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Influence of Meteorological Variables on Suburban Atmospheric $PM_{2.5}$ in the Southern Region of Peninsular Malaysia

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ABSTRACT

Air pollution is a crucial contributor to premature mortality and health problems. The excessive inhalation of fine particulate matter ($PM_{2.5}$) is strongly associated with adverse health effects due to its capability to penetrate deep into the human respiratory system. This study aimed to analyze the seasonal cycles of 24 h average $PM_{2.5}$ mass concentrations in a suburban area in the southern region of Peninsular Malaysia. The meteorological variables and $PM_{2.5}$ data were obtained via a Grimm Environmental Dust Monitor from August 2017 until January 2018. The maximum 24 h mass concentration was 44.6 µg m^{-3}, with a mean value of 21.85 µg m^{-3}, which was observed during the southwest monsoon. 43.33% and 8.33% of the daily concentrations exceeded the 24 h World Health Organization Guideline and Malaysian Ambient Air Quality Standard, respectively. The variation in the $PM_{2.5}$ mass ranged between 0.53 and 0.90 times of the PM_{10} mass, indicating that the $PM_{2.5}$ consistently contributed 52–92% of the PM_{10} mass concentration. During the monsoon seasons, the ambient temperature exhibited a significant positive correlation ($p < 0.05$) with the $PM_{2.5}$ mass concentration (r = 0.425–0.541), whereas the wind speed (r = –0.23 to –0.0127) and the relative humidity (r = –0.472 to –0.271) displayed strong negative correlations with it. Additionally, the rainfall was weakly correlated with the mass concentration. The presence of northeasterly wind at the study site suggests that the $PM_{2.5}$ originated from sources to the northeast, which are influenced by anthropogenic activities and high traffic.

Keywords: Atmospheric $PM_{2.5}$; Meteorological influence; Particulate matter; Suburban area.

INTRODUCTION

Atmospheric aerosols are of global importance because they affect the climate via direct and indirect radiative forcing and adversely impact the human health and ecosystems. Atmospheric particles of different size ranges exhibit wide chemical compositions and characteristics (Rinaldi *et al.*, 2007). Different-sized particles originate from different sources, have different chemical characteristics, impose different health problems and require different removal processes (Akyuz and Cabuk, 2009; Li *et al.*, 2013). One of the main pollutants which contributes to the negative impact of the global climate is airborne particulate matter ($PM_{2.5}$) (Mallet *et al.*, 2016).

$PM_{2.5}$ is particulate matter that has an aerodynamic diameter of less than 2.5 micrometers and is known to be toxic to mankind. Previous studies showed that $PM_{2.5}$ has a high association with morbidity and mortality (Brunekreef *et al.*, 2005; Tong *et al.*, 2009). Most studies show that the adverse effects of fine particles ($PM_{2.5}$) on human health are much worse than coarser particles (Bai *et al.*, 2007). The World Health Organization (WHO) mentioned that 1/8 of premature deaths are caused by airborne pollution. WHO also reported that more than 3 million premature deaths every year is caused by exposure to the pollution of ambient air (WHO, 2014). $PM_{2.5}$ has the capacity to adsorb carcinogenic elements due to their great surface area (Kawanaka *et al.*, 2002) and contains toxic elements such as hydrocarbons from combustion, and heavy metals from polluted environment. These particles have the ability to deteriorate the local and regional air quality, as well as the atmospheric visibility (Cascio *et al.*, 2009).

Furthermore, there are a few factors that could influence the concentration of particle mass which are the earth topography, emission sources, monsoon seasons and the meteorological parameters (relative humidity, wind speed, temperature) (Afroz *et al.*, 2003; Tai *et al.*, 2012; Amil *et al.*, 2016). This is because these variables affect pollution concentration, as well as the removal, transportation and dispersion of the airborne particles (Tian *et al.*, 2014).

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Due to the industrialization, use of vehicles, and expansion of suburban areas into close proximity with industrial areas, the particle pollution in ambient environment is increasing (Khan *et al.*, 2016a). Hossain *et al.* (2007) stated that the $PM_{2.5}$ emitted from the anthropogenic emissions are associated with these industrialization sectors. Since the atmospheric $PM_{2.5}$ has the residence times of days and weeks, the anthropogenic emissions can result in the issues of regional and global concern (Cohen *et al.*, 2004) due to the particles affecting the other countries through the transboundary transport, which later causes the global climate change implications (Gatari *et al.*, 2006). This is because, for the travel distance of $PM_{2.5}$ pollutants, the particles usually remain in the atmosphere layer for about several days till a week prior to dropping to the ground or are rained out. On the other hand, the particles located at a higher level of atmosphere layer travel beyond and remain prolonged in the layer of atmosphere for years. Skudai is a rapidly growing town and has various types of industries that could worsen the pollution level, as well as the health of the human population. However, there is a limited number of studies that focus on the temporal variation of particulate matter in this expanding suburban region.

The main objective of conducting a study at this area is due to the needs to investigate the effects of local and transboundary (air issues which are long-range transported from the urban city of Johor Bahru, the polluted industrial areas of Pasir Gudang and Senai, or from the neighboring countries) pollution towards the suburban area of mixed industrial-residential airshed in Skudai, Iskandar Puteri, developing region. Since the area has less population density and is located far from the industrial activities, city center and commercial areas, the site is perceived to have significantly clear days throughout the years. Hence, the aim of this study is to analyze the variation of $PM_{2.5}$ mass concentration and its effects towards the meteorological influence in the southern region of Peninsular Malaysia, over a 6-month period to cover the southwest, inter-monsoon and northeast monsoons of Malaysia.

METHODS

The sampling period was conducted for 60 days to represent the seasonal variations of the $PM_{2.5}$ mass concentration, covering the southwest monsoon (from August to September 2017) and the northeast monsoon (from December 2017 to January 2018). Samples were also collected during the inter-monsoon period from October to November 2017 (Wahid *et al.*, 2013). Fig. 1 shows the location of the monitoring site, together with the zoomed-in map.

Monitoring Site

The location is selected at southern part of Malaysian Peninsula with coordinates 1°33′56.7″N 103°38′21.5″E, located at Universiti Teknologi Malaysia (UTM) Skudai, Johor Bahru, for continuous sampling of aerosols in order to study the ambient air quality. The sampler was placed on the rooftop of N12 building, Faculty of Chemical Engineering. The study area, UTM Skudai, has a population of 29,319 on campus, with an increasing population growth rate especially after the expansion of Skudai suburban town into the developed region of Iskandar Puteri (UTM, 2018). The suburban area is surrounded by woods, dense residential-cum-commercial areas and literally sandwiched among different types of industrial areas within the circumference of 30 km (Satellites, 2018). The study area is situated 3–5 km away from the residential areas of Taman Universiti, Taman Sri Pulai, Taman Teratai, Taman Sri Pulai Perdana and Taman Sri Skudai; 5 km away from industrial areas of Johor Technology Park and Taman Universiti; 5–10 km away from Skudai and Senai Highway with frequent heavy vehicular traffic volume; 20 km away from Nusajaya and Iskandar Puteri developed regions; 20 km away from Johor Bahru city center and 30 km away from Pasir Gudang. Traffic congestion is quite common around the area due to the sampling site being 5 km away from queuing vehicles at Skudai toll plaza. On

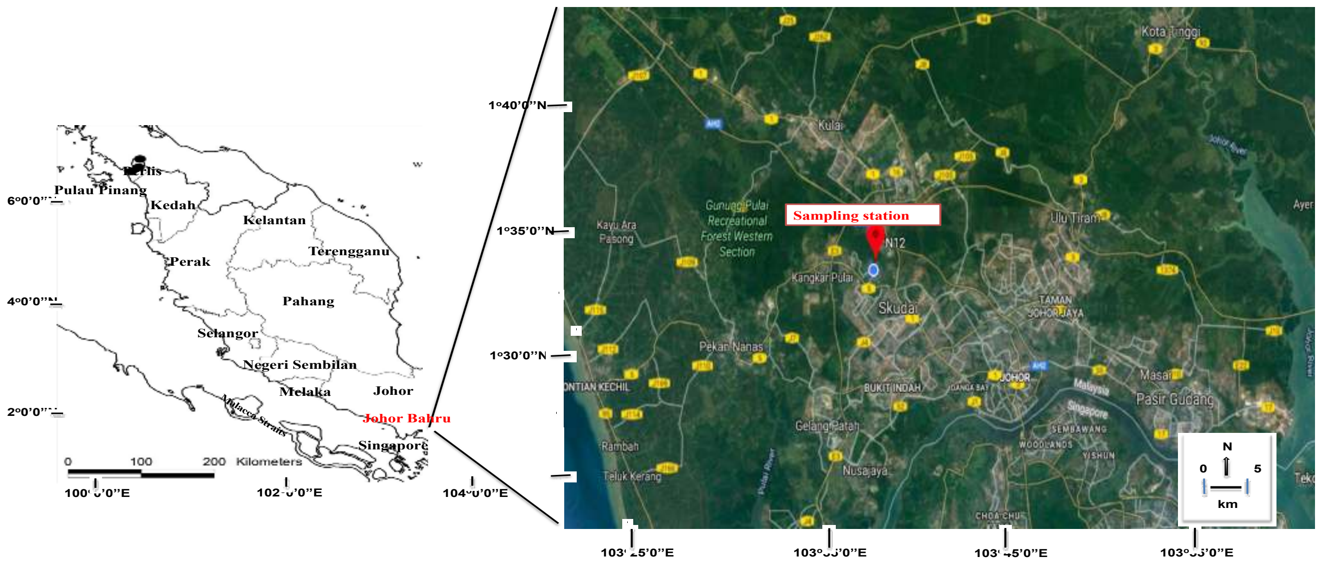

Fig. 1. Location of the monitoring site.

top of that, the location itself has intense human activity and heavy traffic flow due to great population and vehicle numbers in the premier education center of 3020 acres. With rapid urbanization, industrialization, development, transportation, economic and population growth rate around the campus area as well as the Skudai region, the particle mass concentration is expected to be around the ambient level of the National Ambient Air Quality Standard of Malaysia, hence the location of sampling site.

Monitoring Device

The data collection of atmospheric $PM_{2.5}$ as well as meteorological parameters such as wind speed, temperature, relative humidity and rain volume were monitored via Grimm Environmental Dust Monitor (EDM 164). Grimm was programmed to run automatically at an air flow rate of 1.2 L min^{-1} to collect $PM_{2.5}$ and meteorological parameters during the sampling period. The parameters were monitored daily and hourly from August 2017 to January 2018. The sampler is placed approximately 30 m above ground level, while the inlet is set to be at 2 m above roof surface. Careful consideration of the emission source distribution and dispersion patterns is taken when selecting the site. Ideally, the sampler is placed in such a way that the inlet is not too close to interferences and disturbances (Boman and Gaita, 2015).

Data Interpretation and Analysis

The sample air at a volume flow of 1.2 L min^{-1} was directly fed into the measuring cell by passing through a TSP (total suspended particles) head and the probe inlet. The optical system was optimized in such a way as to ensure that the refractive change (color) is negligible. Even in the nano-size range the sensitivity across the size channels is excellent. All particles (aerosol) passing through the measurement cell were classified by size distribution into 31 channels. The figures for $PM_{2.5}$ were received by multiplying the obtained count concentrations with the corresponding specific density factors then to be added to the total masses of each PM channel. This was all done automatically by the instrument. Data were available in real time, stored in the internal memory and can be read out with the included PC software.

Next, descriptive statistics were carried out on $PM_{2.5}$ mass concentration and meteorological parameters. Correlations among variables of $PM_{2.5}$ (µg m^{-3}), relative humidity (RH; %), wind speed (WS; m s^{-1}), wind direction (WD; °), rainfall (RF; L m^{-2}) and temperature (T; °C) data were assessed by Pearson's correlation coefficients to measure the strength of relationships among variables.

RESULTS AND DISCUSSION

Mass Concentration and Meteorological Variables

Contrasting to other regions with four seasons, Southeast Asia (SEA) nations or especially Malaysia's weather is classified into four categories of seasons including southwest monsoon (June–September), northeast monsoon (November–March) and two inter-monsoons (March–May and October–November). For SEA regions such as Malaysia, Singapore, Vietnam and Thailand, the climate is described as tropical, meaning that the weather tends to be hot and humid most part of the year. Meanwhile, regions other than SEA countries may include winter, spring, autumn and summer seasons throughout the year.

Fig. 2 shows the diurnal trends of $PM_{2.5}$ mass concentrations, which were monitored with 24 h time resolution (Roig *et al.*, 2013). PM_{10} mass concentration trends are also plotted in the graph as a comparison study. 60 samples were collected to represent the seasonal variations of the $PM_{2.5}$ and PM_{10} mass concentration. *S1–S20* represent the southwest monsoon (SW), *S21–S40* represent the inter-monsoon (IM), and *S41–S60* represent the northeast monsoon (NE). Boman and Gaita (2015) also analyzed $PM_{2.5}$ findings collected over a 3-month period, from December 2013 to March 2014, in Kingston, Jamaica. Meanwhile, Khan *et al.* (2016b) investigated $PM_{2.5}$ mass from July to September 2013, and January to February 2014, to cover different monsoon periods, and Sulong *et al.* (2017) also chose the second half of the year as the sampling period of the study. Fig. 2 shows the diurnal trends of particle mass concentrations for both particle fractions of $PM_{2.5}$ and PM_{10} (µg m^{-3}).

The reference lines in Fig. 2 show the 24 h permissible value of $PM_{2.5}$ mass concentration according to World Health Organization Guideline and 2020 Malaysian Ambient Air Quality Standard. Some of the PM_{10} data in the graph are missing due to technical errors. About ~20% of the PM_{10} mass data were lost. However, since the PM_{10} mass data acts only as the reference and secondary information to the main data of $PM_{2.5}$ mass, this issue is considered not severe. In a previous research in Lembang, Indonesia, Lestiani *et al.* (2012) reported that there were no samples taken for 3 months due to technical problems. The temporal variations in Fig. 2 indicate that the particle mass concentrations of both $PM_{2.5}$ and PM_{10} have almost the same trends throughout the southwest, inter-monsoon and northeast monsoons. Assumptions that the PM_{10} findings are always almost the same trend as the $PM_{2.5}$ data, and that the concentration values are always slightly greater than $PM_{2.5}$ data, are made. The variation of $PM_{2.5}$ level is constantly 0.53–0.90 the level of PM_{10} mass, which shows that the $PM_{2.5}$ mass is consistently 52–92% of PM_{10} mass concentration. The $PM_{2.5}$ mass is observed to increase too as the PM_{10} increases. This also reveals that $PM_{2.5}$ mass concentration is consistently 52–92% of PM_{10} level. The diurnal variations of the PM_{10} mass tend to be generated constantly at a greater level than the mass of $PM_{2.5}$. The greatest values of 24 h mean concentrations are 44.6 µgm^{-3} and 49.44 µgm^{-3} for $PM_{2.5}$ and PM_{10}, respectively. These high concentrations were produced during the southwest monsoon. However, the lowest values of 24 h mean concentrations for the suburban area are 8.06 µgm^{-3} and 17.71 µgm^{-3} for $PM_{2.5}$ and PM_{10}, respectively. The values of PM_{10} mass concentrations range from 11.43 µg m^{-3} to 49.44 µg m^{-3} throughout the SW to NE monsoons. The 24 h mean concentrations of PM_{10} are considered safe as the values do not exceed the 24 h Malaysian Ambient Air Quality Standard (100 µg m^{-3}) (DOE, 2013), World Health Organization Guideline (50 µg m^{-3}) (WHO, 2016) and U.S. National Ambient Air Quality Standard (150 µg m^{-3}) (U.S. EPA, 2017). Meanwhile, the $PM_{2.5}$ mass concentrations

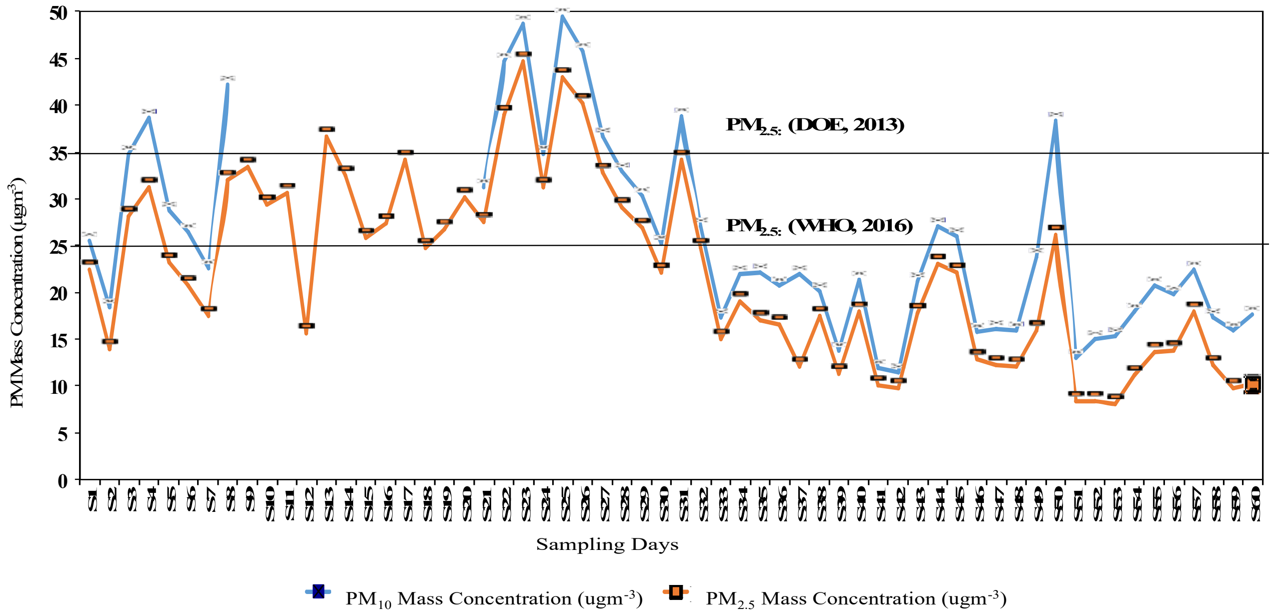

Fig. 2. Diurnal trends of $PM_{2.5}$ and PM_{10} mass concentration (µg m^{-3}).

range from 8.06 µg m^{-3} to 44.6 µg m^{-3} with 24 h mean values of 26.80 µg m^{-3}, 26.08 µg m^{-3} and 13.76 µg m^{-3} for the southwest monsoon, inter-monsoon, and northeast monsoon season, respectively. The overall mean $PM_{2.5}$ mass concentration is 21.85 µg m^{-3}. However, the highest value of 24 h $PM_{2.5}$ mass concentrations which is 44.6 µg m^{-3} that occurred during the southwest monsoon season exceed the 24-h World Health Organization Guideline (25 µg m^{-3}) (WHO, 2016) and 2020 Malaysian Ambient Air Quality Standard (35 µg m^{-3}) (DOE, 2013). Of the 24 h $PM_{2.5}$ mass concentration means, 43.33% exceed the 24 h World Health Organization Guideline and 8.33% exceed the 24 h Malaysian Ambient Air Quality Standard, while none of the values of $PM_{2.5}$ mass concentration exceed the 24 h Interim Target 1 and Interim Target 2 of Malaysian Ambient Air Quality Standard.

The time series plot in Fig. 2 shows two distinct peaks that spike in the SW monsoon, for both $PM_{2.5}$ and PM_{10} data. This phenomenon occurred probably due to strong seasonal variation, as well as local anthropogenic activities at the region of monitoring location. In the past years of 1997, 2005, 2013, and 2015, Malaysia and Singapore experienced intensified haze episodes during the southwest monsoon seasons (Mahmud, 2009; Betha *et al.*, 2014; Othman *et al.*, 2014; Ahmed *et al.*, 2016; Dotse *et al.*, 2016). However, in the year 2017, no haze occurred during this particular monsoon. The higher particulate mass concentration level at the site is probably due to motor vehicle activities and strong winds, besides the presence of dry atmospheric condition that re-suspended the road dust and soil particles (Amato *et al.*, 2009; Filonchyk *et al.*, 2019). Due to the short distance between sampling site and the local anthropogenic sources, these sources may be the main reason for the high $PM_{2.5}$ mass concentrations reported during the sampling period. However, transboundary pollution may also contribute to the $PM_{2.5}$ mass. The concentration is normally reported more than 50 km from the source origin (Reid *et al.*, 2005). Besides that, Barbante *et al.* (2001) stated that $PM_{2.5}$ pollutants may be transported over long distances (even over 1000 km), before being deposited to the ground surface. The graph displays that Skudai region is not affected by any haze occurrence or regional biomass burning activities, but instead reveals the likelihood of the high level of pollutants resulting from other factors such as local motor vehicles and nearby industries (Afroz *et al.*, 2003), as well as prolonged dry season due to El Niño's Southern Oscillation (ENSO) phenomenon. Rahman *et al.* (2015) revealed that 30% of the total emission of fine particles ($PM_{2.5}$) originates from transportation, while Ee-Ling *et al.* (2015) reported motor vehicles and soil dust as the main sources. Nevertheless, the particulate mass concentration plot starts to gradually decrease in the NE monsoon. The concentration of the pollutants starts to reduce drastically as the wind flow patterns of the northeast monsoon change, indicating the beginning of rainy seasons over Malaysia (Juneng *et al.*, 2009; Md Yusof *et al.*, 2010; MMD, 2012). The intensity of rainfall during this season is high resulting in the pollutants being diminished from the atmosphere through wet deposition processes (Liss and Johnson, 2014).

Fig. 2 also presumes that the particle mass concentrations from the SW monsoon are transported by the prevailing southwest winds during the southwest monsoon, which is also known as the dry season in Malaysia. On the other hand, the fine particles from October to November were produced during the inter-monsoon season while $PM_{2.5}$ generated from December to January was collected during the northeast monsoon, which is normally known as the wet season in Malaysia. During the southwest monsoon, the winds commonly come from the southwest quadrant of the SEA region, which is Sumatra Island of Indonesia. Meanwhile, $PM_{2.5}$ and PM_{10} pollutants are usually carried by the prevailing northeast winds from the Chinese mainland, Indochina region, and the Philippines, during the northeast season

(MMD, 2012). The sources of the $PM_{2.5}$ pollutants are the primary and secondary particles. Primary particles usually originate from soil-related and organic carbon particles from the combustion of fossil fuels and biomass burning. Sources of soil-related particles include road dust, construction activities and agriculture processes (Huang *et al.*, 2018). Other sources of primary particles are volcanic eruptions, biomass burning, biological particles (mineral dusts) and traffic-related suspension such as brakes and tires, road dusts and mechanical processes particles (Tiwary and Colls, 2010). The mixture of the primary and secondary particles that are produced in the atmosphere, such as sulfate and nitrate, which are derived from combustion-related sources such as industrial activities, combustion sources, automobile exhaust and heavy transportation (Moreno *et al.*, 2004; Cheng *et al.*, 2010; Li *et al.*, 2013).

These data agree well with Khan *et al.* (2016b) as this study contributes a similar, albeit slightly higher level of daily mean concentration of fine particles, which was also conducted in a suburban area. The $PM_{2.5}$ mass concentrations are 24.5 ± 12.0 µg m^{-3} and 14.3 ± 3.58 µg m^{-3}, during pre-haze and post-haze periods, respectively, which are comparable with the result of this study due to the same type of sampling location. Dahari *et al.* (2019) summarizes that the 24-h mean $PM_{2.5}$ mass concentration of the semi-urban and urban regions in Malaysia is in the range of 5.30–55.89 µg m^{-3} and 11–72.3 µg m^{-3}, respectively (Tahir *et al.*, 2013; Betha *et al.*, 2014; Ahmed *et al.*, 2016; Ahmed *et al.*, 2017; Sulong *et al.*, 2017). The greater mass concentration in the semi-urban area is due to the heavy transportation while the high $PM_{2.5}$ mass in the urban area is due to the haze events in Kuala Lumpur that occurred during 2015. Hence, the $PM_{2.5}$ mass concentration of this study is comparable with the previous studies in Malaysia which did not involve haze occurrence. Contrarily, the $PM_{2.5}$ mass obtained is not within the average range of the adjacent nation of Hanoi, Vietnam, and Lanzhou, China, which were 76–134 µg m^{-3} and 41–254 µg m^{-3}, respectively (Hai and Kim Oanh, 2013; Filonchyk *et al.*, 2019). Unlike Malaysia, these regions were undergoing dry season, where there would be an increase in fires and burning activities (Zhang *et al.*, 2005b; Ho *et al.*, 2014; Zhang *et al.*, 2015a).

It was reported that 70% of the PM emission during non-haze periods originate from traffic activities (Awang *et al.*, 2000). In addition, Karaca *et al.* (2005) and Aarnio *et al.* (2008) who conducted research in Istanbul and Helsinki, respectively, reported daily $PM_{2.5}$ mass of 20.8 µg m^{-3} and 20.3 µg m^{-3}, respectively. For a haze occurrence period in the urban city of Kuala Lumpur, the concentration value is 61.2 ± 24 µg m^{-3} (Amil *et al.*, 2016). Likewise, large cities such as Zhuhai and Hong Kong reported fine particle mean concentrations of 59.3 µg m^{-3} and 54.5 µg m^{-3} (Cao *et al.*, 2012). The average levels of $PM_{2.5}$ mass concentration in urban areas is also similar with those in Manila (44 µg m^{-3}), Bangkok (50 µg m^{-3}), Bandung (53 µg m^{-3}) and Chennai (46 µg m^{-3}) (Kim Oanh *et al.*, 2016). Fig. 3(a) shows the hourly distribution of the $PM_{2.5}$ mass concentrations that represented the southwest monsoon, the inter-monsoon, the northeast monsoon, while Fig. 3(b) displays the distribution patterns of temperature (°C), rain volume (L m^{-2}) and relative humidity (%). Moreover, Fig. 3(c) plots the diurnal distributions of the $PM_{2.5}$ mass concentrations (µg m^{-3}) and the daily mean wind speed (m s^{-1}). Although the number of monitoring days is considered small to properly characterize the hourly plot, as well as the weekday-to-weekend variation, but since the hourly extracted data is too abundant for a half-year monitoring session, only a limited time frame is required to tabulate the graph. Therefore, the 7-day hourly graph is plotted as in Fig. 3(a), using 1-week data to represent each month, which in turn represents each season.

From Fig. 3(a), it is clearly seen that the total mass concentration of fine particulates decreases significantly from the SW through the NE. The graph shows that the emission of this particular pollutant decreased according to the seasonal monsoons. However, the values of $PM_{2.5}$ during weekends are not significantly different from those of weekdays, as there is only a slight decrease in the fine particulate mass concentrations observed during the weekends,

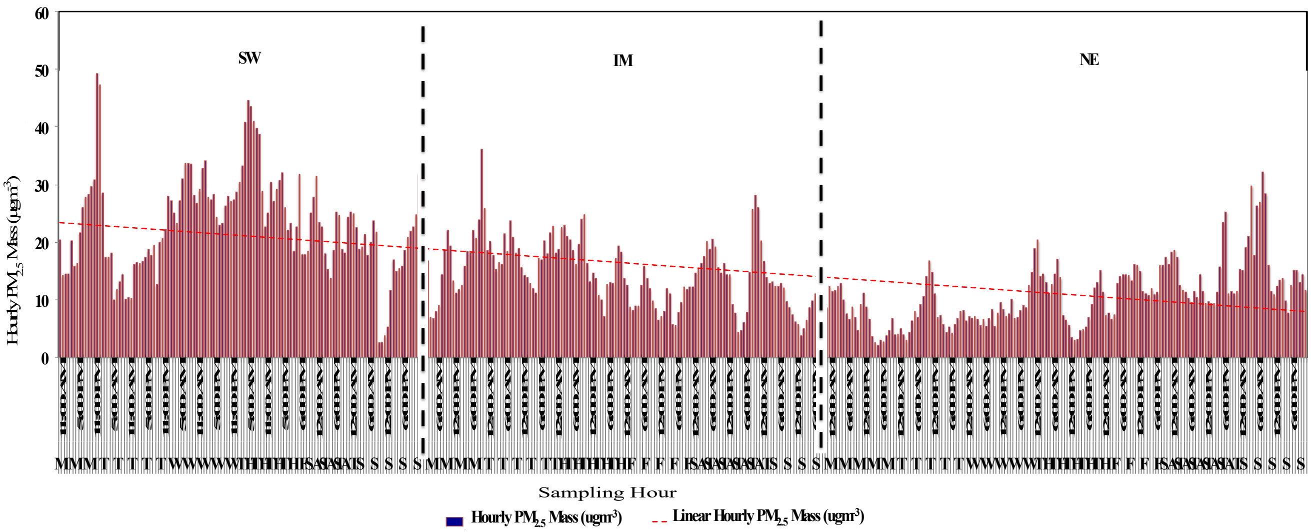

Fig. 3(a). Hourly variation of $PM_{2.5}$ mass concentrations (µg m^{-3}).

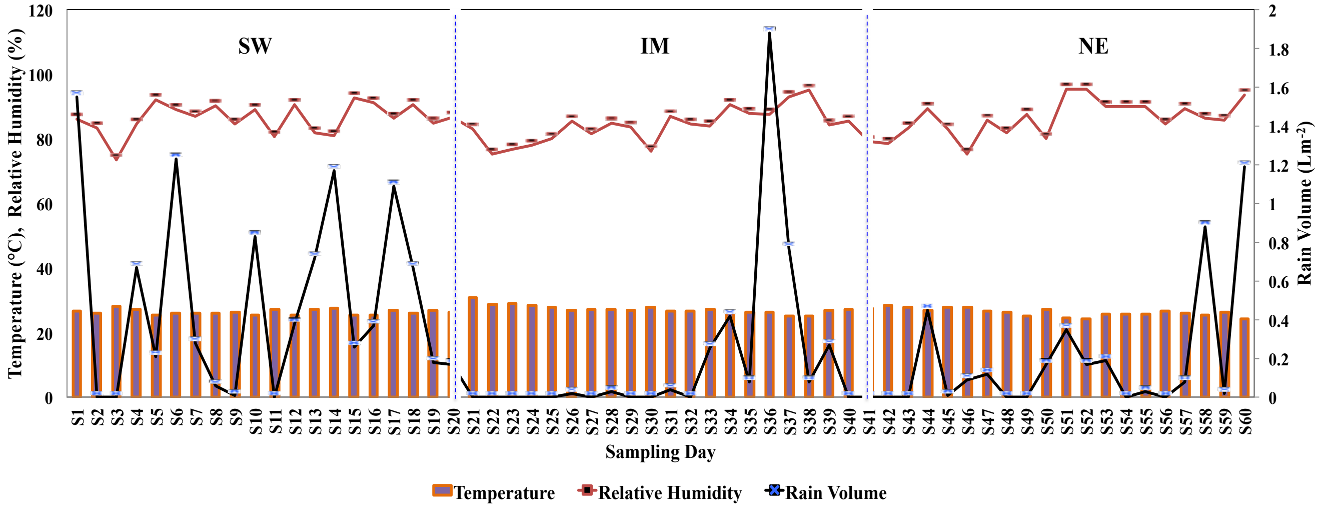

Fig. 3(b). Distribution pattern of temperature (°C), rain volume (L m^{-2}) and relative humidity (%).

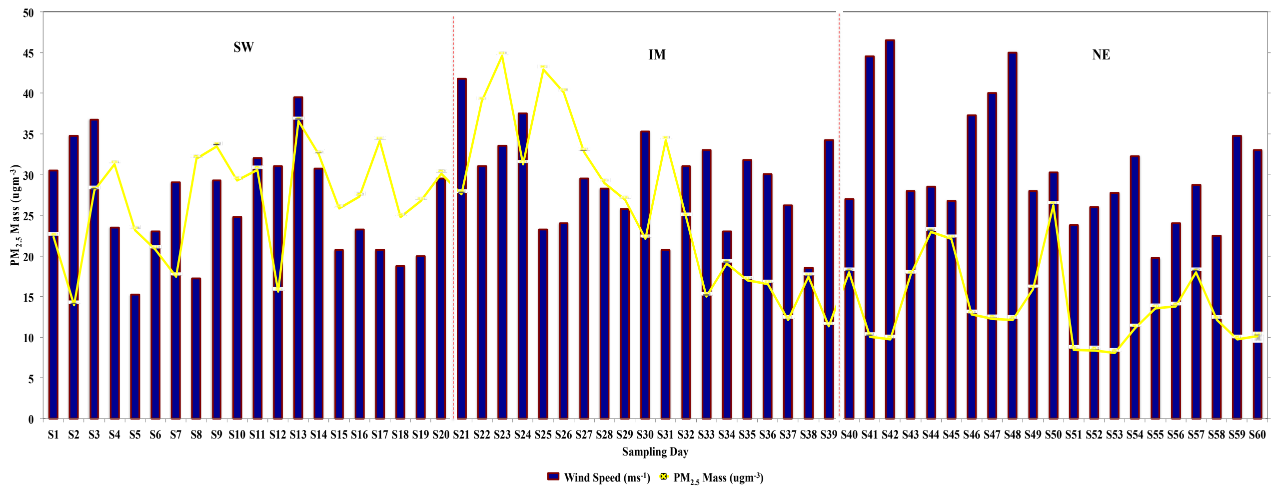

Fig. 3(c). Diurnal distribution of $PM_{2.5}$ mass concentrations (µg m^{-3}) and wind speed (m s^{-1}).

probably due to the lesser amount of primary particles being emitted into the ambient air. However, as reported by Canepari *et al.* (2014), despite the pollutant sources, the level of PM concentration is almost stagnant in a region due to the meteorological factors enhancing the mixing of the lower atmosphere. Subsequently, during rainfall or the wet season, the stagnant condition reduces the efficiency of atmospheric dilution as the mixing height is much lower than the dry season. Rainfall occurrence during the study period resulted in a slight increase in precipitation intensity, which acts as a mechanism of washing out pollutants from the ambient air. This is due to the inhibition process that will eventually decrease the pollution level, as well as limiting the performance of particle precipitation from regional sources, as rain is essential in scavenging pollutants. In addition, due to the geographical location and maritime exposure of the southern region in Peninsular Malaysia too, the climate has uniform temperature and pressure, high humidity and abundant rainfall.

Meanwhile in Fig. 3(b), the average temperatures are 26.42°C, 26.28°C, and 25.39°C for the SW, IM and NE, respectively. From the figure, as the monthly temperature decreased, the monthly particle mass concentration and the daily $PM_{2.5}$ mass concentration decreased as well. The hourly distribution patterns of the particulate mass concentration indicated a decreasing trend throughout most days, especially towards later in the day, approximately around 14:00 until 16:00. A previous study revealed that the $PM_{2.5}$ mass concentration reduces as the temperature increases throughout the day (Wu *et al.*, 2013). This is because the intense radiation from maximum temperature heats the underlying surface of the area, resulting the turbulence to strengthen, hence the unstable lower atmosphere. The increasing diffusion rate of the $PM_{2.5}$ consequently results in the decreasing number of pollutants in the atmosphere. Due to the volatilization at a higher temperature, the $PM_{2.5}$ concentration is inversely proportional with the temperature (Dawson *et al.*, 2007). The low values of PM concentration towards the evening were probably due to the reduced emission strength and the enhanced mixing of the lower atmosphere. On the other hand, from Fig. 3(b), the mean value of relative humidity for the SW, IM and NE are 85.42%, 87.98% and 89.95%, respectively. It is clearly seen that there are upward spikes of temperature on Day S3, S11, S21, S30, S46, S50 and S56 which indicate downward spikes of relative humidity, and vice versa for Day S5, S10, S12, S15, S31, S44, S49, S51 and S60. The graph proved that there is a strong positive correlation between ambient relative humidity and temperature. However, the fluctuation of average relative humidity has a slight impact on $PM_{2.5}$ mass. The particle hygroscopic growth and condensation in a high-relative humidity atmosphere will subsequently increase the mass concentration of PM (Martuzevicius *et al.*, 2004). This information in Fig. 3(b) can be correlated with the observations found in Fig. 3(a) which show that the $PM_{2.5}$ mass was normally high in the morning (07:00–08:00) throughout the study period. High relative humidity in the morning has a positive correlation with the values of $PM_{2.5}$ mass. The increasing values of relative humidity, as well as other current conditions such as low temperature in the morning, together with low wind speed too, have the capability to enhance the formation of lower planetary boundary layer heights, thus reducing the $PM_{2.5}$ dispersion activity (Deshmukh *et al.*, 2012), hence causing the pollutants to accumulate within the area (Gao *et al.*, 2015; Wang *et al.*, 2015). The relative humidity factor has the capability to form and favor the growth of airborne particles in the atmosphere, which enhances the local pollutant emission. Relative humidity depresses the gas-phase organic particle absorption into the particle surface, which consequently accelerates particle removal via the dry deposition process (Shi *et al.*, 2012). On top of that, the vehicle emissions in the morning probably contributed to the increasing mass concentration of this pollutant, due to the influence of the primary emissions on campus, as well as in the nearby residential areas, which in turn increases the production of secondary particles. The maximum value of PM concentration at 07:00 was associated with the anthropogenic activity of morning transportation rush hours around the region. The high levels of $PM_{2.5}$ mass concentrations were observed during the evening rush hours (17:00). On the other hand, the particulate emission was seen to increase intermittently during nighttime (21:00–22:00). This is because, during the night, the production of the particulate matter accumulates and the emission for heating is enhanced. Consequently, the nocturnal phenomena was observed due to the relatively low and stable boundary layer development, as well as the low capacity of atmospheric transport and dispersion performance. During this time, the prevalent unstable atmosphere favored the dispersion of pollutant emission over a mixed atmospheric air. Nevertheless, the level of $PM_{2.5}$ mass concentrations was not only affected by the condition of meteorological factors, but also by the emissions of the local anthropogenic activities at the study area.

From Fig. 3(c), the average wind speed readings for the SW, IM and NE are 1.076 m s^{-1}, 1.089 m s^{-1} and 1.09 m s^{-1}, respectively. Based on the figure, it is seen that the $PM_{2.5}$ mass concentrations are negatively influenced by the wind speed, because as the magnitude of the wind speed increased throughout the months, the level of particle mass concentration reduced significantly. Hence, the low levels of PM concentration during the northeast monsoon season in January. This strong wind condition indicated a clearer visibility of the atmosphere as the emission strength is reduced. A similar study done by Dawson *et al.* (2007) shows that the reduced amount of $PM_{2.5}$ emission is partly due to the increasing wind speed. This is because, strong convection due to strong winds has the capability to ventilate the daily boundary layer height (Lelieveld *et al.*, 2001). On the other hand, the readings of the wind speed during the southwest monsoon seemed to be at a higher magnitude level, causing the reduction of the dispersion processes of the particulates thus, inducing the increase of $PM_{2.5}$ mass concentration values.

Meanwhile, Fig. 4 shows the wind rose (°) which plots the wind direction throughout the SW, IM and NE. Wind rose is plotted in order to identify the effect of the wind parameters, hence determining the general direction and the source origin of the pollutant emission for each season. The figure indicates that the major source of emission is located at 0–20° from the sampling site for the whole monsoon. Although the main source of emission is constantly located at the same range of degrees for each season, the wind speed among the SW, IM and NE are of the different ranges of magnitude. The winds from these said locations are characterized by very low magnitudes which are in the range of 0.61–1.58 m s^{-1}, 0.74–1.67 m s^{-1} and 0.79–1.86 m s^{-1} for the SW, IM and NE, respectively. The emissions were mostly originated from the northeast direction, and were probably influenced by nearby industrial emissions and local anthropogenic activities transported from industrial areas of Johor Technology Park, Senai Technology Park and road activities from Skudai Highway. The high wind speed enhances the pollutant dilution, thus reducing the level of secondary PM formation.

Statistical Results between $PM_{2.5}$ Mass Concentration and Meteorological Parameters

Table 1 tabulates the statistical results of the Pearson correlations of the $PM_{2.5}$ mass concentration and the meteorological factors, characterized by the different monsoon seasons. The meteorological parameters involved are relative humidity, ambient temperature, rain volume and wind speed. Throughout the monsoon seasons, some meteorological variables indicate positive correlation coefficients (r), such as ambient temperature with a correlation range of $r = 0.425$–0.541, while the rest (relative humidity and wind speed variations) with a range of $r = -0.472$ to –0.271 and $r = -0.23$ to –0.0127, respectively, display negative relationships with $PM_{2.5}$ mass concentration.

The negative correlations between wind speed and $PM_{2.5}$ mass concentration suggest that wind speed is a good indicator for pollutant distribution. The highest correlation coefficient was observed during the southwest monsoon season while the lowest correlation coefficient is seen in the inter-monsoon season. Nevertheless, during all monsoon seasons, there is no significant correlation between rain volume and other meteorological variables, as well as particle mass concentrations. The correlation patterns during the southwest, inter-monsoon and southwest monsoons are predominantly similar. With this analysis, it is clearly observed that wind speed and relative humidity are essential in influencing the $PM_{2.5}$ mass level in ambient atmospheres.

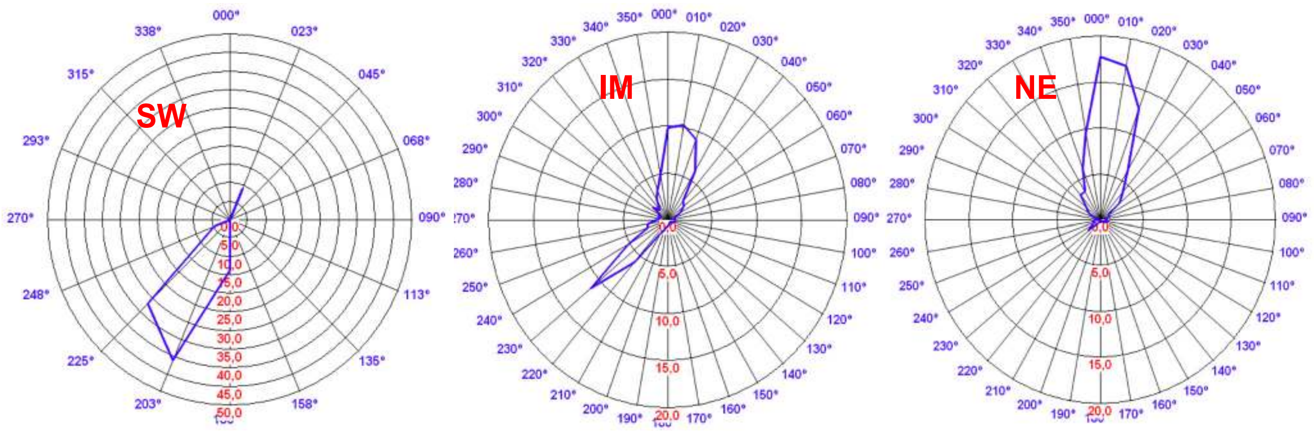

Fig. 4. Wind rose (°) of $PM_{2.5}$ pollutants for the SW, IM and NE.

Table 1. Statistical result of Pearson correlations between seasonal $PM_{2.5}$ mass and meteorological variables.

VARIABLES	$PM_{2.5}$	Temperature	Relative Humidity	Wind Speed	Rain Volume
*SW**					
$PM_{2.5}$	1				
TEMPERATURE	0.4725	1			
RELATIVE HUMIDITY	–0.2916	–0.902	1		
WIND SPEED	–0.0127	0.48	–0.721	1	
RAIN VOLUME	0.078	0.105	0.098	–0.044	1
*IM**					
$PM_{2.5}$	1				
TEMPERATURE	0.541	1			
RELATIVE HUMIDITY	–0.472	–0.971	1		
WIND SPEED	–0.052	0.689	–0.746	1	
RAIN VOLUME	–0.448	–0.390	0.345	–0.049	1
*NE**					
$PM_{2.5}$	1				
TEMPERATURE	0.425	1			
RELATIVE HUMIDITY	–0.271	–0.877	1		
WIND SPEED	–0.230	0.462	–0.579	1	
RAIN VOLUME	–0.104	–0.485	0.417	–0.225	1

* Correlation is significant at 0.05 level ($p < 0.05$).

Implications of Study

In this globalization era, metropolitan city of Johor Bahru is competing to become economical. Major economic activities are normally concentrated within the existing city boundaries. However, once the city is packed with the human population, transportations, buildings and traffic activities, the urban sprawl trend is implemented to introduce the new developments in the suburban areas. Due to the lower living cost in the suburban area of Skudai and expensive housing prices in Johor Bahru city center, more population decides to reside in this peripheral area rather than in the city. Therefore, this occurrence enhances the socio-economics gaps between these two areas. In addition, the development of transportation system is basically due to the urban sprawl activities. The trip distance that increases tremendously suggests the needs to promote sustainable transportation. A previous study reported that the urban sprawl leads to the increase of long-distance travel demand and vehicle miles travelled (Camagni *et al.*, 2002). Therefore, this issue would aggravate the pollution of local ambient air.

Hence, a stronger development management measure needs to be enforced. Although many advanced innovations of fuel technologies in reducing vehicle emissions and fuel usage had been introduced, the increasing number of car ownerships counterbalances these inventions. Thus, more effective policy and regulatory measures need to be suggested and introduced in order to minimize the transport environmental effects. These could include limiting the source emission, changing modes of the transportations and proposing a stricter air quality standard, as well as planning the land use.

Additionally, this research may accurately conclude the air quality problems of Skudai once a more comprehensive study over an extended period of time is conducted. Since the $PM_{2.5}$ mass concentration was measured at only one site of Johor Bahru, the findings obtained from this study may have some limitations that a future study can resume. A similar intensive research may be conducted within a larger network of SEA region (where the estimated error degree can be minimized) as well as generating a more intensive study of the chemical characterization of $PM_{2.5}$ pollutants. However, this research does give insights about future implications of the developing suburban area of mixed commercial-industrial-residential airshed.

CONCLUSIONS

Because the study site was located in a non-busy city, most of the observed days were clear. However, the $PM_{2.5}$ mass concentration, which varied according to meteorological conditions, exceeded the permissible limit on some days, ranging from 8.06 to 44.6 µg m^{-3} during the monsoon seasons. The variation in the $PM_{2.5}$ mass ranged between 0.53 and 0.90 times of the PM_{10} mass. The PM_{10} mass concentration was only slightly higher than that of the $PM_{2.5}$, exhibiting a maximum 24 h value of 49.44 μgm^{-3}.

The $PM_{2.5}$ mass concentration was significantly affected by the temperature ($p > 0.05$), which averaged between 25.39°C and 26.42°C during the monsoon seasons, and exhibited a strong positive correlation ($r = 0.425$–0.541) with it. However, the mass concentration displayed a negative correlation with the wind speed ($r = -0.23$ to -0.0127), with high wind speed co-occurring with low concentrations due to dispersion in the atmosphere via mechanical and thermal turbulence.

In conclusion, the $PM_{2.5}$ mass concentrations at the study site are affected by meteorological conditions as well as local anthropogenic activities. The direction of the wind (0–20°) at this location during the SW, IM and NE suggests that the primary sources of $PM_{2.5}$ lie to the northeast, where they are influenced by anthropogenic activities and high traffic. The results of the Pearson correlation analysis indicate that temperature, wind speed and relative humidity are the dominant factors affecting the mass concentration.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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