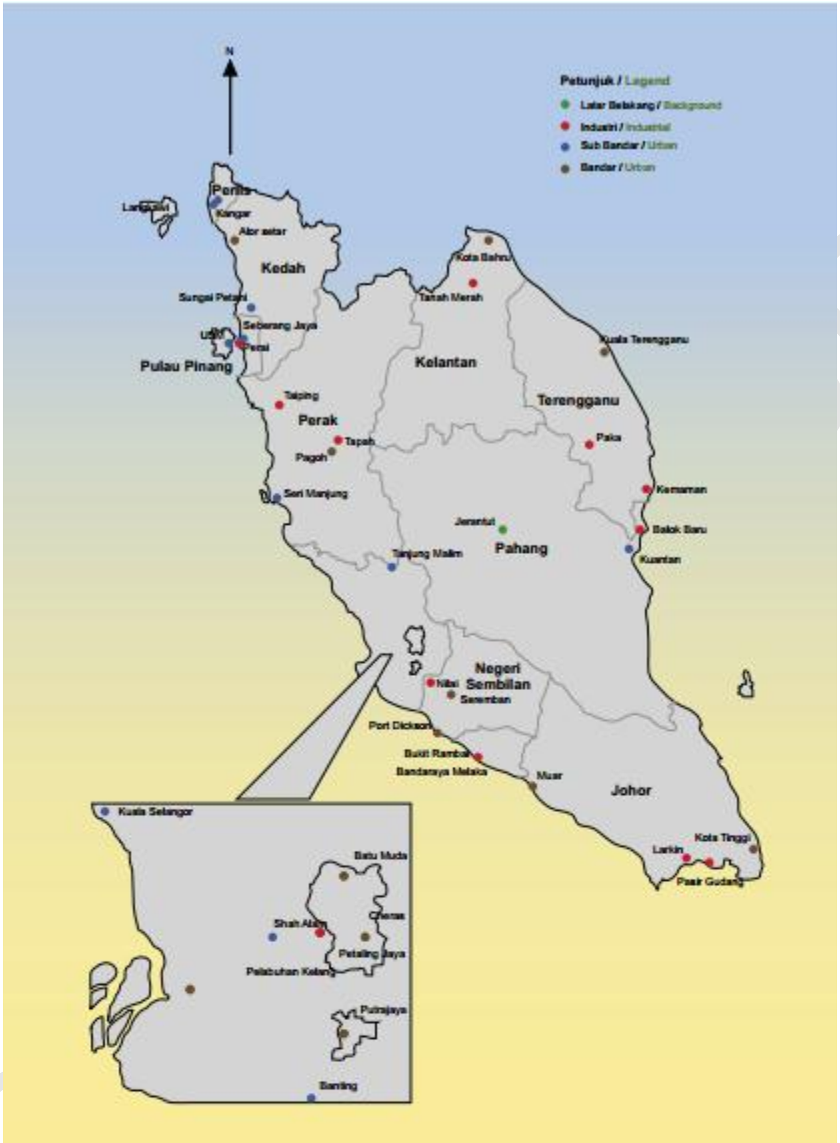

Figure 2 : Location of CAQM stations in Peninsula Malaysia

1.6 Significance of study

This study aims to integrate the application of remote sensing and ground based aerosol monitoring to address the weaknesses of the current aerosol monitoring in Malaysia. Remote sensing of aerosols via satellite sensors provides the solution for the lack of spatial coverage by ground-based stations. In addition, this approach addresses the issue of measuring columnar aerosol instead of surface aerosol only, which is measured by the ground-based stations. The use of remote sensing in detecting atmospheric aerosol has gained popularity in recent years due to its large spatial coverage, high frequency data, large database and highly accurate data which are being improved constantly time with the introduction of better algorithms.

The spatial and temporal distribution and source apportionment of aerosol in the east coast of Peninsula Malaysia are able to be analysed more effectively via the application of remote sensing and ground-based data. The correlation between the remote sensing data and ground-based data is validated. The patterns of aerosol concentrations in the study area, using data from both remote sensing and ground-based monitoring, are assessed and discussed. The temporal and spatial distribution pattern of aerosol concentration are determined using statistical analysis. Source apportionment of aerosol is also possible through the use of the remote sensing data products. The impact of meteorological factors, such as wind speed, rainfall, humidity and temperature, on the aerosol concentration is also quantified. Further application of remote sensing will also be helpful in studying the impact of regional atmospheric occurrences such as the Asian Dust, to Malaysia.

This study will help to increase the current in-depth knowledge of aerosol in Malaysia, especially in the study area. The information is helpful to the policy makers (state and federal government) to not only monitor and control aerosol concentration, but also to be considered in future planning of the country's development.

1.7 Objectives

1.7.1 General

The purpose of this study is to investigate the pattern and the characteristics of aerosol in the east coast of Peninsular Malaysia by integrating remote sensing and ground-based aerosol monitoring.

1.7.2 Specific objectives:

The objectives of this study are;

i. To validate the correlation between the remote sensing and ground-based aerosol concentration
ii. To assess spatial and temporal variability of aerosol in East Coast of Peninsular Malaysia.
iii. To characterize type of aerosol based on its sources in the East Coast of Peninsular Malaysia.

iv. To quantify the influence of meteorological factors on aerosol concentrations in the study area.

1.8 Thesis outline

This thesis consists of five chapters. The chapters are structured as follows:

Chapter 1 - Introduction

The importance of aerosol concentrations in Southeast Asia and the need for understanding their patterns are discussed in this chapter. A case study of Malaysia, research questions, aims and objectives are described.

Chapter 2 - Literature Review

The key features of aerosol variability are described in this chapter. This chapter also provides explanations on the climate and the characteristics of aerosols in Malaysia.

Chapter 3 – Methodology

Aerosol data from both satellite and ground-based data sources are described in this chapter to determine the best data that can be used to study aerosol concentration in this region. The quality control method and the methodologies of the analyses of the data, with inter-comparative analysis for reliability purposes are also explained in this chapter.

Chapter 4 – Results and Discussion

Chapter 4 discusses the results which includes the correlation between ground-based PM_{10} monitoring and remote sensing based aerosol measurements, aerosol patterns including temporal and spatial distribution during specific months, and apportionment of aerosol sources using remote sensing data products.

Chapter 5 – Conclusions and Recommendations

The implications of this research are described and discussed in this chapter. Based on the findings from a case study in Malaysia, the wider implications for aerosol variability in Southeast Asia and the study area for future studies are discussed.

1.9 Summary

As a summary, this chapter introduced the issues of aerosol in Malaysia, especially in the study area, and the problems related to aerosol, particularly in monitoring. The objectives of this study posts to prove that application of remote sensing in conjunction with ground-based monitoring is a good solution to the current problem. The following chapter will provide further scientific information and evidences, gathered from the literatures to support the solution recommended by this thesis.

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