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Research article

2019 Southeast Asia Transboundary Haze and its Influence on Particulate Matter Variations: A Case Study in Kota Kinabalu, Sabah

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Abstract: In 2019, Malaysia faced a deterioration of air quality due to transboundary haze, which brought negative implications, especially for public health. In light of the above scenario, continuous particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) and meteorological parameters amid the haze period were taken to unravel the influence of haze on particulate matter variations and to investigate the association between particulate matter concentrations with meteorological parameters and fire hotspots in Kota Kinabalu, where it is rarely studied. Particulate matter and the meteorological parameters were monitored during the haze season, continuously from 21 August–30 September 2019, using AirMate, a ground-based air monitoring equipment. Air mass backward trajectories were simulated using the HYSPLIT Model, and fire hotspot data was obtained from the Greenpeace Global Fire Dashboard. The results showed increasing particulate matter concentrations during the haze period, with $PM_{2.5}$ exceeding the New Ambient Air Quality Standards (2020) on multiple days. For meteorological parameters, all parameters showed a significant weak positive relationship with respective particulate matter. However, the correlation between particulate matter and fire hotspots in Indonesia showed a moderate positive relationship. The backward trajectories simulated indicated the influence of south-westerly winds in transporting the pollutants from fire hotspots in the Indonesia region. Thus, we provide beneficial information about the impacted area during the 2019 transboundary haze episode, where the interactions between the particulate matter variations and the parameters studied were unraveled.

Keywords: transboundary haze; particulate matter; meteorology; transport air mass; air quality

1. Introduction

The Southeast Asia region is always subjected to transboundary haze occurrences, which deteriorates the regional air quality hence negatively impacting the citizens' quality of life. Haze pollution is a major environmental problem due to its implications for humans and the environment. It is defined as the increased load of atmospheric aerosol which causes the deterioration of atmospheric visibility [1]. It is also often linked with high particulate matter concentrations in the atmosphere that reduce horizontal visibility (<10km), resulting in opalescent weather [2,3]. Particulate matter consists of very small solid and liquid particles suspended in air, with varying sizes and compositions [4]. Typically, it is categorized by its sizes such as: coarse particles PM_{10} (with aerodynamic diameter <10 μm), fine particles $PM_{2.5}$ (aerodynamic diameter <2.5μm) and fine particles PM_1 (with an aerodynamic diameter <1μm) [5].

Haze in Malaysia is not a new phenomenon as it has been formally recorded since late 1982 [6]. Severe episodes of haze afterward, include 1997, 2005 and 2015 episodes, during the drier months [7]. The episode in 1997 involves Sarawak being affected the worst, with Sarawak's Air Pollution Index (API) reaching above 500 [8]. In the year 2005, which was claimed to be the worst haze episode post 1997, it badly impacted Peninsular Malaysia, and Haze Emergency was declared in Port Klang and Kuala Selangor as their API exceeded 500 [8,9]. In 2015, the strongest and worst episode in Malaysia's history was recorded which lasted nearly two months, as 34 areas were recorded at an unhealthy air quality status [7,8]. Previous studies have linked that during any haze period, particulate matter concentrations in the area will be elevated [10,11].

The main source of the transboundary haze is usually associated with biomass burning actions for economic and land use changes purposes in Indonesia, usually from peatland fires [12,13]. The smoke haze was further spread to neighboring countries in the Southeast Asia region, including Malaysia, which was transported by the south-westerly winds [3,14]. Haze's intensity is also exacerbated by certain weather and climate conditions, particularly dry weather and the occurrence of El Nino, conditions, especially strong ones [15]. El Nino is an inter-annual phenomenon that could be defined as an unusual increase in temperature at the ocean surface [16]. The event is frequently associated with the intensification of wildfire occurrences as it brings drier weather and causes prolonged drought [17]. For instance, the super strong El Nino event is considered to be the precursor for the 2015 transboundary haze in Malaysia that lasted nearly two months [10].

The seasonal haze dangerously contributed to public health implications and visibility problems and influenced ecosystem and agricultural production [17]. This includes adverse effects on respiratory health and asthma exacerbation [18]. A study by Othman et al. [19] in the Kuala Lumpur area found that smoke haze events are associated with an increase in inpatient cases annually, with a 31 percent increase compared to normal days, and lead to average annual economic loss at RM273,000. Smaller PMs ($PM_{2.5}$ and PM_1) were found to pose more harm to human health compared to PM_{10} [20]. The smaller the size of particulate matter, the more harmful it is to health, especially leading to greater short-term health complications as proven by previous literature, which focus on the risks PM_1 poses to public health [21–23]. Hence, due to the dangers of PM to public health, it is important to assess its concentrations not limited to PM_{10} amid the haze period where PM concentrations will elevate.

Malaysia experienced deterioration in air quality in 2019 when episodes of transboundary haze occurred from July to September, which was associated with the biomass burning in Indonesia. Hence, we attempt to focus on the particulate matter variations with respect to the occurrence of transboundary haze in 2019. We also explore the association of the particulate matter with meteorological parameters and fire hotspot occurrence within the same period.

2. Materials and methods

2.1. Study site

Kota Kinabalu is an urban area that accounts for the busiest area and capital city of Sabah, Malaysia [24]. The climate in Kota Kinabalu is hot and humid, influenced by the circulation of monsoons, namely Northeast Monsoon and Southwest Monsoon [25]. Kota Kinabalu experiences uniformly high and consistent temperatures and high humidity [26]. The location is topographically homogeneous, and it is located on a narrow flatland between the Crocker Range to the east and the west is the South China Sea [24]. Typically, the Kota Kinabalu industry is inactive, and most particulate matter emissions are associated with traffic exhaust [27,28]. Universiti Malaysia Sabah is the representative location for Kota Kinabalu as shown in Figure 1, which was impacted by the 2019 transboundary haze.

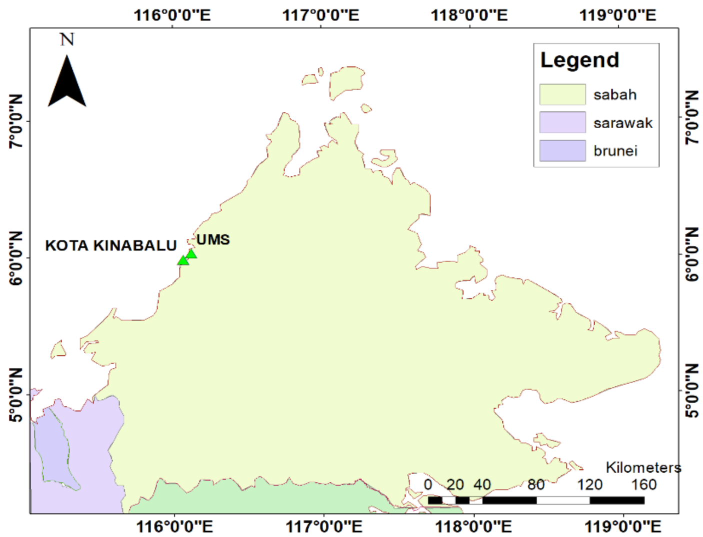


Figure 1. Study Area.

2.2. Ground-based sampling (PM and meteorological parameters)

Measurements of particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) alongside meteorological parameters (temperature, humidity and pressure) were measured using AirMate, which is an integrated real-time particulate matter measuring instrument for air quality monitoring. Its system applies the laser scaterry technique, where the systems can simultaneously measure PM concentrations at varying sizes. This equipment has a built-in data logging system that enables continuous remote monitoring. The added feedback mechanisms will notify users when certain particulate matter concentrations exceed the threshold. The measurements were done continuously from 21 August to 31 September 2019 in UMS ground amid the haze to assess the influence of haze with the variations of particulate matter. The sampling point was ~4m above ground to study atmospheric air quality with minimal interference from nearby sources [29].

2.3. Data analysis

The measured data (PM and meteorological parameters) was statistically analyzed using the Analysis Toolpak in Excel. The measured data include daily averaged and minute averaged data within the study period. Descriptive statistics where mean, maximum, minimum, standard deviation and variance for daily data of particulate matter were calculated. In addition, the Pearson correlation test was employed between particulate matter and meteorological conditions, utilizing minute averaged data, to find the relationship and the strength at a 5% level of significance between the two. The interpretation of the correlation coefficient, r, includes a weak relationship (0–0.3), a moderate relationship (0.3–0.7) and a strong relationship (0.7–1.0) [30]. Daily data of PM were plotted into a time-series graph in Excel.

2.4. Air mass trajectory and fire counts

Air mass backward trajectories were simulated using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (https://www.ready.noaa.gov/HYSPLIT.php). The model was developed by NOAA, a powerful, versatile and practical tool for computing the trajectory, complete dispersion, and concentration of pollutants from a point source, line or area [31]. Specifically, in this study, the model was run backward at 120h (5 days), with several altitudes chosen (1500m,1000m and 500m) at selected dates, to observe the long-range transport of pollutants.

Daily fire hotspot data from over Indonesia within the study period were obtained from the Greenpeace Global Fire Dashboard (https://maps.greenpeace.org/fire_dashboard/). The global map provides high spatial resolution (1km) and high temporal resolution (12 hours), provided by MODIS sensors. The daily fire hotspots were further correlated with the daily particulate matter obtained to study the influence of fires on the variations of particulate matter.

3. Results and discussion

3.1. Particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) temporal variations

Particulate matter was measured through a ground-based method. Table 1 shows the descriptive statistics of particulate matter in the air on a 24-h average. The average concentration for PM_{10} is 32, with a maximum of 91.60 and a minimum of 3.13. $PM_{2.5}$ recorded a mean of 28.01, with a maximum of 85.82 and a minimum of 2.78. Next, PM_1 recorded 11.55, 17.88 mean, 50.48 maximum and 2.16 minimum. Amongst the PM, PM_{10} recorded the highest daily mean value overall. As showcased in Figure 2, PM_{10}, $PM_{2.5}$ and PM_1 have similar trends, with PM_1 having the highest values. Major peaks can be seen in September. All PM showcased peaks specifically on 7–8 September, 11–12 September, 14–16 September, 21–22 September and plummets on 23-September.

In comparison with the New Malaysia Ambient Air Quality Standards 2020 [32], PM_{10} does not exceed the standard (100 µg/m3), while $PM_{2.5}$ exceeded the standard (35 µg/m^3) on multiple dates, specifically between 7- September–23- September. $PM_{2.5}$ have small diameters yet large surface areas and can carry various toxic substances through nose hair filtration, reaching the end of the respiratory tract with airflow and accumulating by diffusion, further damaging other body parts through air exchange in the lungs [33]. Hence, the exceedance of $PM_{2.5}$ is concerning as previous literature reported the adverse human health implications of smaller particulate matter, namely $PM_{2.5}$ [34,35].

As shown in Figure 2, the elevations of particulate matter through the high peaks in mid-September align with the transboundary haze episode associated with biomass burning in Kalimantan and Sumatra [36]. Haze resulting from biomass burning is usually associated with elevated PM levels in the SEA region [37]. Thus, the increment of $PM_{2.5}$ amid the haze period implies the influence of biomass burning as peatland fire or biomass burning usually showed higher $PM_{2.5}$ concentrations [38,39].

Table 1. Descriptive statistics of particulate matter concentrations in Kota Kinabalu, Sabah amid haze episode

Particulate Matter	Minimum	Maximum	Mean	Std. Deviation	Variance
PM_{10}	3.13	91.60	32.00	23.38	546.53
$PM_{2.5}$	2.78	85.82	28.01	20.19	407.58
PM_1	2.16	50.48	17.88	11.55	133.40

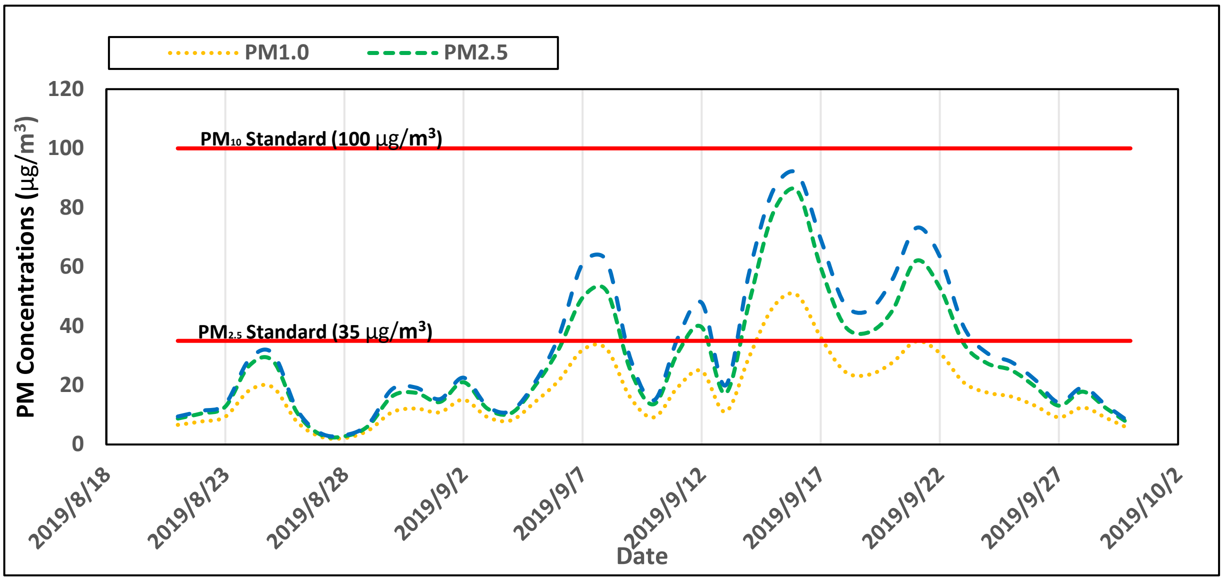


Figure 2. Temporal variations of particulate matter (24-h average) in Kota Kinabalu, Sabah amid haze episode.

3.2. Correlation of particulate matter with meteorological conditions

The relationship of PM variations with meteorological parameters (temperature, humidity and pressure) was studied to understand the influence of meteorological conditions with the PM variations, as shown in Table 2. Meteorological parameters do affect PM concentrations in the air through their complex interactions, such as diffusion, dilution and deposition and accumulation [4,40]. Hence, minute-averaged PM variations alongside minute-averaged meteorological factors were correlated. The results in Table 2 show that all correlation was very significant, with a weak positive relationship. PM_1 has the highest correlation coefficient (r = 0.1) with temperature. Thus, the positive relationship might be due to dust deposition and secondary formations [41]. PM_{10} has the highest correlation with pressure (0.066). This postulates that pressure induces particulate accumulation in the air as it adds weight to the particulates [42]. PM_1 has the highest correlation with humidity (0.134). Humidity is associated with reducing the diffusion of particulate matter as it causes the particulates to become moist and add weight to the particle [43]. This significant relationship signifies that the meteorological parameters studied influenced the PM variations; however, the weak relationship indicates that there are other important determinant factors that impact the PM variations, such as other meteorological parameters that are not being studied in this paper.

Table 2. The correlation coefficients (r) and *P*-values of meteorological parameters and fire counts with each particulate matter

Particulate Matter	Temperature		Pressure		Humidity		Fire Hotspots	
	r	*P*-value	r	*P*-value	r	*P*-value	r	*P*-value
PM_{10}	0.068	<0.001	0.066	<0.001	0.124	<0.001	0.486	0.006
$PM_{2.5}$	0.074	<0.001	0.054	<0.001	0.127	<0.001	0.460	0.003
PM_1	0.100	<0.001	0.054	<0.001	0.134	<0.001	0.456	0.003

3.3. Correlation of particulate matter with meteorological conditions

A total of 120-h air mass backward trajectories were simulated on selected dates amid the study period, as shown in Figure 4. Simulated backward trajectories indicated the influence of both south-westerly and north-easterly winds. South-westerly winds were detected in the early period of study, whereas the PM concentrations were founded high, the south-westerly winds transported the transboundary haze towards Kota Kinabalu as the south-westerly winds passed through the fire hotspots from Indonesia. As the concentration of PM decreases on 24th September, the backward trajectory showcases the north-easterly wind pattern until the end of the study period. The north-easterly wind patterns explained the reduction of PM concentrations as it did not pass through the fire hotspots in Indonesia and brought transboundary haze to Kota Kinabalu.

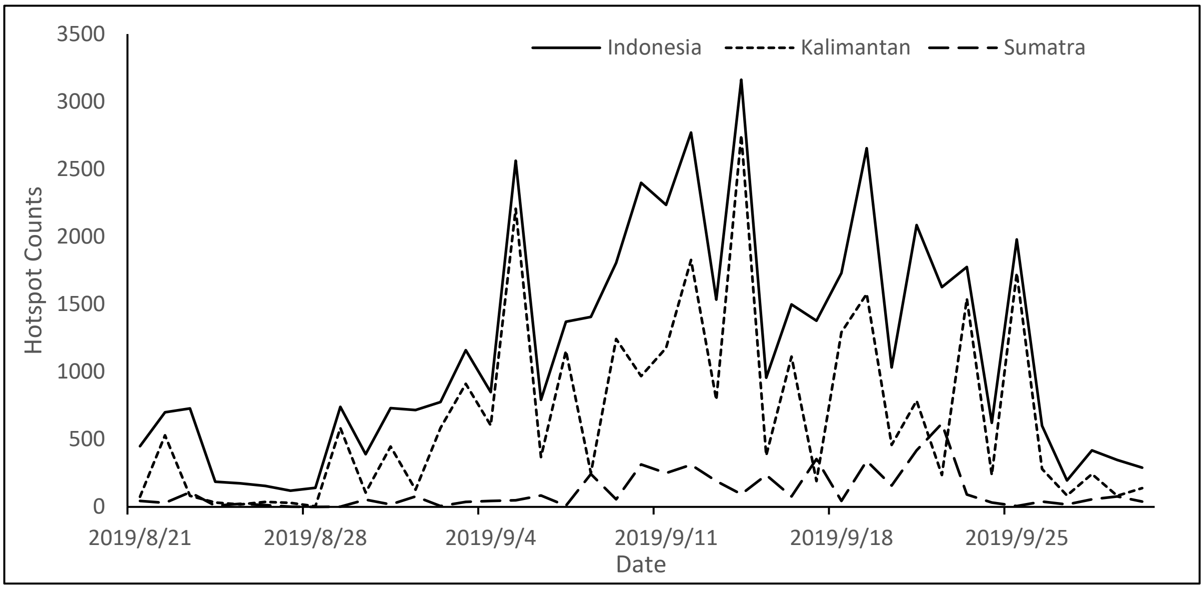
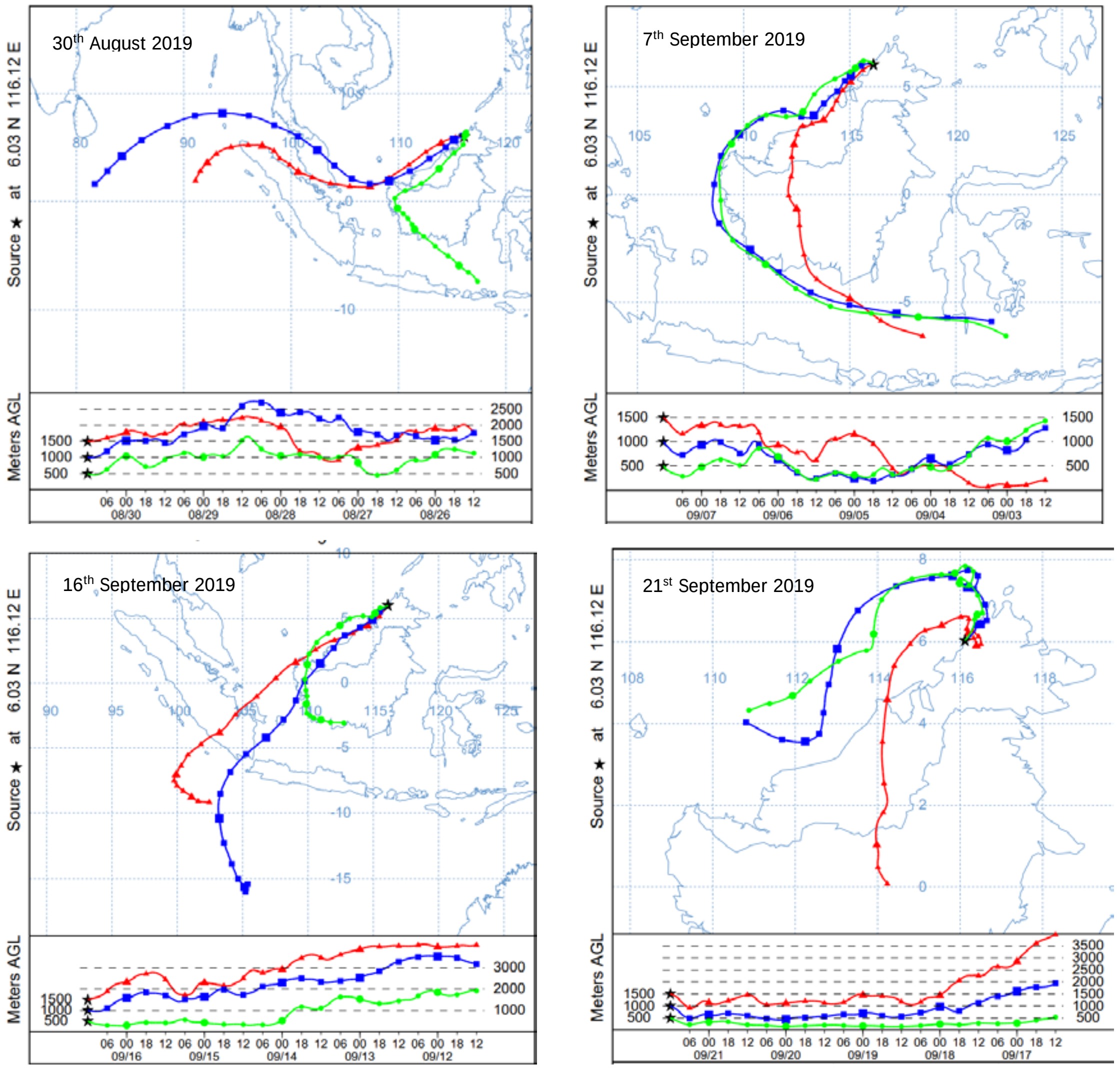


Figure 3. Fire counts from Indonesia.



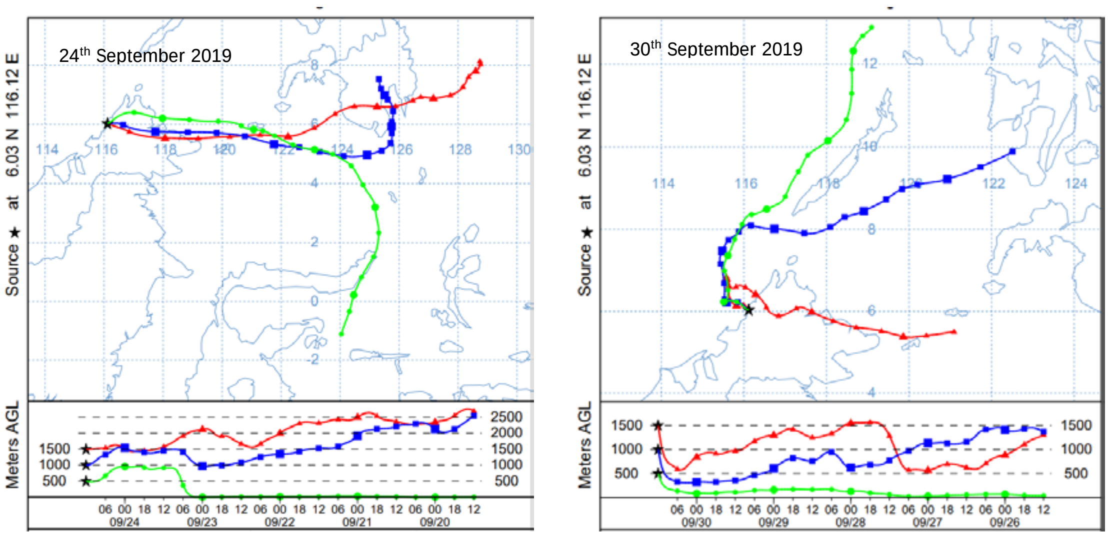


Figure 4. Air mass backward trajectories.

Indonesia is known for biomass-burning activities, which is the primary source of transboundary haze to the Borneo region [7,44]. The fire hotspots in Indonesia during the study period were observed, as shown in Figure 3. The fire hotspots showed great intensity from early September, with Kalimantan having higher numbers of fire hotspots than Sumatra. Although the number of fire hotspots elevated by 25th September, it did not impact Kota Kinabalu, as indicated by the decreasing amount of particulate matter due to north-easterly wind, as showcased in Figure 4. As shown in Table 2, a significant moderate positive relationship was obtained between the fire hotspots and respective particulate matter, which postulates its influence.

4. Conclusions

Elevations of particulate matter were seen during the transboundary haze period, specifically in early to middle September 2019. Although PM_{10} is the highest particulate matter, $PM_{2.5}$ exceeded the New Malaysia Ambient Air Quality Standards 2020, which is concerning for public health. Meteorological parameters (temperature, pressure and humidity) showed a significant weak positive relationship with respective particulate matter. The relationship postulates that the meteorological parameter studied has a small influence, and other important factors might need to be studied. Thus, future recommendations include studying more meteorological parameters, including wind, which is not studied in this paper. Biomass burning from Indonesia is associated with transboundary haze in the neighboring country. Air mass backward trajectory simulations indicated the influence of both south-westerly and north-easterly winds in the PM variations. The increment of PM is associated with the south-westerly winds that transported the pollutants from the Indonesia region. The PM decrease by 24th September is associated with the north-easterly winds that did not pass through the Indonesia region with fire hotspots. The relationship between particulate matter and the fire hotspots in Indonesia within the study period also showed a moderate positive relationship, indicating its influence on the variations of PM. Consequently, this finding is essential in understanding the varying sizes of particulate matter variations amid the haze period and the potential factors that might influence its variations. The findings are also crucial in informing local and international policymakers to provide strategic meaning to protect public health amid the regularly occurring haze.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare that they have no conflict of interest.

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