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Influence of Southeast Asian Haze episodes on high PM_{10} concentrations across Brunei Darussalam☆

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A B S T R A C T

Particulate matter (PM_{10}) is the key indicator of air quality index in Brunei Darussalam and the principal pollutant for haze related episodes in Southeast Asia. This study examined the temporal and spatial distribution of PM_{10} base on a long-term monitoring data (2009–2014) in order to identify the emission sources and favorable meteorological conditions for high PM_{10} concentrations across the country. PM_{10} concentrations measured at the various locations differ significantly but the general temporal characteristics show clear patterns of seasonal variations across the country with the highest concentrations recorded during the southwest monsoon. The high PM_{10} values defined in the study were not evenly distributed over the years but occurred mostly within the southwest monsoon months of June to September. Further investigations with bivariate polar concentrations plots and k-means clustering demonstrated the significant influence of Southeast Asian regional biomass fires on the high PM_{10} concentrations recorded across the country. The results of the polar plots and cluster analyses were further confirmed by the evaluations with Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) backward air masses trajectories analysis and the Moderate Resolution Imaging Spectroradiometer (MODIS) fire records. Among the meteorological variables considered, temperature, rainfall and relative humidity were the most important meteorological variables that influence the concentration throughout the year. High PM_{10} values are associated with high temperatures and low amounts of rainfall and relative humidity. In addition, wind speed and direction also play significant role in the recorded high PM_{10} concentrations and were mainly responsible for its seasonality during the study period.

1. Introduction

The smoke-haze episodes in the Southeast Asia (SEA) region for the past three decades has been an almost annual transbounadry pollution problem affecting several countries in the region, including Singapore, Malaysia, Indonesia, Brunei Darussalam and Southern Thailand. Previous episodes were recorded in 1982–83, 1987, 1991, 1994, 1997–98, 2002, 2004, 2005, 2006, 2009 (Tangang, 2010), 2011, 2013 and 2015. Haze in SEA region is largely due to the long-range transport of pollutants from biomass fires in Indonesia, namely the island of Sumatra and the Kalimantan region on Borneo Island (Radojevic and Hassan, 1999). Fires are typically lit for agricultural purposes during the regular dry season (Hendon, 2003), but their impacts are heightened during years of anomalously low rainfall (Field et al., 2009; Wooster et al., 2012) which usually associated with the El Niño, a climatic phenomenon that often leads to prolonged and drier weather conditions in the region. However, 2013 severe episode occurred in a non-drought year. Recent observations show that extreme haze episodes in Southeast Asia are no longer restricted to drought years (Gaveau et al., 2014). Brunei has in recent years experienced haze conditions which range from slight transient haze episodes to severe haze episodes, which in some cases lead to the closure of schools and the rescheduling of work hours in offices of both Government and the private sector (Anaman and Ibrahim, 2003). Local fires in Brunei and in neighbouring Malaysian states of Sabah and Sarawak have

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also contributed to some of the haze episodes especially over Brunei (Radojevic and Hassan, 1999).

Atmospheric aerosols (or particulate matter) emitted by the biomass fires in SEA is the dominant pollutant causing exceedances of ambient air quality thresholds on a regional scale (Heil et al., 2006, Abas et al., 2004a, Heil and Goldammer, 2001). During haze episodes in Brunei, the Pollutant Standard Index (PSI) is invariably based on Particulate Matter (PM) less than 10µm in aerodynamic diameter (PM_{10}), as the concentrations greatly exceed those of other criteria pollutants, SO_2, CO, NO_2 and O_3 (Radojevic and Hassan, 1999). It has also been consistently used in the neighbouring country of Malaysia as the principal specification for the calculation of the Air Pollution Index (Afroz et al., 2003; Awang et al., 2000). A number of studies have been carried out on characteristics and impacts of the resultant particulate pollutants from biomass burning in SEA (e.g Gaveau et al., 2014, Tangang, 2010, See et al., 2006, Abas et al., 2004a, 2004b; Muraleedharan and Radojevic, 2000; Balasubramanian et al., 2003; Pentamwa and Kim Oanh, 2008). Globally, PM has become the most important constituent of atmospheric pollutants and it is currently a subject of extensive research, with at present1500–2000 papers per year addressing research topics related to atmospheric aerosols (Fuzzi et al., 2015). This is due to the potential effects on air quality, humans, and ecosystem well-being (WHO, 2013; Fowler et al., 2009), and also plays an important role in the Earth's climate system (IPCC, 2013). The 1997–98 SEA haze episodes considered to be the worst air pollution incidents on record in Brunei has been linked to significant visibility reduction and incidence of respiratory diseases (Asthma, Acute Respiratory Infections and Influenza (ARII)) in the country (Yadav et al., 2003, Muraleedharan et al., 2000, Anaman and Ibrahim, 2003, Anaman and Ibrahim, 2000). Volatile organic compounds (VOCs) and heavy metals, some of which are known or suspected carcinogens, mutagens, and teratogens, and have the potential to cause serious long-term health effects were characterised in the 1998 haze episode (Muraleedharan et al., 2000).

Several factors influence air pollutant concentrations and exposure time which include meteorology, topography and emission sources. However, meteorological variables play an important role in the dispersion, transformation and removal of atmospheric pollutants from the atmosphere; they affect the spatial-temporal characteristics and pollution levels of atmospheric pollutants (Tian et al., 2014). Statistical studies using meteorological data and air pollution monitoring data have confirmed that PM exhibit typical diurnal, weekly, seasonal and annual cycles due to changes in meteorological parameters (Tian et al., 2014; Choi et al., 2008; Sfetsos and Vlachogiannis, 2010; Lee et al., 2011; Mamtimin and Meixner, 2011; Unal et al., 2011). The SEA PM_{10} is strongly influenced by the monsoon seasons and meteorological conditions such as temperature, humidity and wind speed (e.g Juneng et al., 2009; Abas et al., 2004a; Afroz et al., 2003), synoptic patterns as well as regional hotspot number (Juneng et al., 2011).

Particulate matter monitoring in Brunei started in October, 1997 in response to the 1997 severe haze pollution (Radojevic and Hassan, 1999) and this has seen systematically designed monitoring stations located across the country. Adequate knowledge of the temporal and spatial patterns of PM_{10} across Brunei can be obtained from the analysis long-term routine monitoring data that will provide useful support to the National Haze Action Plan on how best to mitigate impacts of future haze episodes. More importantly instances of high particulate matter events can be identified for further investigation into the potential sources and transport pathways. Previous studies on sources and characteristics of haze in Brunei were episodic and limited to air quality during 1997–98 episodes (Radojevic and Hassan, 1999, Muraleedharan and Radojevic, 2000; Muraleedharan et al., 2000; M. Radojevic, 2003). Also, most of these studies did not cover the entire country. There is no or limited studies based on a long-term monitoring data on the distribution and processes affecting concentrations of particulate matter during hazy and nonhazy days in Brunei.

The bivariate concentrations polar plots and k-means cluster analysis of air pollutant concentrations introduced by Carslaw and Beevers (2013) have been proven to be useful techniques for identifying the presence and characteristics of different sources of air pollution using available ambient monitoring data (e.g Elangasinghe et al., 2014; Stojić et al., 2015; Buchholz et al., 2016). The plots provide a modeled surface that represents the relationship between air pollutant concentration, wind speed and wind direction, using a Generalised Additive Modeling (GAM) technique to extract real source features rather than noise. Carslaw et al. (2006) used this technique to isolate nitrogen oxide emissions from aircraft movements in an airport. Carslaw and Beevers (2013) performed k-means clustering on bivariate polar plots to separate nitrogen oxide emissions from London Heathrow airport. They found that the time variation of the estimated emissions is in agreement with the time variation of emission estimates based on aircraft movement records. Backward air mass trajectories modeling are also commonly used to analyse pollution episodes and transport pathways of potential sources (Draxler and Hess, 1998; B. Wang et al., 2009).

In this study we examined the temporal and spatial distributions of PM_{10} base on a long-term monitoring data (2009–2014). The main goal is to identify the emission sources and favorable meteorological conditions for high PM_{10} concentrations across the country. Bivariate polar plots and k-means clustering techniques were used in order to characterised and extract emission sources of high PM_{10} concentrations from selected air quality monitoring stations across Brunei. The transport pathways identified through backward air masses trajectories analysis of high PM_{10} concentrations events using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) modeling (Stein et al., 2015). The Moderate Resolution Imaging Spectroradiometer (MODIS) fire records provided by the Fire Information for Resource Management System (FIRMS) Web Fire Mapper (https://firms.modaps.eosdis.nasa.gov/firemap/) was combined with the backward air masses trajectories analysis. The influence of individual meteorological variables on PM_{10} trends and variability were also assessed through time series plots and correlations analysis.

2. Materials and methods

Brunei Darussalam (Latitude 4.8903N, Longitude 114.9422E) is a small country with an area of 5765 sq km and with a population of 393,372 in 2011 based on the final data of the Population and Housing Census, 2011 (BDKI, 2014). The climate of Brunei is generally hot and wet throughout the year, governed by its location on the northwest coast of Borneo within the equatorial tropics, and the wind systems of Southeast Asia which result from the atmospheric pressure distribution over the region as a whole (Brunei Darussalam Meteorological Department, www.met.gov.bn). The climatic variation is dominated by the monsoon winds resulting from the seasonal fluctuation of the inter-tropical convergence zone (ITCZ) in the South China Sea area. The annual movements of the ITCZ and the associated “Trade” wind fields produce two main seasons in Brunei, separated by two transitional periods: Northeast Monsoon (December to March), Southwest Monsoon (June to September), first transitional period or Intermonsoon (April and May) and the second transitional period or Intermonsoon (October and November), (www.met.gov.bn). The country is made up of four districts: Brunei-Muara, Tutong, Belait and Temburong (Fig. 1). The