TRANSBOUNDARY HAZE AND GENERAL AEROSOL CHARACTERISTIC OVER PULAU PINANG USING AERONET AND MODIS MONITORING SYSTEM

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by

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LIST OF SYMBOLS

τ_a	Aerosol optical thickness
°	degree
°C	Degree Celsius
$S(\tau)$	Direct signal at ground level
km^2	Kilometer square
m/s	Meter per second
µm	micrometer
nm	nanometer
τ	Optical thickness
τ_{O_3}	Ozone optical thickness
τ_r	Rayleigh optical thickness
m	Relative mass
s	second
$S_o(\tau)$	Signal at the highest point of the atmosphere

LIST OF ABBREVIATIONS

AOD	Aerosol optical depth
AERONET	Aerosol Robotic Network
API	Air pollution index
AE	Angstrom exponent
AM	Ante meridiem
ARSET	Applied Remote Sensing Training
BMA	Biomass aerosol
CD	Cloud fraction
.csv	Comma-separated values
DT	Dark target
DCS	Data collection system
DB	Deep blue
DA	Dust aerosol
ENSO	El Nino-Southern Oscillation
.xlsx	Excel Microsoft Office Open XML Format Spreadsheet
FIRMS	Fire Information for Resource Management System
GMS	Geostationary meteorological satellite
GOES	Geostationary operational environmental satellite
.hdf	Hierarchical data format
ITCZ	Intercontinental convergence zone
IAMAT	International Association for Medical Assistance to Travelers
LAADS DAAC	Level-1 and Atmosphere Archive and Distribution System Web Interface
LIDAR	Light detection and ranging

MAMPU	Malaysian Administrative Modernization and Management Planning Unit
MA	Maritime aerosol
MC	Maritime continent
MADIS	Meteorological assimilation data ingest system
METEOSAT	Meteorological satellite
MIXA	Mixed aerosol
MODIS	Moderate Resolution Imaging Spectroradiometer
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NRT	Near real-time
NE	Northeast
PM10	Particulate matter (less than 10 micrometer radius)
PM2.5	Particulate matter (less than 2.5 micrometer radius)
PWS	Personal weather system
PSI	Pollutant Standards Index
PM	Post meridiem
PW	Precipitable water
SEA	Southeast Asia
SW	Southwest
TOD	Total optical depth
TSP	Total suspended particle
UN	United Nations
USM	Universiti Sains Malaysia
UIA	Urban/industrial aerosol

JEREBU MERENTAS SEMPADAN DAN CIRI UMUM AEROSOL DI PULAU PINANG MENGGUNAKAN SISTEM AERONET DAN MODIS

ABSTRAK

2015 telah mencatat rekod di Semenanjung Malaysia dengan jerebu merentas sempadan yang sangat teruk pada musim monsun barat daya. Kajian untuk mengenalpasti dan mengukur tahap pencemaran telah dilakukan, tetapi kebanyakan hanya untuk merangkumi 2015 sahaja. Kajian ini bertujuan untuk mencirikan tahun seterusnya, 2016, dari segi kedalaman optik aerosol (AOD), mengenalpasti mana-mana kesan berpanjangan jerebu yang lepas, dan menyemak kesesuaian integrasi data AOD MODIS dan AERONET. Ciri-ciri atmosfera di Pulau Pinang dari segi AOD, eksponen Angstrom (AE), dan air mampu mendak (PW) telah dikumpul. Dengan menggunakan data 500 nm sebagai fokus untuk parameter AOD, anomali-anomali pada bacaan harian AOD telah dikenalpasti dan disiasat. Musim pra-monsun telah mencatatkan purata AOD tertinggi pada 0.4879, diikuti oleh musim timur laut, barat daya, dan pasca-monsun. Nilai tertinggi AOD juga telah direkodkan pada musim pra-monsun dengan nilai 1.7788 dan telah dikaitkan dengan pencemaran awan manakala nilai terendah telah dilihat pada musim pasca-monsun dengan nilai 0.033 dimana proses landa bawah aerosol oleh hujan yang kerap telah berlaku. Tambahan lagi, siri peningkatan mendadak yang menonjol pada musim pra-monsun telah dihipotesis disebabkan oleh pemindahan badan aerosol dari kawasan Bayan Lepas. Pengenalan jenis aerosol juga telah dibuat menggunakan plot taburan α–τ untuk AOD 500 nm dan AE 440-870 nm mendapati jenis aerosol yang dominan bergantung pada musim monsun dimana BMA dominan pada musim monsun timur laut (30%) dan pra-monsun (65%), manakala MA pada musim monsun barat daya (33%) dan pasca-monsun

(75%). Seterusnya, data AOD MODIS Collection 6.1 telah dikaitkan dengan data AOD AERONET 500 nm dan korelasi yang baik telah dilihat (R^2 = 0.5827 untuk Terra dan 0.4839 untuk Aqua), tetapi ia sendiri masih cenderung dengan jurang data. Akhir sekali, perbandingan data lima (5) tahun sebelumnya telah menunjukkan jerebu pada tahun 2015 tidak meninggalkan kesan yang berpanjangan pada tahun seterusnya.

TRANSBOUNDARY HAZE AND GENERAL AEROSOL CHARACTERISTIC OVER PULAU PINANG USING AERONET AND MODIS MONITORING SYSTEM

ABSTRACT

2015 introduced Peninsular Malaysia with one of the worst recorded transboundary haze during the southwest monsoon period. Studies to identify and quantify the level of pollution have been done, but most are limited to year 2015 data only. This study aim to characterize the consequent year, 2016, mainly in terms of aerosol optical depth (AOD), identify any lingering effect of the subsequent haze, and assess the suitability of integrating MODIS AOD data with AERONET AOD data. The atmospheric properties of Pulau Pinang in terms of AOD, its Angstrom exponent (AE), and precipitable water (PW) were acquired. Using the 500 nm data as the main focus for the AOD parameters, anomalies in daily AOD reading were identified and investigated. Pre-monsoon season was found to have the highest mean AOD at 0.4879, followed by the northeast, southwest and post-monsoon season. The max AOD recorded was also during pre-monsoon season at 1.7788 and was associated with cloud contamination while the vice versa was observed during the post-monsoon season at 0.033 where downwashing of aerosol by constant rainfall was observed. Additionally, a peculiar series of spikes found in the pre-monsoon season was hypothesized to be the result of a transported aerosol mass from Bayan Lepas area. Aerosol type identification done using α–τ scatter plots for the 500 nm AOD and 440-870 nm AE found the dominant aerosol type were seasonally-dependant with the most dominant was BMA during the northeast and pre-monsoon season at 30% and 65%, followed by MA in the southwest and post-monsoon season at 33% and 75% respectively. Next,

Collection 6.1 MODIS AOD data was correlated with the AERONET data and was found to have a good correlation with 500 nm AERONET AOD data (R^2 = 0.5827 for Terra and 0.4839 for Aqua), but it also experienced frequent data gaps on its own. Finally, five (5) years of historical data comparison showed the 2015 haze has no significant impact on the following year.

CHAPTER 1

INTRODUCTION

1.1 Overview

Issues related to air quality and public concerns regarding it is a typical situation in developing countries where the main focus is rapid growth. The severity of environmental degradation usually ties directly to the degree of the country growth, especially in the early stages of development (Perrings et al., 1995). Developing country such as Indonesia and Malaysia in the Southeastern region of Asia continent (SEA) faced with similar problem. Furthermore, owing to multiple condition such as convoluted meteorological scales, high biological productivity, high variance of geographic and/or socioeconomic features, and a wide range of atmospheric pollutants, the SEA region are infamous for its complicated atmospheric environments which impede atmospheric and remote sensing studies in the area (Reid et al., 2013).

Difficulties relating to atmospherical studies in this region have been expressed multiple times by researchers in recent years. Main issue is usually related to aerosol properties observability which includes uncertainties resulting from cloud contamination (Huang et al., 2011; Hyer et al., 2011; Witek et al., 2013) or the complete removal of recorded data due to strict screening stages (Van Donkelaar et al., 2011). These limitations further exacerbate the existing problem of uncontrolled forest fires which is steadily rising in the region, Indonesia especially, for the past few years (Field et al., 2009). These fires do not only contaminate the land from which they originate, but their effects extend to neighboring countries as well, contaminating atmospheric space and worsening the air quality, thus demanding immediate assessment in both short and long-term effect by both involved parties (Hyer and Chew, 2010; Reid et al., 2013; Salinas et al., 2013). This occurences of foreign, airborne pollution transported over to a new region by the prevailing winds are generally classified as a transboundary haze.

Despite all of the problems addressed earlier, small-scale studies, mostly revolving around aerosol optical properties, have shown to be acceptable in term of its accuracy, sacrificing both the broadness and period covered of the study area in favor for more accurate results and conclusions. Local studies utilizing the sun and sky-scanning radiometers of AERONET have been performed before with the study area limited to over a city or a small region, therefore these studies are used as complementaries in more elaborate studies of aerosol (Alam et al., 2011; Alias et al., 2014; Kanniah et al., 2014; Tan et al., 2015c).

Consequently, this type of method is suitable for detecting changes in atmospheric properties of a region that experiences rapid changes due to either local activities or external factors. Malaysia has a long history of being affected by transboundary haze, earliest official conduct of study was in 1980 (Palanissamy, 2013). Annual analysis of aerosol trend over cities that are affected the worst by the haze will benefit not only its public citizen health, but will be crucial in understanding local aerosol behaviour while serving as an early detection system in case of unexpected events.

1.2 Introduction to atmospheric aerosol

Atmospheric aerosol is a complex and dynamic combination of solid and liquid particles from both naturally-occuring and anthropogenic sources. Naturally-occuring aerosol such as dust storms, sea spray, and volcano eruptions, exists in the atmosphere even in the absence of human activity. Anthropogenic aerosols on the other hand originates from any human-related activity such as open burning and industrial emissions. The particle sizes vary, depending on their sources, being anywhere between 1 x 10^{-3} to 100 μm. Differentiation between these two types of aerosol can be difficult, but generally, anthropogenic aerosols have much smaller effective radius though this is not always the case. Their lifetime in the atmosphere vary, partly due to their size differences with the larger ones having much larger sedimentation velocities. This also creates the possibility for anthropogenic aerosol to being transported via wind over large distance. Coupled with the different possible aerosol sources in a location, aerosols are highly variable, both in space and time.

Aerosols affect the properties and the functionality of the climate system both direct and indirectly. The former involves scattering of the incoming radiation, dispersing a portion of the radiation akin to an umbrella effect, effectively cooling the atmosphere although they can also absorb some of the radiation instead which in this case, leads to the heating of the atmosphere. The defining factor between these two behaviour lies in the aerosol properties itself with aerosol such as mineral dust and carbonaceous aerosol tends to absorb short and long-wave radiation. Next, the indirect forcing refers to their tendency of being a condensation nuclei which lead to cloud formation, effectively influencing the atmospheric composition. Due to how aerosols play an important role in climate forcing, influencing atmospheric composition, and having direct impact on human health, the importance of characterizing each of their properties cannot be stressed enough.

To enable an easier method to understand aerosol characteristic, the aerosol optical depth parameter (τ_a), or AOD, is an important paramater and is used to describe the optical influence of aerosols in an atmospheric column. AOD parameter can be obtained via multiple ways, be it ground or satellite-based. One of the more popular ways of doing so is via the high resolution, highly-accurate, ground-based sunphotometer which measure direct or/and indirect sun irradiance. Other measuring instruments that were used before in past studies includes hand-held sunphotometers, light detection and ranging system (LIDAR), spectroradiometers, and pyrheliometer. Compiled and comprehensive disucssion regarding these AOD measuring instruments were presented by Holben et al., 2001. For this study, both ground and satellite-based measurements are taken into account, in effort to minimize data holes or gaps. This problem is particularly prevalent in the study area due to constant cloud cover which results in elimination of data in screening process.

1.3 Problem statement

Malaysia is one of the rapidly-developing countries in the SEA region which inevitably faced with the rising issues of excessive aerosol production from its booming population growth, industrialization, and urbanization activities. However, studies of aerosol characterization in this region is still quite limited in terms of its coverage, be it spatial and temporal, and much work needs to be done before a proper understanding of aerosol system and its effect in this region can be achieved. The island part of Pulau Pinang is one of the densest city in Malaysia, with a very high population of gasoline-powered vehicles and is also heavily industrialized. Additionally, a proper assessment of the aerosol properties for the year 2016 monsoonal cycle has yet to be done and studies covering a small locality or coverage has not be done frequent enough in this region albeit the importance of it due to the high complexity and variability of atmospheric properties in this region. Therefore, annual assessments of a city/town/small-scale area needs to be performed more frequent as those can provide accurate general observations that are useful to detect changes in daily AOD values and consequently help to understand this region's aerosol system.

In 2015, Pulau Pinang unfortunately has been affected by a haze incident that originated from the Indonesian region. Other states also have reported a huge increase in their daily API reading, most noticeably during the haze event period, which occurred during early June and July. Sources of these influx aerosols was found to be from agricultural open burning activites done by farmers and local plantation in the Indonesian region and the pollutant was transported by the prevailing southwest monsoon (SW). The immediate effect of these transboundary haze has been characterized but its long-term effect has yet to be confirmed. It is important to evaluate whether the 2015 haze has any noticeable impact on Pulau Pinang atmospheric properties so that proper countermeasures, if necessary, can be taken.

Lastly, gaps in AERONET optical depth data in this region are frequent due to the constant cloud cover in the area. Apart from AERONET, another global atmospheric monitoring system known as MODIS are also widely used in research and studies. With the newly launched Collection 6.1 of MODIS AOD data, verification of its suitability to be used in this part of the SEA region for aerosol research purposes needs to be confirmed and its usability with tandem with AERONET AOD data needs to be evaluated.

1.4 Scope of study

The scope of this research in term of study domain primarily revolves around part of Pulau Pinang island, excluding the mainland part of the state. Data limitations includes the weather data where the data sets are obtained from Weather Underground historical data archive. The site point was set to Penang International Airport (5.293°

N, 100.274° E) as it was the closest site available to the AERONET site, located in the USM School of Physics rooftop (5.358° N, 100.302° E). The location difference of the weather observation site and the AERONET data site is around 9 km. Since AERONET only measures data during cloudless and non-rainy days, a weather disparity between these two locations can cause data to exist in the AERONET data sets even though that particular instance was considered unsuitable by AERONET measuring algorithm. The data from AERONET system presented in this research is also limited in terms of its accuracy, since it is a point-based measurement. The data should be valid up to 15 km radius from the point of measurement (AERONET site).

For air quality assessment records, the chosen data source is the freely available, nation-wide API data. The data sets are daily-averaged and obtained from the MAMPU website (http://www.data.gov.my), with the measuring point positioned at Minden, Pulau Pinang (5.356° N, 100.308° E) (station code: CA0038).

Regarding the AOD data sets, only the AERONET's AOD Level 2.0, V3 algorithm which was quality-checked and quality-assured data are used, including the PW and AE parameter. Other version of the AERONET AOD data such as the sets that were passed through the previous quality check algorithm (V2) are not discussed here as the newer V3 algorithm has multiple improvements compared to its predecessors (Holben et al., 2016).

Whereas for the MODIS AOD data, the data set with the highest available spatial resolution are used, which are the 5 minutes interval, Level-2 processed, 3 km swath data from the Collection 6.1. Both Terra and Aqua satellites data sets are utilized. The relatively small study domain prompts for this option even though according to the data general information on the Level-1 and Atmosphere Archive and Distribution System Web Interface (LAADS DAAC) webpage, the data sets are more susceptible to noises (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MYD04_3K/).

1.5 Objectives

This research mainly revolves around recognizing the atmospheric properties of Pulau Pinang, which can be divided into three particular objectives as below:

- To verify the existance of 2016 transboundary haze and describe the overall behaviour and pattern of AERONET AOD data in Pulau Pinang for the year 2016.
- To assess the suitability of the new Collection 6.1 MODIS AOD data relative to the study domain and its degree of correlation in complementing AERONET AOD data in the region.
- To examine the continuity and effects of the 2015 haze on the following year (2016) in term of AERONET AOD reading.

1.6 Thesis outlines

This thesis consists of six chapters, which are briefly described as follows:

Chapter 1 provides an overview of this study. This chapter also presents a brief background of atmospheric aerosols. A statement of the problem and the scope of the study are presented, so are the objectives.

Chapter 2 provides an overview of the literature and related works on aerosol issues and tasks and explains the relevance of these studies to the present study. The computation of AOD is briefly described in this chapter, and previous studies on AOD characterization attempt and assessment of previous haze event’s impact in this region are also discussed. In addition, the aerosol classification method and several threshold criteria suggested in the literature are also presented.

Chapter 3 describes the study area, instrumentation data, and data processing elaborately. The research procedures are explained for each datasets and what steps the data go through for analysis is mentioned. Post-processing steps which finalize the datasets so that its ready for analysis are also mentioned.

Chapter 4 includes the presentation and analysis of all the gathered data. First, the general analysis and observations of the data collected are briefly described and discussed. Then, a more thorough analysis by separating the data seasonally are presented, mainly discussing about the pattern and anomalies. Supplementary data are also presented in the case of proposing possible causes for anomalies found. Next, a comparison of historical data for multiple parameters is shown followed by the correlation analysis between the MODIS AOD and AERONET AOD data.

Chapter 5 finally summarize the whole research, its initial purposes of being conducted, and what have been achieved. This chapter also provide possible insights for similar, future conducts, highlighting weaknesses and improvements that could be applied in future studies for better research yield.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the more common issues regarding aerosol pollution experienced by countries in the SEA region which then describes how it would affect the study area. Additional information regarding past studies conducted in the region, their methods, findings, and difficulties are also briefly mentioned.

2.2 Pollution problem in general

With the rapid onset of industrial activities in the countries, inter-regional pollution especially between neighboring ones has become more common yet still remains a particularly difficult problem to solve due to differing interests of involved nations. Large scale issues originating from anthropogenic activities not only cause a number of problems that need to be addressed quickly but it can also disturb the relationship between countries in proximity within each other. For example, a radioactive material leakage in a country can alert the entire region altogether (Van Noorden, 2007) and the transport of smoke from mass-scale intentional burning can raise concerns from nearby nations due to it possibly affecting the regional overall air quality (Tay, 1998). Actions have been taken in form of treaties, both regional (e.g. Convention on the Protection of the Rhine (Bern, 1999)) and international (e.g. Montreal Protocol on Ozone Emissions (Secretariat, 2006)), in effort to clarify the responsibilities of the involved parties in maintaining the environmental health.

Among the reported occurences of air pollution, one prominent case of inter-regional pollution in SEA is the transboundary aerosol transport in the Indonesian region and its neighboring countries. The haze which has been observed particularly in 2015, originated mainly from the agricultural burning of small farm and plantation owners and logging companies with majorities being in the Indonesian region. The haze introduced multiple issues to the countries in the region such as public health degradation and tourism sector declination (Jones, 2006). Main concern regarding the haze is the health hazard it introduces to the affected region since multiple studies have shown that an increase in the atmospheric pollutant, especially PM2.5, which has a positive relationship with the mortality rate relating to chronic coronary heart disease (Hu, 2009).

In recent years, the SEA region has saw an increase of open burning activities taking place without proper management and control. The rise of demands for agricultural land to be used as food plantations, such as rice farms and sugar cane, has lead to an alarming expansion of deforestation, which in turn lead to more open burning activites. Ultimately, all of these activities generate air pollutants, contributing to the deterioration of air quality alongside other already problematic sources such as biomass burning, industrial activities, vehicle emissions, and household cooking (Oanh et al., 2011). The huge amount of aerosols emitted into the atmosphere by the countries in the SEA region, particularly by open burning activities, has peaked interests among researchers as to how it would affect the atmospheric composition of the region and forces the climate around it (Lin et al., 2014; Reid et al., 2013; Wang et al., 2013).

Consequently, the released aerosols and air particulates are also subjected to transport by the movement of the wind, or specifically the sea breezes, trade winds, typhoons, and the topographical properties of the land, which causes the infamous transboundary haze (Reid et al., 2013; Wang et al., 2013). Countries that were affected by the haze includes Indonesia, Singapore, and Malaysia with sectors such as agricultural production, air transport, bio-diversity, public health and tourism were negatively impacted (Jones, 2006).

2.3 Complexity of aerosol system in the SEA region

The complex nature of meteorological systems in SEA region has lead to many studies done in the past. The cause for this complexity originate from the locality and the topography of the region itself, as reported by Ramage, 1968 who described the problematic continental (dry) – maritime (wet) interactions of the Maritime Continent (MC) regions. Reid et al., 2013 also mentioned how the complexity can be attributed to convoluted meteorological scales which not only affect the aerosol sytem locally, but extends to all over the globe while Vayda, 2006 also added that human factors also are among the contributing roles.

On top of that, aerosol system in this region is also affected by large-scale metorological factors such as the El Nino Southern Oscillation (ENSO), the variation of the Inter-tropical Convergence Zone (ITCZ), Madden-Julian Oscillation, and the occasional formation of tropical cyclones, all of which the exact nature of their interactions remained unclear to this day (Reid et al., 2012). Reid et al., 2013 also mentioned that how meteorological data in SEA such as aerosol information from satellite observations, clouds, and precipitation seems much more divergent compared to other parts of the world which might be linked to geography and topography complexity, socio-economics, and atmospheric distribution and its microphysical properties.

2.4 Aerosol optical depth (AOD) measurement and derivation

The aerosol optical depth, or AOD for short, is an important parameter in atmospheric studies. AOD is a wavelength-dependent unit which measure the total extinction of incoming solar irradiance caused by absorption and scattering. It can be described as the parameter which denotes the transparency of an atmospherical column. An atmospherical column is an imaginary column from the point on the ground where the measurement is made all the way up to the top of the atmosphere. Hence, the light passing through the column from the top of the atmosphere to the intrument's sensor is subjected to absorption and scattering by all of the aerosols contained in its path.

Atmosphere columns are usually composed of a mixture of aerosol and other gases. In order to obtain the AOD from the incoming sun radiation, other constituents of the atmospheric column must be identified and removed from the total optical depth (TOD). This can be done by utilizing the Beer-Lambert-Bouguer law presented in Equation 2.1:

$$V(\lambda) = V_0(\lambda) d^2 \, e^{-\tau(\lambda)_{TOD} * m} \tag{2.1}$$

where V stands for the digitial voltage measure at a certain wavelength, λ, V_o for the extraterrestrial voltage, d is the actual Earth-to-Sun distance ratio, τ_{TOD} is the total optical air depth, and m is the optical air mass (Holben et al., 1998). The voltage (V) measured by a sunphotometer would be proportional to the spectral irradiance (I) arriving on the instrument' sensor on the surface. For V_o on the other hand, which is the estimated top of the atmosphere spectral irradiance (I_o), is recorded by sun photometer measurements located at Mauna Loa Observatory in Hawaii.

Next, computing for TOD includes extinction by unwanted constituents such as mixed gasses, ozonne, and water vapour. Additionally, Rayleigh scattering also falls into one of the additional extinction. Hence, via subtraction from the TOD, calculation for AOD can be expressed as Equation 2.2:

$$\tau(\lambda)_{Aerosol} = \tau(\lambda)_{TOD} - \tau(\lambda)_{water} - \tau(\lambda)_{Rayleigh} - \tau(\lambda)_{O_3} - \tau(\lambda)_{NO_2} - \tau(\lambda)_{CO_2} - \tau(\lambda)_{CH_4} \quad (2.2)$$

Aerosol study has expanded greatly with the help of emerging technologies, contributing to many fields such as weather forecasting and environmental assessments. Hence, a single, comprehensive variable that can measure and express the aerosol load in the atmosphere such as AOD, is a very important parameter and is widely used in atmospheric studies and air quality assessments.

2.5 Aerosol Robotic Network (AERONET)

Aerosol Robotic Network, or AERONET for short, has been the most succesful attempt at monitoring and providing aerosol-related parameters globally at near real-time. It is a joint effort done by National Aeronautics amd Space Administration (NASA) and Photometrie pour le Traitement Operationnel de Normalisation Satellitaire (PHOTONS). The network coverage are also greatly expanded by collaborators that consists of national agencies, institutes, universities, individual scientists, and partners, collectively creating a mesh of 1,527 established nodes (as of date of writing), as shown in Figure 2.1 below.

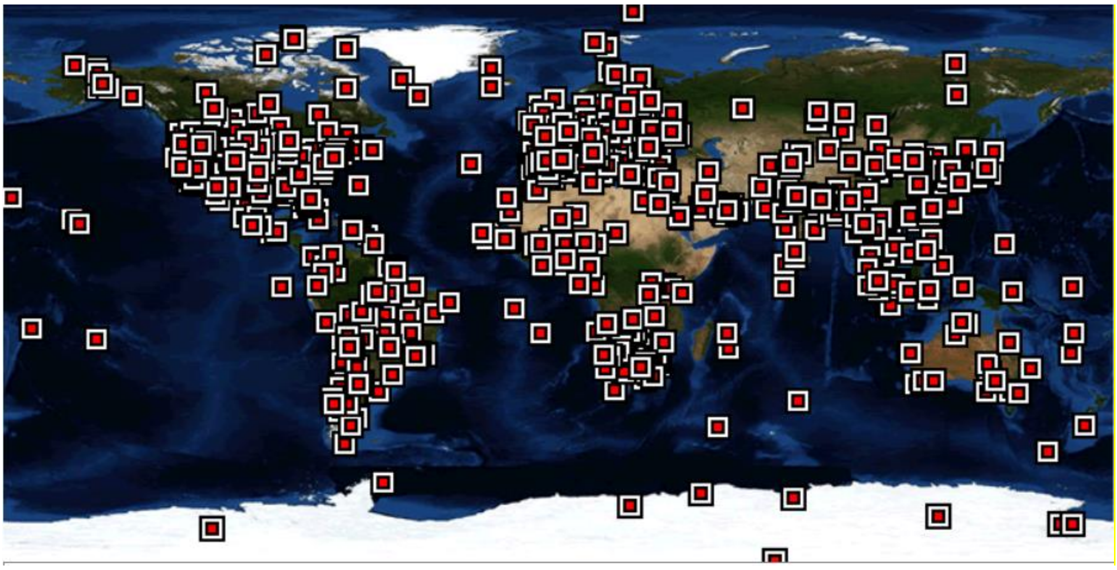

Figure 2.1 Nodes of AERONET station scattered across the globe (Giles, 2020)

For the last 25 years that it has been operating since, the network has provided a continuous and readily-accessible aerosol-related parameters data that has been used for aerosol studies and characterization and ground truth data for satellite data retrievals. Fundamentally, AERONET official radiometer, the CIMEL Electronique 318A spectral radiometer, makes only two types of measurements; direct sky or sun. Direct sun measurements were done in eight spectral bands (anywhere between 340 nm and 1020 nm; 440 nm, 670 nm, 870 nm, 940 nm, and 1020 nm are the standard) and required approximately 10 seconds. In addition, they also took the reading three times in successions, all separated between 30 seconds gap, creating a triplet observation per wavelength. This is particularly useful to distinguish between clouds or aerosol variations because time variation of clouds is typically greater than that of aerosols (Holben et al., 1998). These programmed sequence of measurements start at an air mass of 7 in the morning and end at an air mass if 7 in the evening. The optical depth is then derived from the spectral extinction of direct sunlight radiation at varying wavelength.

2.6 Classification of dominant aerosol type utilizing AOD and AE parameter

With the increased coverage of aerosol remote monitoring, multiple studies involving aerosol type classification have been done in multiple region around the globe. Studies in Singapore (Salinas et al., 2009a), Brazil, Italy, Nauru, Saudi Arabia (Kaskaoutis et al., 2007), Spain (Toledano et al., 2007), Malaysia (Abd Jalal et al., 2012), and even over some oceanic region (Atlantic Ocean, Northern and Southern Pacific, South Indian Ocean, Southern Ocean, Arctic Ocean, and inland seas) as done by Smirnov et al., 2011, are a few examples of the effort made in characterizing aerosols. Scatter plots of AOD and AE are made to classify the dominant type of aerosol in the atmosphere during the time of measurement. AOD of 400 nm wavelength are preferred in these scatter plots due to their indicative nature of turbidity conditions and aerosol type (Cachorro et al., 2001; Smirnov et al., 2002) while the AE 440-870 nm has been the typical wavelength set for identifying aerosol size from spectral AOD (Eck et al., 1999). Different particles exhibit different patterns in the scatter plots hence they are divided into following classes: biomass burning (BMA), desert dust (DA), maritime (MA), urban/industrial (UIA), and mixed (MIXA) which indicates everything else that are hard to distinguish (Ichoku et al., 2004). These sets of aerosol criteria, or generally known as threshold criteria, were used in this study and are also generally practiced and recommended by other researchers. Table 2.1 below lists the studies done and their respective location.

Table 2.1 List of studies and their respective location

Author	Location of study conducted
Salinas et al., 2009a	Singapore
Kaskaoutis et al., 2007	Brazil, Italy, Nauru, Saudi Arabia
Toledano et al., 2007	Spain
Abd Jalal et al., 2012	Malaysia
Smirnov et al., 2011	Atlantic Ocean, Northern and Southern Pacific, South Indian Ocean, Southern Ocean, Arctic Ocean, and inland seas

2.6.1 Aerosol size classification study and threshold suggestion

A study published by Salinas et al., 2009 suggested that AE <1 signify an atmosphere dominated by coarse-mode particles such as dust and sea salt (usually >0.5 um radii) whereas if the value of AE is >1, it is mostly fine particles which consists of biomass, industrial, and/or urban pollutants (<0.5 um) (Eck et al., 1999; Gobbi et al., 2007; Kaskaoutis et al., 2007; Kaufman, 1993; Salinas et al., 2009; Schuster et al., 2006). Coarse mode particles are associated with airborne dust and sea salt in the atmosphere and the fine mode particles are usually anthropogenic, originating from factories and vehicle emissions (Eck et al., 1999; Kaskaoutis et al., 2007). For aerosol groups, firstly DA, it was stated that its corresponding AOD (500 nm) should be >0.2 while its AE (500 nm) <1.0 since this group of aerosol tend to exists in large concentrations and sizes. Next, for MA, it should exhibit AOD values of <0.2 with AE <1.0 and for cases of AOD between 0.2 and 0.4 with its AE >1.0 but <2.0, it is an indication for industrial or urban pollutants from fossil fuel burning and mixtures of free dust and sea-salt aerosols. Additionally, BMA was expected to have AOD values >0.8 and AE>1.0 (Salinas et al., 2009)

Now, although the study mentioned earlier utilized 500 nm AOD with AE that is also on 500 nm, the 400-870 nm AE is also acceptable for this range of threshold since 500 nm wavelength is taken into account when interpolating for the 440-870 nm AE. Consequently, a study by Abd Jalal et al., 2012 which was done in reference to Salinas et al., 2009 proposed another set of aerosol thresholds utilizing AOD 440 nm and AE 440-870 nm. For DA, they suggested AOD values of >0.7 and AE in the range of <1.0 while MA should be represented by AOD with values <0.3 and AE values in between 0.5 and 1.7. Next, for UIA, it is suggested that this class of aerosol will show AOD values from 0.2 to 0.4 while its AE should be >1.0. Finally for BMA, it should have AOD values of >0.7 and AE >1.0.

Additionally, Toledano et al., 2007 also proposed a set of thresholds at 440 nm AOD and 440-870 nm AE. In this case, DA was specifically suggested to be evaluated using AOD 870 nm and its value should be >0.11 for AOD and <1.05 for AE. For MA, AOD should be <0.2 and AE should be between 0 and 2.0. Next, values in between 0.2-0.35 and >1.05 were suggested for AOD and AE respectively for the UIA class and for the BMA class, its value should be >0.35 for AOD and >1.4 for AE.

Table 2.2 summarizing the threshold discussed is prepared below, listing the thresholds and their repective author.

Table 2.2 Threshold list

Author	Threshold value suggested
Salinas et al., 2009	• DA = AOD > 0.2 and AE <1.0 • MA = AOD < 0.2 and AE <1.0 • UIA = 0.2 < AOD < 0.4 and 1.0 < AE < 2.0 • BMA = AOD > 0.8 and AE > 1.0
Abd Jalal et al., 2012	• DA = AOD > 0.4 and AE < 1.0 • MA = AOD < 0.3 and 0.5 < AE < 1.7 • UIA = 0.2 < AOD < 0.4 and 0.5 < AE < 1.7 • BMA = AOD > 0.7 and AE > 1.0
Toledano et al., 2007	• DA = AOD > 0.11 and AE < 1.05 * • MA = AOD < 0.2 and 0 < AE < 2.0 • UIA = 0.2 < AOD < 0.35 and AE > 1.05 • BMA = AOD > 0.4 and AE > 1.4

* Use 870 nm AOD

2.7 Aerosol characterization study

An excess of aerosol in the atmosphere alone introduces multiple problems not just to human, but also to the environment. These anthropogenic pollutants are common in industrial area, worse in developing countries where rapid growth is usually tied to an increase of population and fossil fuel combustion, especially in ones which lack proper regulations. It is essential to understand how much these particulate matter can affect the human health and the environment. Mukai et al., 2006 mentioned how these pollutant can directly affect the climate by increasing haze, fog and cloud, which ultimately decreasing the visibility of the affected region.

The ensuing effects of an excess aerosol emission in the atmosphere also depends on the type of aerosol emitted. This is particularly important to note since Asian sources of aerosol are different compared to their North American and European counterpart. The Asian region tends to have larger coal and biomass burning emission which leads to a greater quantity of absorbing soot and organic components in the Asia-Pacific atmosphere. This is also assisted by the prominent wind in the region, transporting the emitted aerosol to great distance (Huebert, 2003; Lelieveld et al., 2001; Seinfeld et al., 2004). A local study in Pulau Pinang conducted by Tan et al., (2015c) found that the transboundary haze during the SW monsoon season in Pulau Pinang was primarily BMA, calculated at 50%, followed by UIA at approximate 30%. Additionally, UIA and BMA were said to be the most common aerosol type, largely due to industrial activities, local burning, and foreign-blown aerosol (Tan et al., 2015c).

Studies regarding aerosol has answered many uncertainties, particularly the climate change and have improved much of the understanding regarding the characteristics of aerosol, though there are improvements to be made such as analysis on a much larger, regional scale (Srivastava et al., 2012). The long-range tranport of aerosol also introduces other questions as well such as the interaction of the local aerosols and the transported ones and the possibility of microphysical properties alteration, changing the precipitation process and the radiative properties of aerosols themselves (Andreae and Rosenfeld, 2008; Ichoku et al., 2004; Lin et al., 2013; Rosenfeld, 2007). In addition, efforts in determining the origin of aerosols and and their distribution in the atmosphere has been deemed important and necessary to understand the reasoning behind the variability of aerosol in certain locations and how certain processes such as monsoons and seasonal changes affect them.

2.8 MODIS AOD data

Moderate Resolution Imaging Spectrometer (MODIS) is one of the Earth-observing satellite instruments that is used to retrieve the more common parameters in the aerosol study field such as AOD and AE, which depicts AOD's spectral dependence over a given wavelength range. MODIS retrieval algorithm can be classified into three major parts; the Dark Target (DT) which specializes around land retrievals on dense, dark vegetation area (Kaufman et al., 1997; Levy et al., 2013), Deep Blue (DB) for brighter area such as deserts (Hsu et al., 2004), and the previously mentioned DT but is applied on water surfaces (Levy et al., 2013; Tanré et al., 1997). The DT land and ocean are algorithmically different from each other in a sense that they are independent from one another. The satellite-mounted sensor on both Aqua and Terra satellites provides, in a perfect condition, a continuous data since the early 2000s. MODIS also implements various on board calibrations and screenings for cloud contamination, allowing for high accuracy; calculated at ±0.05 AOD under a clear condition, else ±0.15 AOD under a moderately contaminated condition (Remer et al., 2008). MODIS AOD data has been used regularly in this region for aerosol study. Due to its relatively lower resolution MODIS retrievals are often paired with AERONET AOD data which the AERONET AOD data acted as ground truth (Kanniah et al., 2014; Levy et al., 2010; Loría-Salazar et al., 2016). Validation for usage in this region has been done for the previous Collection 5 which saw that MODIS AOD data is decently correlated with the MODIS AOD data ($R^2 = 0.55$)(Kanniah et al., 2014).

However, the version of MODIS data intended to be used in this research is the newly released Collection 6.1. MODIS AOD data Collection 6.1 is the improved product over its previous version, Collection 6. Apart from the number of changes and bug fixes, the revised MODIS Dark Target AOD retrievals algorithm over urban areas has been implemented in this newer collection (Gupta et al., 2016). Seeing how much of the study area itself can be categorized as urban areas, the changes brought by Collection 6.1 should be able to provide datasets with high accuracy.

2.9 Summary

In conclusion, the importance of aerosol studies cannot be stressed any further seeing how much side-effects have been brought by rapid developments in some countries in the SEA region. These complications not only affect the local environment, but can extends to thousands of kilometres. Apart from the lack of understanding how the aerosol would affect the weather and climate system worldwide, many limitation exists in the form of aerosol monitoring itself. Satellite-based monitoring systems do exist, but are greatly hindered by the constant cloud cover in the region while the ground-based systems lack coverage. In addition, complex meteorology in the region also dampens the effort to study and characterize aerosol properties. In spite of all these limitations, studies were still conducted, but usually they involves a much smaller scale in effort to reduce uncertainties. Methods used were discussed briefly, particularly the aerosol classification technique which was reviewed to great lengths.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, details regarding the study area, data sets used, and stages of data processing are discussed. Most of the steps involve transforming data entries into readable graphs and plots. A detailed workflow of the process is presented at the end of the chapter, in addition with a summary flow chart.

3.2 Study site

The study area for this research is Pulau Pinang, shown in Figure 3.1. It is an island that is situated at the northwestern part of Peninsular Malaysia and is connected to its mainland part by the Penang bridge. Pulau Pinang is well-known for its compactness in terms of both residents and building per area even among other major cities in Malaysia. Population in 2017 was estimated to be around 1.746 million people with the total area of the island being approximately 1,048 km^2.

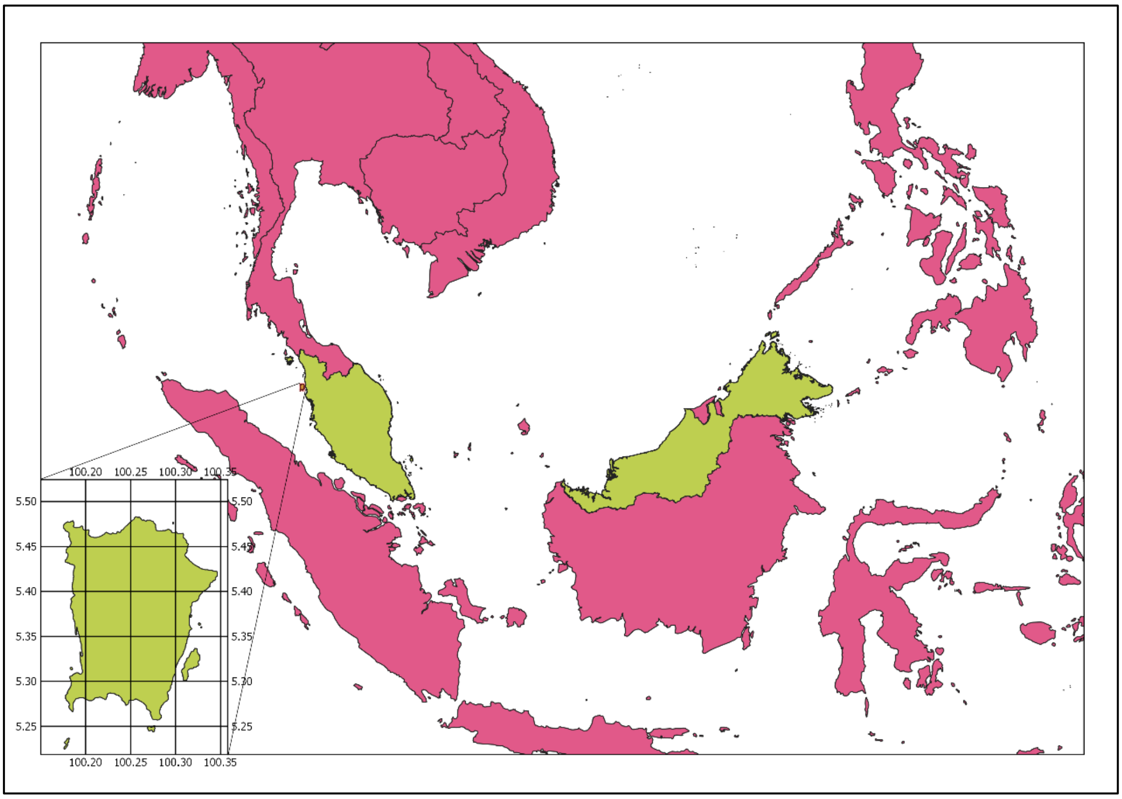

Figure 3.1 Overview of the study area (enlarged in bottom left corner). The main focus is the island part of Pulau Pinang

3.3 Data description

Data used in this study comes from various sources which in this section they are discussed in detail. The sources are also generously described regarding their own individual processes of data acquisition. Data used includes AERONET and MODIS aerosol data, historical weather records, local API measurements and MODIS fire data.

3.3.1 AERONET data

Image generated from the .shp file for Pulau Pinang is presented below in Figure 3.2, depicting the position of the AERONET site used in this study.

Figure 2.2 .shp file generated for Pulau Pinang (study area) and the USM_Penang AERONET site

The AERONET site for this area is in USM, codenamed as USM_Penang (5.358N, 100.302E) in the AERONET official website, which is situated at the eastern part of the island and it has been operating since 2011. AERONET data is uploaded from the memory of the sun photometers to one of the three geosynchronous satellite (GOES, METEOSAT, or GMS) via the Data Collection System (DCS) hourly of half-hourly. It will then be transmitted back to appropriate receiving station on the ground. At this stage, the data is readily accessible and can be retrieved for processing via Internet, creating a near real-time data repositories from any node from the network with exclusion of site above 80 degrees poleward.