

SPATIAL AND SEASONAL VARIATIONS IN PARTICULATE MATTER (PM_{2.5} AND PM₁₀) AND METEOROLOGICAL PARAMETERS IN SARAWAK, THE NORTHWEST OF BORNEO ISLAND: A COMPREHENSIVE ANALYSIS FROM 2017 TO 2021

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Abstract: The study assessed pollutants during distinct monsoonal seasons and examined PM₁₀ and PM_{2.5} concentrations for the period of five years, from 2017-2021 at the tropical island of Borneo. The air pollutant concentrations and surface meteorological data was obtained from the Department of Environment (DOE) and the Natural Resources and Environment Board (NREB), Malaysia. Analyses such as Analysis of Variance (ANOVA), Pearson correlation analysis, and Kernel Density (KD) estimation were employed to explore the characteristics of the air pollutants. During the Southwest Monsoon (June-August) and Inter-monsoon 2 (September-November), elevated PM₁₀ and PM_{2.5} concentrations were detected. Northeast Monsoon (NEM), Inter-monsoon 1 (Inter1), Southwest Monsoon (SWM), and Inter-monsoon 2 (Inter2) had the highest mean PM₁₀ values and the mean PM_{2.5} readings also followed a similar pattern. Some PM_{2.5} levels were marginally over standard during SWM and Inter2, although they stayed within other stipulated limits. Sri Aman and Lawas had the highest and lowest PM_{2.5} values, respectively. The highest pollution concentrations were likely attributable to biomass burning and other sources in 2019. The study also looked at meteorological characteristics and discovered strong links between hotspots and pollution in Borneo.

Keywords: Monsoonal season, correlation analysis, hotspot, transboundary haze.

Introduction

For the past three decades, transboundary haze has been an annual problem almost every year in the Southeast Asia (SEA) affecting Singapore, Malaysia, Indonesia, Brunei Darussalam, and the Southern Thailand (Dotse *et al.*, 2016). Smoke haze episodes were recorded in April 1983, August 1990, June 1991, October 1991, August 1994 (Othman *et al.*, 2014) and the worst was in 1997, where Forsyth (2014) reported that cities such as Kuala Lumpur, Singapore, some parts of Bangkok, Brunei, and Jakarta were affected for a few weeks. Following that, haze episodes continued to be reported in 2005, 2006, (Othman *et al.*, 2014) and in 2015, it lasted for about two months (Latif *et al.*, 2018; Samsuddin *et al.*, 2018).

The occurrence of haze is usually attributed to the El-Nino-Southern Oscillation (ENSO), which is often associated with prolonged

drought and intensified forest fires (Quah, 2002). Interactions between ENSO and other weather phenomena including the Indian Ocean Dipole (IOD) and the Madden-Julian Oscillation (MJO) were found to delay the monsoons contributing to exacerbated haze and fire (Van Der Werf *et al.*, 2008; Ser *et al.*, 2016; Islam *et al.*, 2018). With the northerly winds in June-October, gaseous emissions and particulate matter produced during this burning season is carried across the SEA countries especially Indonesia, Brunei, Malaysia, Singapore, and Thailand (Othman *et al.*, 2014; Ser *et al.*, 2016).

Particulate matter with a diameter ≤ 2.5 μm (PM_{2.5}) is the main particles found in haze and the most lethal one. Approximately 94% particles in the haze were below 2.5 μm in diameter and therefore can easily bypass the body's defences (Ramadhan *et al.*, 2017; Latif *et al.*

al., 2018). The $PM_{2.5}$ has been identified as one of the major carcinogens by the International Agency for Research on Cancer and the World Health Organization (Cao *et al.*, 2018). The most common man-made sources of $PM_{2.5}$ include motor combustion, power plant combustion, industrial processes, domestic burning, fireworks, and smoking (Seidel & Birnbaum, 2015; Loffredo *et al.*, 2016; Environmental Protection Agency, 2020). The adverse effects of $PM_{2.5}$ can reach intercontinental scales (Anenberg *et al.*, 2014; Khan *et al.*, 2016) as the particles can travel through atmospheric circulation contributing to haze and pollution (Du *et al.*, 2019; Halkos & Tsilika, 2019; Zhang *et al.*, 2020).

Meteorological factors, physical, and chemical interactions play a profound role in affecting the dispersion of suspended particles and their composition during transportation (Dotse *et al.*, 2016; Khan *et al.*, 2016a; Latif *et al.*, 2018). As reported by Guttikunda and Gurjar (2012), the air quality in Delhi was more polluted during winter than summer. Ramsey *et al.* (2014) on the other hand revealed that an increase in temperature and decrease in precipitation over summer could cause the increment of ozone concentrations in Oklahoma city.

The authors also reported that as the wind speed increased, the concentration of ozone reduced as a result of the dilution factor. The local-scale meteorological specifically temperature was found to have a significant influence on ozone concentrations in Melbourne (Pearce *et al.*, 2011). Vogel *et al.* (2009) reported on the aerosol radiative force during cloudy conditions. The absorption of solar and infrared radiation by dust aerosol changed the stability of the atmosphere consequently influenced cloud formation (Vogel *et al.*, 2009; Han *et al.*, 2012). Despite numerous studies on the relationships between the air pollutants and meteorological parameters, the transport of haze in Borneo is not well studied. The latest study in Borneo was carried out by Khan *et al.* (2020), where the wind field and trajectory analysis concluded that the haze in Southern Peninsular and Borneo was

caused by wildfire and peat fire from Indonesia.

Recently, researchers employed advance statistical analysis in their studies to explore the characteristics of air pollutants and relationships with the local meteorological parameters. Rahman *et al.* (2022) employed Pearson Correlation Coefficient to determine the strength and direction of the linear relationship between $PM_{2.5}$ concentrations and meteorological factors. The correlation coefficients helped in interpreting how changes in one variable such as PM_{10} or CO are associated with changes in $PM_{2.5}$ levels. This information is crucial for understanding the sources and dynamics of air pollution and this adds robustness to the findings.

On the other hand, Wang *et al.* (2019) employed utilised non-parametric Kernel Density Estimation (KDE) to explore the distribution characteristics and dynamic evolution of urbanisation and air quality, where this approach allowed for a more understanding of the relationship over time, moving beyond static panel or time series analyses. KDE is widely used in various fields, including economics, biology, and environmental science, for tasks such as visualising data distributions, identifying modes (peaks) in the data, and analysing the relationships between variables (Wang *et al.*, 2019).

Study on the relationships between the meteorological parameters and the transportation of haze would help to better understand the movement of pollutants and their impact on pollution planning (Guttikunda & Gurjar, 2012). This will shorten the response time taken during haze crisis, cutting down the cost and impact. Latif *et al.* (2018) emphasised the forecasting ability so that the potentially areas affected by haze can be earmarked for early warnings. By understanding the directional source of haze affecting Borneo, it will allow the government in Malaysia and Indonesia to have more targeted and improved local fire prevention strategy. Hence, this study reports the spatial and seasonal variations particulate matters and meteorological characteristics in Sarawak between 2017 and

2021. Particulate matter includes both primary particles such as soot and dust from combustion sources and agricultural practices and secondary particles such as sulphate and nitrate that form through chemical reactions in the atmosphere from sulphur dioxide, nitrogen oxide, and ammonia emitted from power plants, industries, automobiles, and agriculture. On the other hand, meteorological characteristics refer to local surface-level conditions, including datasets such as Relative Humidity (RH), Ambient Temperature (AT), Wind Speed (WS), Wind Direction (WD), and pressure. The findings would benefit international collaborations such as ASEAN and Sosial Ekonomi Malaysia Indonesia (Sosek-Malindo) to develop more effective inter-governmental policies on issues such as the formulation of biomass disposal and emission control policies to prevent transboundary haze in the future.

Materials and Methods

Data Collection

The air pollutant concentrations and surface were obtained from the Department of Environment (DOE) and the Natural Resources and Environment Board (NREB), Malaysia for the duration of 5 years from 2021 to 2024. The data originated from 12 Air Quality Monitoring Station (AQMS) operated by the DOE and four from NREB as shown in Figure 1. The AQMS was located at urban, sub-urban, and industrial areas throughout the main towns in Sarawak. For the sites along the Sarawak-Kalimantan border in Lundu, Tebedu, Lubok Antu, and Lawas, the AQMS is maintained and operated by NREB. The location, description of each site, and data parameters are summarised in Table 1.

The data consists of average daily measurement of ambient temperature (AT, °C), relative humidity (RH, %), pressure, wind speed

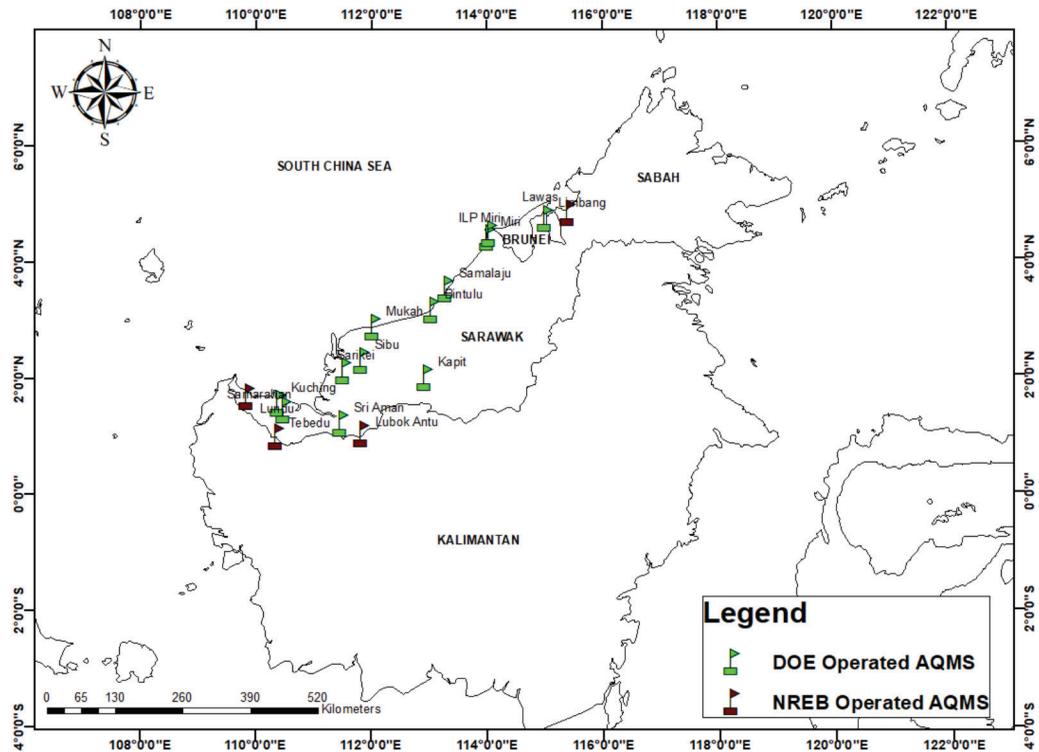


Figure 1: The location of the AQMS at major towns in Sarawak and along the border between Sarawak, Malaysia and Kalimantan, Indonesia

Table 1: The site description of the AQMS at major towns in Sarawak and along the border between Sarawak, Malaysia and Kalimantan, Indonesia

Operated by	AQMS	Coordinates	Site Description/Location	Data Parameters
DOE	Kuching	N1° 33' 44.0244" E110° 23' 20.2488"	Medical store	PM ₁₀ , PM _{2.5} , Wind speed, wind direction, relative humidity, ambient temperature
	Sibu	N2°18'51.8682" E111°49'54.8976"	Police Station, Sibu	
	Bintulu	N 3° 10' 37.5018" E113° 2' 27.927"	Police Station, Bintulu	
	Miri	N4° 25' 28.8444" E114° 0' 44.7336"	Sekolah Menengah Dato Permaisuri	
	Kota Samarahan	N1° 27' 17.4702" E110° 29'29.418"	Samarahan District Office	
	Sri Aman	N1° 13' 10.7616" E111°27'53.2512"	Sri Aman Sport Complex	
	Sarikei	N2°7'58.1118" E111°31'22.3314"	Police Station, Sarikei	
	Kapit	N2°0'52.1928" E112°55'38.4954"	Kapit Indoor Stadium	
	Mukah	N2°52'59.6562" E112°1'11.0706"	Mukah Polytechnic	
	ILP Miri	N4° 29' 41.2476" E114° 2' 36.297"	Industrial Training Institute Miri	
	Limbang	N4° 45' 32.0076" E115° 0' 49.2006"	Dewan Suarah Limbang	
	Samalaju	N3° 32' 13.4124" E113° 17' 42.6048"	Samalaju Industrial Estate	
NREB	Tebedu	N 00°59'18" E 110°21'12"	Immigration, Custom and Quarantine, Tebedu; Border	PM _{2.5} , wind speed, wind direction, ambient temperature, relative humidity, barometer pressure
	Lundu	N 01°40'45" E 109°51'8"	Lundu District Office; Border	
	Lubok Antu	N 01°02'28" E 111°50'10"	Lubok Antu District Office; Border	
	Lawas	N 04°51'13" E 115°24'05"	Lawas District Council; Border	

(WS, m/s), wind direction (WD, °), PM_{2.5}, and PM₁₀ since 2017. The monitoring instruments and operation protocols for the AQMS used were according to the approved guidelines by the United States Environmental Protection Agency (USEPA). The quality control protocols governing fieldwork, analysis, and data handling, data interpretation was implemented

on a regular basis by the appointed contractor. PM_{2.5} was measured continuously using the TEOM® 1405-F Ambient Particulate Monitor with FDMS. The daily hotspots in Sarawak were obtained from the ASEAN Specialised Meteorological Centre (ASMC). The hotspots indicating possible illegal open burning activities were detected via NOAA-20 satellite.

Data Processing and Statistical Analysis

The data available according to study site and parameters is summarised in Table 2. An Analysis of Variance (ANOVA) was performed to determine the significant difference of air pollutants and meteorological parameters between groups ($\alpha=0.05$). Pearson correlation analysis was conducted to determine the relationships between meteorological variables and particulate matters. The correlation test was employed to determine the linear association between $PM_{2.5}$ and other contaminants as well as meteorological parameters. If the two variables exhibit a perfect linear relationship with a positive slope, then, $r = 1$. If the two variables exhibit a perfect linear relationship with a negative slope, then, $r = -1$. A correlation value of 0 indicates the absence of a linear relationship between the variables (Carslaw & Ropkins, 2012; Rahman *et al.*, 2022). The distribution of hotspots in Borneo was visualised using ARCGIS 10.7.

The longitude and latitude of the hotspots were assigned as x and y , the hotspots were visualised on the topographic map of Borneo (Lee *et al.*, 2020). The coordinates of hotspots were obtained from the ASEAN Specialised Meteorological Centre (ASMC) (<https://asmc.asean.org/asmc-hotspot/>). The spatial pattern of Active Fire Counts (AFC) was analysed using Kernel Density (KD) estimation, with spatial interpolation based on fire radiative power (measured in megawatts). The spatial pattern of Active Fire Count (AFC) was investigated using Kernel Density (KD) estimation involving spatial interpolation. The data was smoothed based on inferences drawn from the population of the data sample and the probability density function was estimated (Wu, 1997; Mahmud, 2013).

Quality Control and Quality Assurance

All air quality data from the Continuous Air Quality Monitoring network (CAQM) was verified. Gas detection devices were manually inspected every two weeks while PM_{10} and $PM_{2.5}$ instruments were calibrated monthly, following the standard operating protocols.

Results and Discussion

The descriptive statistical values of particulate matter and local meteorological parameters according to monsoonal seasons - Northeast Monsoon (NEM, December - February), Intermonsoon 1 (Inter1, March - May), Southwest Monsoon (SWM, June - August), and Intermonsoon 2 (Inter2, September - November) are shown in Table 3. The mean values of PM_{10} increased in the order of NEM ($18.12 \pm 0.12 \mu\text{g}/\text{m}^3$), Inter1 ($19.79 \pm 0.12 \mu\text{g}/\text{m}^3$), SWM ($22.47 \pm 0.28 \mu\text{g}/\text{m}^3$) and Inter2 ($21.65 \pm 0.29 \mu\text{g}/\text{m}^3$).

Despite the increasing trend across the four monsoonal seasons, the values were below the limit set by the National Ambient Air Quality Standards (NAAQS) (US EPA, 2015) and Malaysia Ambient Air Quality Standards (MAAQS) (DOE, 2020). As for the mean of $PM_{2.5}$, the value was $8.68 \pm 0.07 \mu\text{g}/\text{m}^3$ (NEM), $10.68 \pm 0.09 \mu\text{g}/\text{m}^3$ (Inter1), $13.70 \pm 0.22 \mu\text{g}/\text{m}^3$ (SWM), and $13.08 \pm 0.24 \mu\text{g}/\text{m}^3$ (Inter2), respectively. The values of $PM_{2.5}$ during the SWM and Inter2 were slightly above the limit set by the NAAQS (US EPA, 2015). However, when compared to the MAAQS (DOE, 2020), the values remained below the guideline limit. Generally, elevated concentrations of PM_{10} and $PM_{2.5}$ were recorded for the months of June to August (SWM) and September to November (Inter2).

For AT, the measurements demonstrated an increase from NEM ($26.92 \pm 1.46^\circ\text{C}$) to Inter-1 ($27.75 \pm 1.70^\circ\text{C}$), followed by a gradual decline towards SWM ($27.56 \pm 1.51^\circ\text{C}$) and Inter-2 ($27.18 \pm 1.30^\circ\text{C}$). The BP and WD were relatively consistent throughout the year for BP, the mean was $1003.63 \pm 4.36 \text{ Pa}$, $1003.72 \pm 3.94 \text{ Pa}$, $1003.70 \pm 4.14 \text{ Pa}$ and $1002.71 \pm 4.23 \text{ Pa}$ for the NEM, Inter-1, the SWM and Inter-2 while for the WD, the mean was $171.25 \pm 56.38^\circ$, $174.66 \pm 45.85^\circ$, $175.01 \pm 40.39^\circ$, and $175.74 \pm 41.51^\circ$. For WS, the mean recorded was $2.30 \pm 5.35 \text{ m/s}$, $2.90 \pm 7.90 \text{ m/s}$, $2.53 \pm 6.67 \text{ m/s}$, and $2.40 \pm 8.92 \text{ m/s}$, for the NEM, Inter-1, the SWM, and Inter-2, respectively. The RH fluctuated with a mean of $86.00 \pm 5.06\%$, $84.02 \pm 5.20\%$, 82.80

Table 2: The overview of the data structure of the study

Category	AQMS Locality	N	Parameter	Data Compiled
Urban	Kuching	1745	PM ₁₀	Since 2017
	Sibu	1745	PM _{2.5}	Since July 2017 onward
	Bintulu	1745	SO ₂	Since 2017
	Miri	1745	NO ₂	Since 2017
			O ₃	Since 2017
			CO	Since 2017
			WS	Since 2017
			WD	Since 2017
			RH	Since July 2017 onward
		AT	Since January-April 2017	
Suburban	Samarahan	1745	PM ₁₀	Since 2017
	Sri Aman	1745	PM _{2.5}	Since July 2017 onward
	Sarikei	1745	WS	Since 2017
	Kapit	1745	WD	Since 2017
	Mukah	1642	RH	Since July 2017 onward
	ILP Miri	1745	AT	Since January-April 2017
	Limbang	1745		
Industrial area	Samalaju	1642	PM ₁₀	Since 2017
			PM _{2.5}	Since July 2017 onward
			SO ₂	Since July 2017 onward
			NO ₂	Since July 2017 onward
			WS	Since 2017
			WD	Since 2017
			RH	Since July 2017 onward
	AT	Since January-April 2017		
Sarawak/Kalimantan border	Tebedu	731	PM _{2.5}	Since year 2020 onward
	Lundu	728	WS	Since year 2020 onward
	Lubok Antu	731	WD	Since year 2020 onward
	Lawas	729	AT	Since year 2020 onward
			RH	Since year 2020 onward
			BP	Since year 2020 onward

$\pm 5.89\%$, and $84.41 \pm 5.30\%$ across the four monsoonal seasons.

Figure 2 shows the distribution pattern of particulate matters and local meteorological parameters from 2017 to 2021 according to study areas. In general, elevated PM_{2.5} was recorded in

the year 2019 with the highest concentrations registered in Sri Aman ($407.15 \mu\text{g}/\text{m}^3$) on 20th September 2019, followed by ILP Miri ($398.74 \mu\text{g}/\text{m}^3$) on 22nd September 2019, and Kuching ($211.90 \mu\text{g}/\text{m}^3$) on 19th September 2019. A similar occurrence was observed by Napi *et al.*

Table 3: Descriptive statistical values for the particulate matter and local meteorological parameters in all the study areas according to seasons

		DJF	MAM	JJA	SON
PM _{2.5}	Min	0.25	1.72	1.27	1.8
	Max	77.69	114.91	398.74	407.15
	Mean ± std	8.68 ± 4.83	10.68 ± 6.20	13.70 ± 16.27	13.08 ± 18.70
PM ₁₀	Min	4.93	2.17	4.17	5.55
	Max	99.83	137.98	475.97	473.93
	Mean ± std	18.12 ± 8.52	19.79 ± 8.37	22.47 ± 20.09	21.65 ± 21.60
AT	Min	21.14	20.28	22.98	22.97
	Max	34.9	36.92	35.4	35.43
	Mean ± std	26.92 ± 1.46	27.75 ± 1.70	27.56 ± 1.51	27.18 ± 1.30
BP	Min	995.7	995.43	996.07	995.57
	Max	1012.05	1010.53	1010.55	1009.88
	Mean ± std	1003.63 ± 4.36	1003.72 ± 3.94	1003.70 ± 4.14	1002.71 ± 4.23
RH	Min	28.96	24.46	57.52	65.1
	Max	100	100	100	100
	Mean ± std	86.00 ± 5.06	84.02 ± 5.20	82.80 ± 5.89	84.41 ± 5.30
WD	Min	7.27	24.3	0.12	13.08
	Max	343.98	327.22	300.94	321.57
	Mean ± std	171.25 ± 56.38	174.66 ± 45.85	175.01 ± 40.39	175.74 ± 41.51
WS	Min	0.3	0.37	0.36	0
	Max	46.76	96.18	162.23	535.22
	Mean ± std	2.30 ± 5.35	2.90 ± 7.90	2.53 ± 6.67	2.40 ± 8.92

* DJF: December, January, February; MAM: March, April, May; JJA: Jun, July, August; SON: September, October, November

(2022) in 2019 where high concentrations of PM_{2.5} were recorded in the months of August to September. The elevated levels of PM_{2.5} and Aerosol Optical Depth (AOD) was attributed to biomass burning in Indochina, Kalimantan, and Sumatra. Both local emissions from natural and human activities as well as non-local emissions have also contributed to the increase in PM_{2.5} (Napi *et al.*, 2022). Higher PM_{2.5} was regularly

registered in Bintulu, Kuching, Sibul, ILP Miri, Miri, and Samalaju across the years ($p < 0.05$). Kapit and Limbang often recorded good air quality with significantly lower PM_{2.5}.

Increased concentration of PM₁₀ was also recorded in the year 2019, especially in the months of August and September; the highest concentrations of PM₁₀ was attained in ILP Miri (475.97 µg/m³), followed by Sri Aman

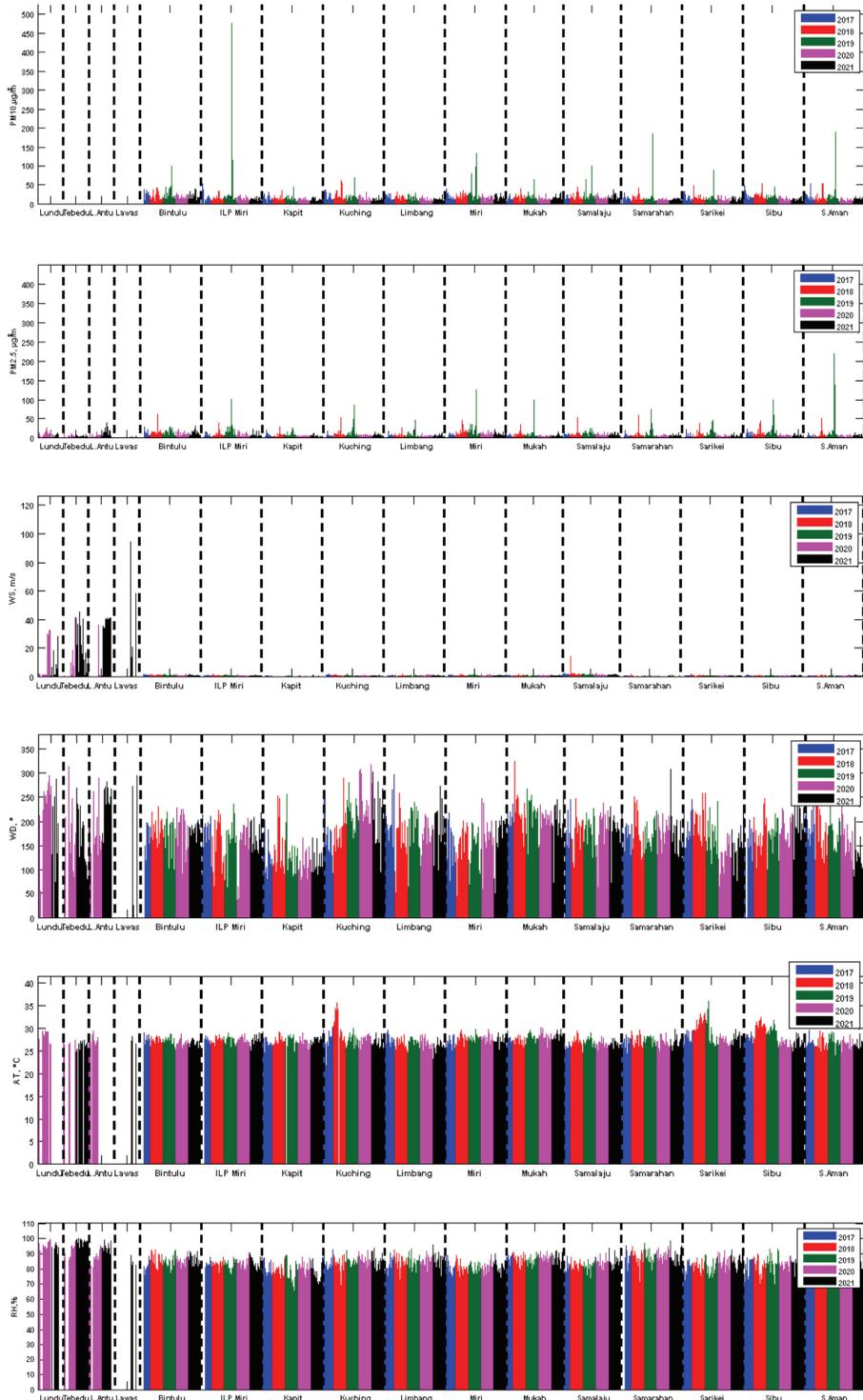


Figure 2: Distribution of PM_{2.5} and PM₁₀ and the meteorological parameters according to the study sites and years

(473.93 $\mu\text{g}/\text{m}^3$), and Sarikei (209.58 $\mu\text{g}/\text{m}^3$). In 2019, there was a period of relatively mild El-Niño conditions between January and June, which transitioned into a neutral phase of the ENSO event that lasted until December 2019 (Malaysian Meteorological Department, 2019; Napi *et al.*, 2022). For these reasons, throughout 2019, the region experienced occasional tropical cyclones during the Southwest Monsoon (SWM), Inter-monsoon, and Northeast Monsoon (NEM). There were notable typhoons in August (Lekima) and November (Nakri) affecting the South China Sea.

Statistically, PM_{10} in Bintulu was significantly higher than most of the locations in 2017, 2018, 2020, and 2021. Significantly higher PM_{10} was also registered in Samalaju (2018, 2020, and 2021), Sibul (2018), ILP Miri (2019 and 2020), Miri (2020 and 2021), and Mukah (2021). Other locations such as Limbang, Sri Aman, Kapit, Sarikei, and Samarahan exhibited lower PM_{10} values. The variation in particulate matter concentration was primarily governed by the activities in the area; Bintulu, Samalaju, Miri, Kuching, and Sibul are industrial and urban areas while Kapit and Limbang are categorised in the sub-urban areas.

In term of WS, higher measurements were recorded in the Northern part of Sarawak, specifically Bintulu, Samalaju, and Miri. A spike in WS was recorded in 2018 from ILP Miri (16th February 2018, 14.02 m/s), Kapit (21st February 2018, 6.53 m/s), Kuching (3rd January 2018, 17.17 m/s), Limbang (19th February 2018, 14.95 m/s), and Samalaju (28th February 2018, 33.00 m/s). For the WD, the dominant course was mainly from the South-West (SW) and South-East (SE) with the record ranging between 1.10 m/s and 2.65 m/s; only Samalaju experienced exceptionally high WS (30.65 m/s - 40.65 m/s). Along Sarawak-Kalimantan border, the dominant WD was likewise from SW except Lawas, where the wind came from the Northwest (NW). The WS along the border was much stronger than that in the towns with velocity between 20.43 m/s to 40.45 m/s. For the AT, the highest mean temperature was

in Sarikei (28.5°C) whilst the lowest was in Limbang (26.60°C). The largest difference in temperature was registered in Kuching (15.78°C/36.92°C - 21.14°C) and the minimum in ILP Miri (5.45°C/29.61°C - 24.16°C). Along the Sarawak-Kalimantan border, the temperature difference recorded was 8.4°C/32.06°C - 23.66°C. As for the mean RH, the measurements attained ranged between 79.64% and 96.13% with the highest recorded temperatures being in Tebedu and the lowest in Kapit. The maximum difference in RH was registered in Sri Aman (69.7%) whilst the minimum was in Mukah (20.42%). The pressure fluctuated between 998.4 Pa and 1,008 Pa with the greatest change recorded in Lawas (8.06 Pa) and the minimum in Tebedu (6.44 Pa).

Generally, the data demonstrated spatial and temporal variations in air quality and meteorological conditions. The dispersion of particulate matter can be influenced by meteorological variables such as Wind Direction (WD), Wind Speed (WS), and Relative Humidity (RH) (Huang *et al.*, 2020). The correlations between the PM and local meteorological parameters are tabulated in Table 4.

In this study, the concentrations of $\text{PM}_{2.5}$ and PM_{10} are positive correlated. The correlation analysis suggested significant relationships between $\text{PM}_{2.5}$ and AT, RH and BP. The PM_{10} was likewise affected by the aforementioned parameters with WS in addition ($p < 0.01$). A positive correlation was deduced between $\text{PM}_{2.5}/\text{PM}_{10}$ and AT whilst an inverse relationship was established with RH. The significant influence of RH and AT on the concentrations of $\text{PM}_{2.5}$ was corroborated by Vaishali *et al.* (2023). A season-wise response between AT and $\text{PM}_{2.5}$ was revealed in Delhi with negative correlation deduced during winter and pre-monsoon seasons, nevertheless, the relationship was inversed over the monsoon season.

The lower concentration of $\text{PM}_{2.5}$ under higher temperature was evidenced to associate with frequent precipitation that led to greater settlement. The elevated temperature also contributed to higher stable boundary layer offering better dispersion of the particulate

Table 4: Pearson correlation coefficient between the particulate matters and local meteorological parameters

	PM _{2.5}	PM ₁₀	WS	WD	AT	RH	BP
PM _{2.5}	1	0.980**	-0.009	0.012	0.228**	-0.256**	0.095**
PM ₁₀	0.980**	1	0.022**	0.010	0.220**	-0.271**	. ^b
WS	-0.009	0.022**	1	0.173**	-0.068**	0.297**	-0.110**
WD	0.012	0.010	0.173**	1	0.051**	0.152**	0.061*
AT	0.228**	0.220**	-0.068**	0.051**	1	-0.514**	0.122**
RH	-0.256**	-0.271**	0.297**	0.152**	-0.514**	1	-0.427**
BP	0.095**	. ^b	-0.110**	0.061*	0.122**	-0.427**	1

** . Correlation is significant at the 0.01 level (2-tailed). * . Correlation is significant at the 0.05 level (2-tailed).

b. Cannot be computed because at least one of the variables is constant.

matter. Nevertheless, when the temperature was higher and the rain is limited, the concentration of PM_{2.5} was found to increase demonstrating positive correlation instead.

The correlation between AT and PM_{2.5} was observed to inter-correlate with RH. At RH greater than 50%, the humidity was found to play a role in absorbing the radiation reducing the surface temperature, which in turn weakened the incoming current, thus, increasing the concentration of PM_{2.5} (Jayamurugan *et al.*, 2013). Sirithian and Thanatrakolsri (2022) likewise examined the relationships between particulate matters and meteorological parameters in Northern Thailand. The study reported similar observations of a positive correlation between PM_{2.5}/PM₁₀ and AT and a negative correlation with RH. The positive correlation between AT and PM_{2.5}/PM₁₀ was attributed to the dry spell and burning activities whilst RH affected the particle movements. Under high RH, the particulates tend to settle down reducing the concentration in the atmosphere. Elevated PM₁₀ was demonstrated with increasing WS but it had no effect on PM_{2.5}.

This observation opposed the findings of Sirithian and Thanatrakolsri (2022), where both PM_{2.5} and PM₁₀ was not affected by the WS. The relationships between particulate matter with AT, RH, and WS are illustrated in Figure 3. Interestingly, the particulate matter concentrations tend to be higher at AT between 25°C and 30°C and RH of between 75%

and 85%. At this temperature and humidity, the conditions fostered the accumulation of particulate matters in the atmosphere. Low WS on the other hand reduced the dispersion of the air pollutants, increasing their concentration in the atmosphere. Although no strong relationship was deduced between WD and air pollutants, Liu *et al.* (2020) suggested that when WS exceeds 4 m/s, the concentration of PM₁₀ particles could increase under certain wind directions such as south, southeast, east, and northeast as a result of disturbed movement of dust particles on the ground.

Understanding the relationship between meteorology and air pollution is crucial for making policy decisions to mitigate air pollution in South Asia (Vinoj & Pandey, 2022). Figure 4 shows the number of hot spots identified in Sarawak, Sabah, Brunei, and Kalimantan for the year 2017 to 2021. Kalimantan consistently showed higher number of hotspots compared to other regions with a record high in 2019. In Sarawak, the hotspots identified ranged between 146 - 436, with the highest registered in 2021.

The number of hotspots identified in Sarawak was comparatively higher than Sabah (65 - 311). The correlation analysis demonstrated significant relationship between the hotspots in Kalimantan and other regions in Borneo ($p < 0.01$). This is likely due to the biomass burning in Borneo. The relationship was corroborated by Mahmud (2013), where deteriorated air quality in Sarawak in 2004 was associated with biomass

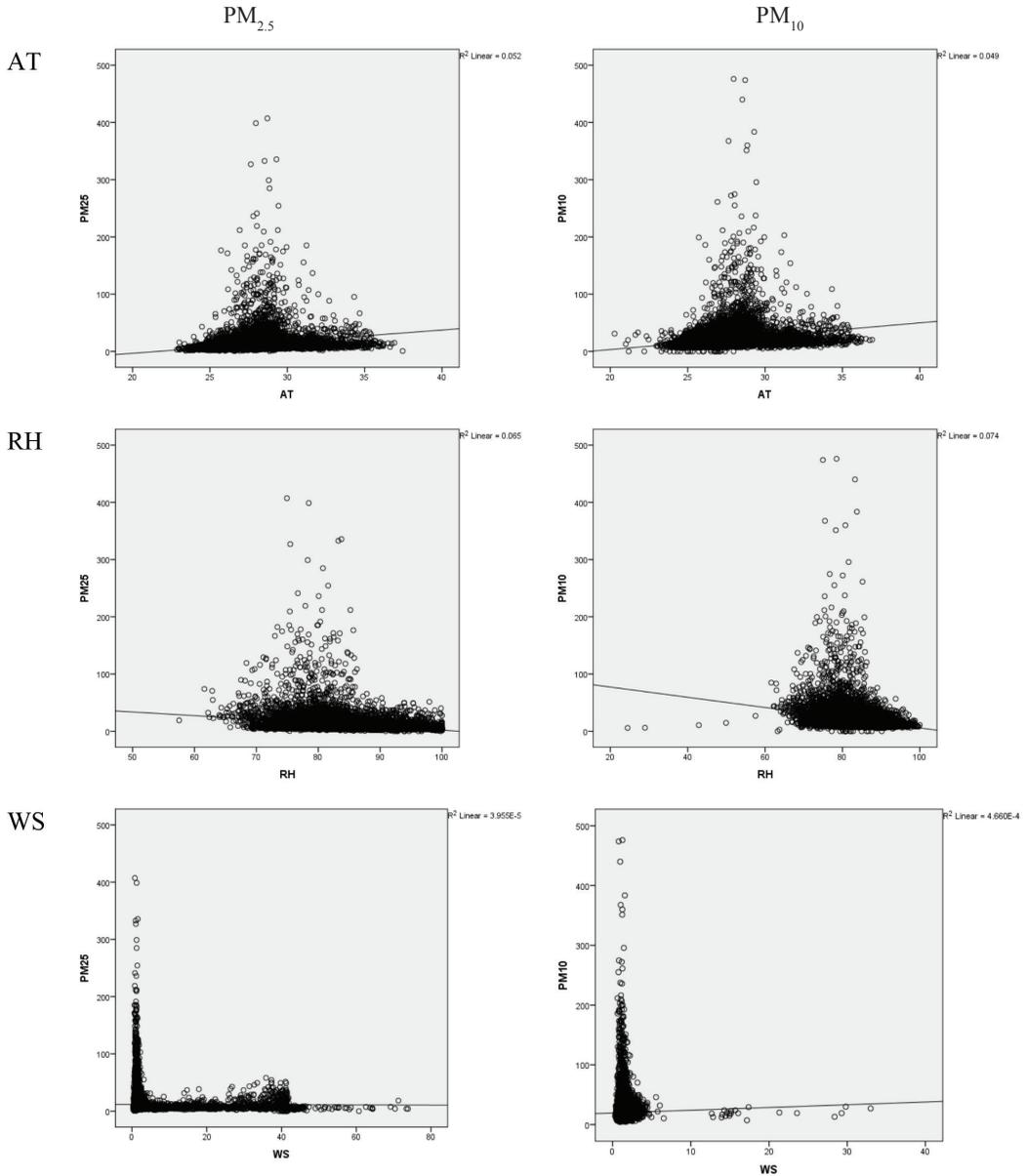


Figure 3: The relationships between $PM_{2.5}/PM_{10}$ and AT, RH, and WS

burning activities in Borneo, especially in the Western and Southern Borneo. During that period, Borneo region experienced SWM, where the wind direction had exacerbated the situation. Hayasaka *et al.* (2014) also highlighted the peat fires in central Kalimantan as a major contributor of photochemical smog and air pollution in the region. The seasonal wind, direction changes and characteristics of $PM_{10}/PM_{2.5}$ have disbursed

them easily in a wide area (Hayasaka *et al.*, 2014).

The Kernel Density analysis of the distribution of hotspots are shown in Figures 5 to 8. Statistically, this method can be employed to estimate the unknown density function. This method utilises existing knowledge of the data distribution, without imposing assumptions

on the data distribution, and analyses the characteristics of the data distribution based on the sample (Jin *et al.*, 2018; Wang *et al.*, 2019). From the analysis, it was found that low density of hotspots was recorded during NEM from DJF. However, the density of hotspots started to peak during the SWM from June to August and lasted until Inter2 from September to November. During the JJA and SON, the hotspots mostly concentrated in the South of Borneo offering an explanation on the deteriorated air quality, which had resulted in the occurrence of transboundary haze in the region.

Conclusions

In conclusion, the study analysed the concentrations of PM₁₀ and PM_{2.5} pollutants during different monsoonal seasons in various study areas in Borneo for a 5-year period. The highest concentrations of PM₁₀ and PM_{2.5} was observed during the Southwest Monsoon (SWM) and Inter-monsoon 2 (Inter2) seasons. While the values remained below the limits set by the NAAQS and MAAQS for most seasons, PM_{2.5} levels during the SWM and Inter2 were slightly above the NAAQS limit. The study also investigated the meteorological parameters, where AT, RH, and WS were found to correlate strongly with the concentrations of air pollutants.

In addition, the study examined hotspot occurrences, indicating significant correlations

between hotspot numbers in Kalimantan and other regions in Borneo. Biomass burning activities in Borneo, particularly during SWM and Inter2, contributed to deteriorated air quality and transboundary haze events. The findings highlight the importance of monitoring and understanding the relationship between meteorological parameters and air quality to mitigate the impact of air pollution and transboundary haze in Borneo. Further measures should be taken to control emissions and address the source of pollutants to safeguard public health and the environment. A predictive model should be explored to forecast the occurrence of transboundary haze.

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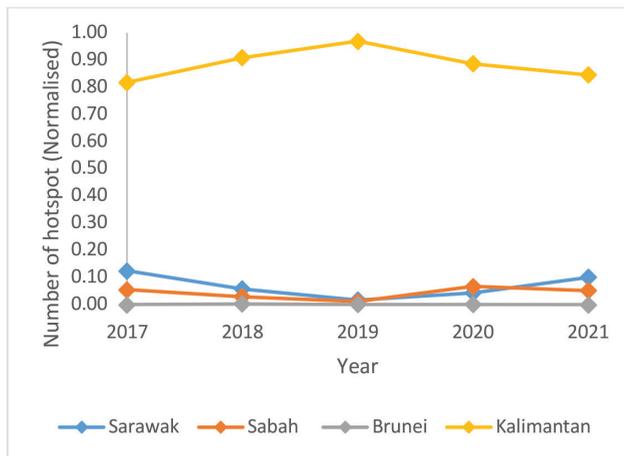
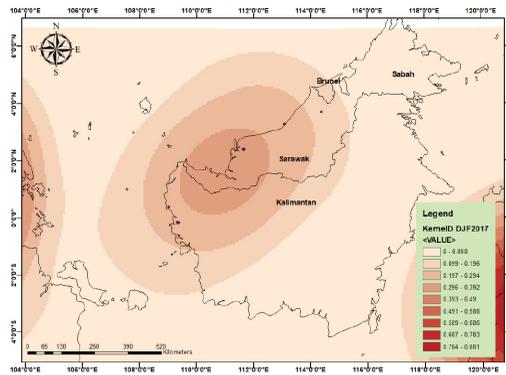
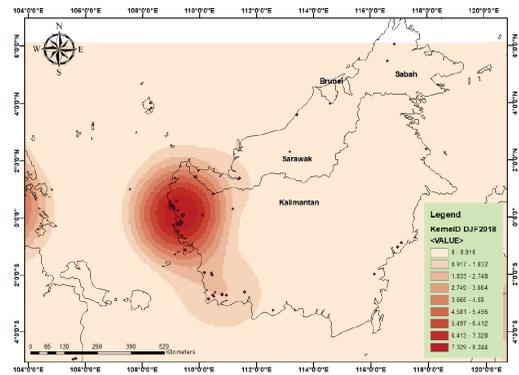


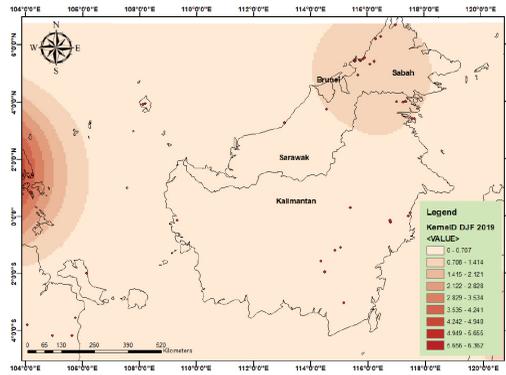
Figure 4: The number of hotspots in Borneo for the year 2017-2021 according to regions



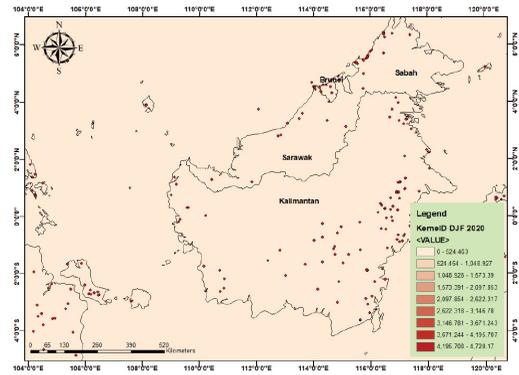
Year 2017



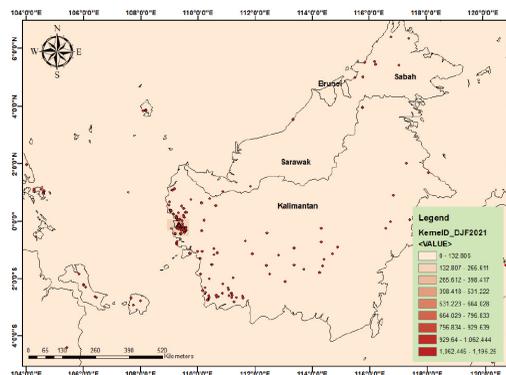
Year 2018



Year 2019

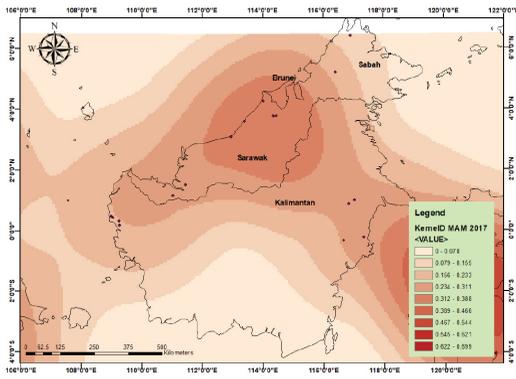


Year 2020

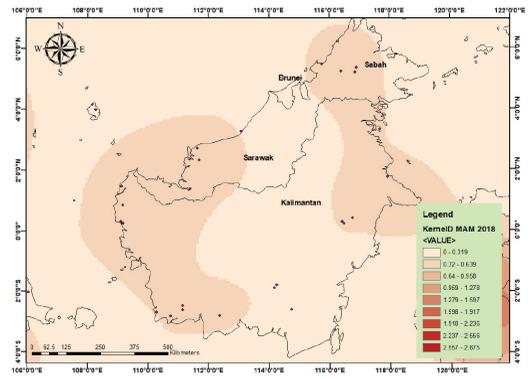


Year 2021

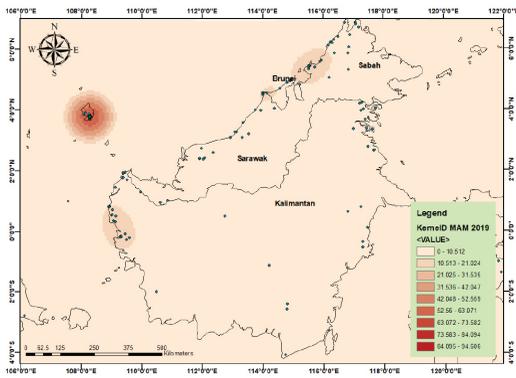
Figure 5: Kernel density analysis on the distribution of hotspot in Borneo according to monsoonal season- Northeast Monsoon (December, January, and February-DJF)



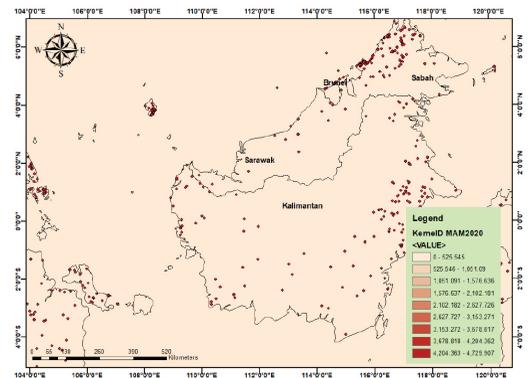
Year 2017



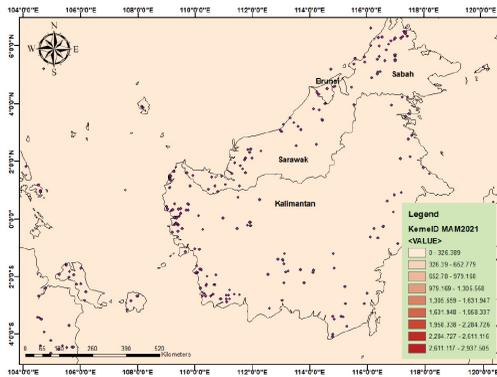
Year 2018



Year 2019



Year 2020



Year 2021

Figure 6: Kernel density analysis on the distribution of hotspot in Borneo according to monsoonal season- Inter-monsoon 1 (March, April, and May-MAM)

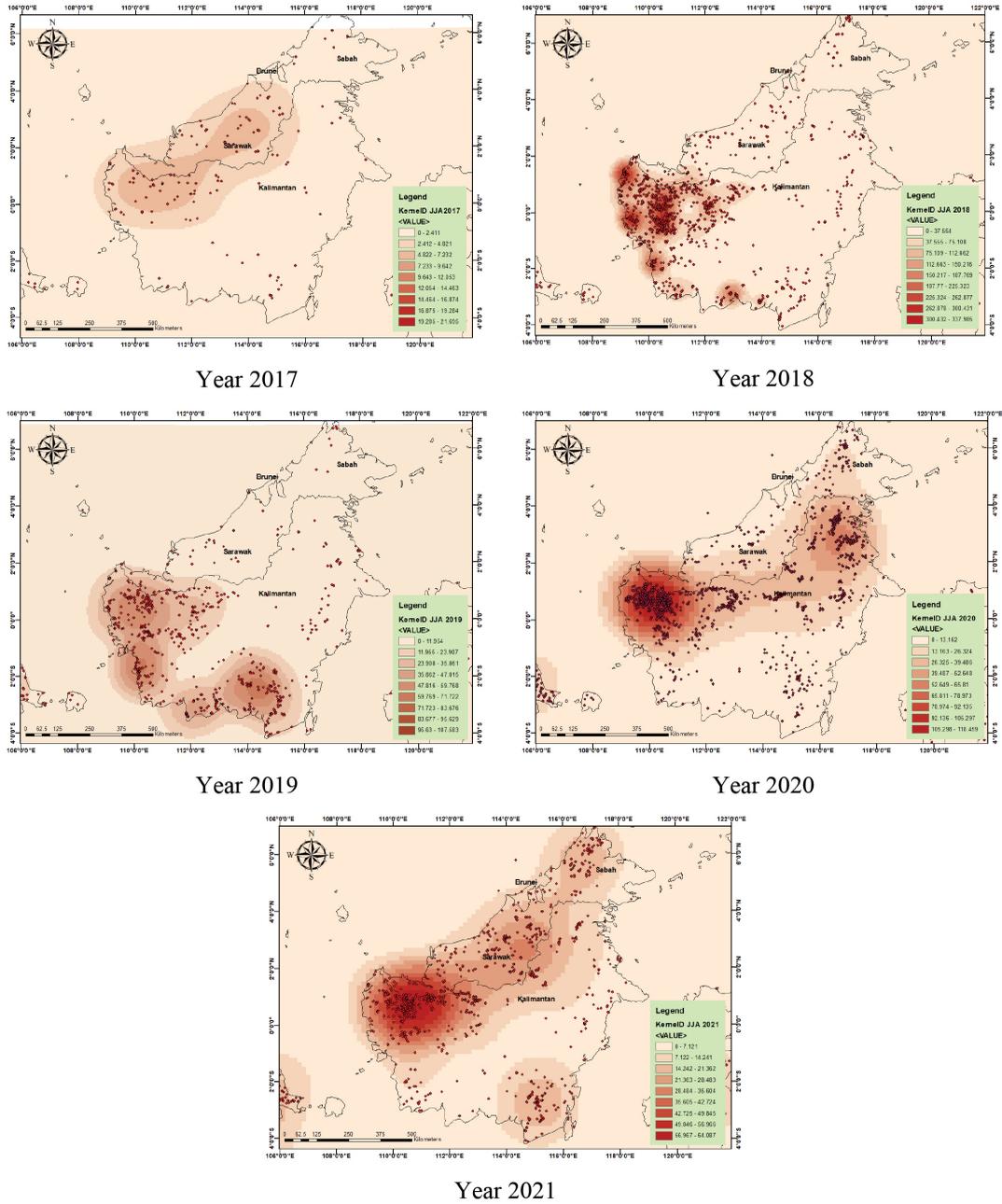
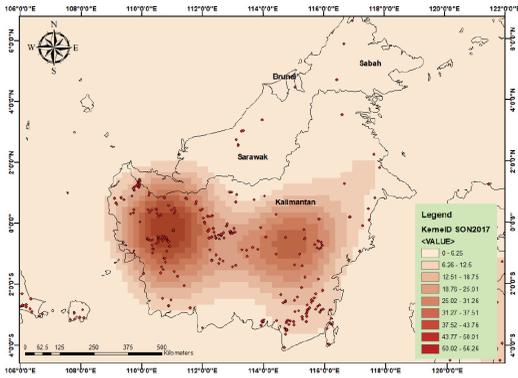
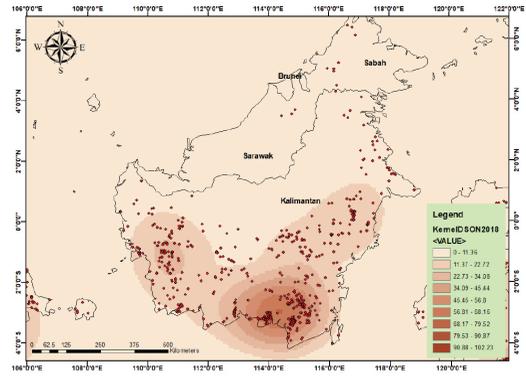


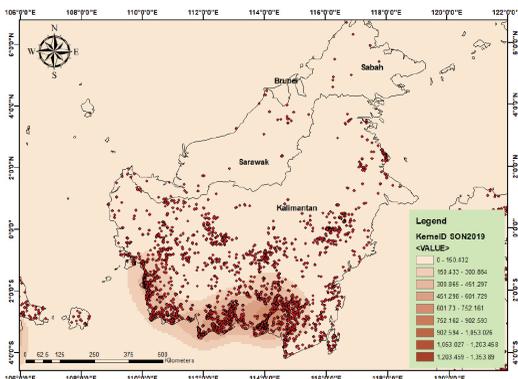
Figure 7: Kernel density analysis on the distribution of hotspot in Borneo according to monsoonal season- Southwest Monsoon (June, July, and August-JJA)



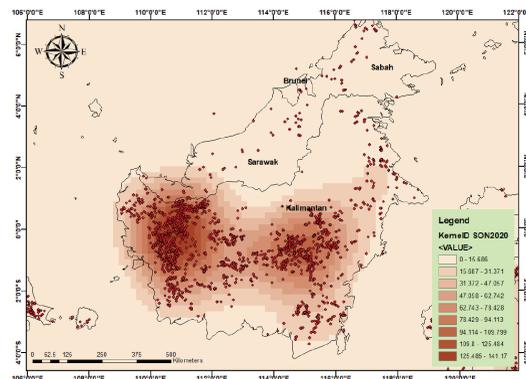
Year 2017



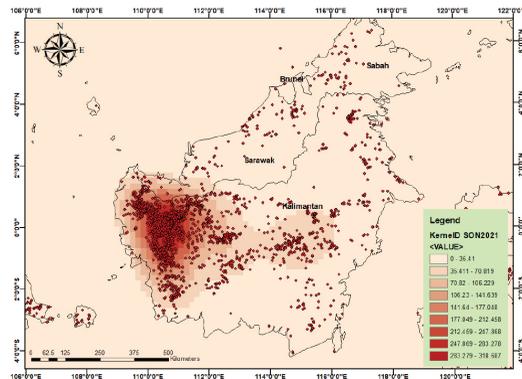
Year 2018



Year 2019



Year 2020



Year 2021

Figure 8: Kernel density analysis on the distribution of hotspot in Borneo according to monsoonal season- Inter-monsoon 2 (September, October, and November-SON)

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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