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Emission level of air pollutants during 2019 pre-haze, haze, and post-haze episodes in Kuala Lumpur and Putrajaya

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Abstract

Nowadays, due to population growth and industrialisation, air quality in Malaysia is becoming a critical threat. Air pollution has become a serious issue due to its impacts on humans, animals, and the environment. Malaysia experienced air quality deterioration in 2019 when the episodes of haze happened from July to September. It was due to the local and transboundary sources such as vehicles, factories, power plants, and biomass burning from Sumatra. This study aims to differentiate the level of the potential air pollutants, examine the influence of meteorological factors on the potential air pollutants and determine the local and transboundary impact on the potential air pollutants during episodes of pre-haze, haze, and post-haze in Kuala Lumpur and Putrajaya in 2019. Secondary physical and data on meteorology were obtained from the continuous ambient air quality monitoring (CAQM) stations by the Malaysian Department of Environment (DOE). The data obtained from CAQM were physical: particulate matters ($PM_{2.5}$ & PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and level ozone (O_3); as well as meteorological: temperature (T), relative humidity (RH), wind speed (WS) and wind direction (WDir). Overall, the particulate matter ($PM_{2.5}$, PM_{10}) and carbon monoxide which are the pollutants that involve the formation of haze in Kuala Lumpur and Putrajaya are higher during haze episodes compared to pre-haze and post-haze episodes while the other pollutants (NO_2, SO_2, O_3) are fluctuated throughout the entire episode due to its sources and the influence of meteorological factors. The backward trajectory indicated that the air pollutants are influenced by wind direction from South West Malaysia (SWM) and North East Malaysia (NEM) throughout the entire year.

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1.0 Introduction

Stepping into 2020, Malaysia is now moving ahead in many industrial sectors and the nation's population continues to increase to 32,157,114 as of 31 December 2019 equivalent to 0.42 percent of the total world population. Following this development and industrialisation, air quality in Malaysia has become a major issue (Mabahwi et al., 2014) also stated that some important contributing factors to pollution are the size of the population and the technology development which however paves the methods used to develop environmental impact. Fig. 1 shows the emission mechanism of air pollutants in Kuala Lumpur and Putrajaya.

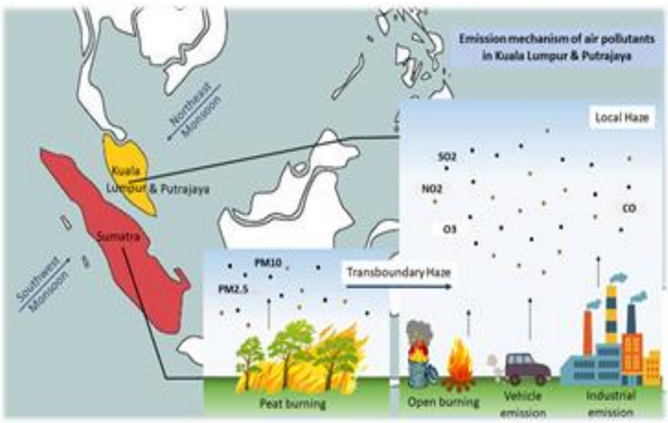

Fig. 1: Emission mechanisms of air pollutants in Kuala Lumpur & Putrajaya

Air pollution issues had been seriously discussed in the past decade because of their alarming condition towards substances harmful to humans and other living organisms. Air pollution is the introduction into the atmosphere of chemicals, particulate matter, or biological materials that cause harm or discomfort or environmental disruption to humans or many other living organisms (Ahmed et al., 2012). The term air pollution refers to a group of airborne pollutants that are believed to lead to a deterioration of life expectancy, which includes carbon monoxide (CO), sulphur dioxides (SO_2), nitrogen dioxides (NO_2), ozone (O_3), and airborne particulate matter (PM) (Martins & Carrilho da Graça, 2018). Local sources such as vehicles, power plants, biomass burning, and factories emission are examples of various sources which conduce to air pollution.

In past decades, Malaysia has seen rapid development in the transport sector compared to other ASEAN countries. The increase in cars in the area of Klang Valley is the highest in comparison to other areas. According to the report on the 2020 Kuala Lumpur Structure Plan, only 20 percent of residents in Kuala Lumpur use public transport. This situation contributes to the increase in the number of cars on the road and causes air pollution. On top of that, the ignorance of Malaysian about the greenhouse gas emission from vehicles would make the pollution rate becoming worse. In 2008, a total of 18 million vehicles were registered in Malaysia (Nadason, 2015). This amount recorded a greenhouse gas emission rate of 4.9 million tonnes into the air and the environment. The increase in the living standards of the people in Malaysia has resulted in an increase in the number of cars on the roads where the number of vehicles registered in Malaysia as of 31 December 2019 was 31.2 million according to the Road Transport Department (Jabatan Pengangkutan Jalan Malaysia, 2020).

Besides local sources, transboundary sources also deteriorating the air quality in Malaysia. In 2019, Malaysia experienced haze after enduring a severe haze episode in 1994, 1997, 2005, 2006, 2010, 2011, 2012, 2013, 2014, and 2015 (Official Portal of Department of Environment, 2015). This is associated with the open burning of biomass and forest fires in Sumatera and Kalimantan, Indonesia. Indonesia is a country where its main economy is from palm oil production. Indonesia provides about half of the world's supply since the country is the largest producer palm oil production increased sharply from 157, 000 tonnes in 1964 to 43.5 million tonnes in 2020 (Barrientos, 2020). Borneo and Sumatra are the islands that account for most of Indonesia's palm oil production. The forest and peatland were usually burned by most of the holders to clear, drain, and re-plant for industrial plantation purposes (Zainal, 2016). The burning of the forest and peatland for industrial plantation purposes lead to the atmospheric phenomenon called haze and these hazes could spread to other neighbouring countries such as Malaysia, Singapore, and other Southeast Asian's countries (Forsyth, 2014) due to the meteorological factors which are temperature (T), relative humidity (RH), windspeed (WS), and wind direction (WDir).

Most of the studies only focused on the level of pollutant and the sources during haze episodes without comparing to the non-haze episodes (Kamaruzzaman et al., 2017; Laden et al., 2000; Khan et al., 2016). Therefore, pre-haze episode, haze episode, and post-haze episode were discussed in this study to make known the difference of the concentration level of the pollutants, the influence of meteorological factors on the air pollutants, and the local and transboundary impact on the air pollutants between episodes of pre-haze, haze, and post-haze.

2.0 Methodology

2.1 Details of the study timeline

According to the newspaper's Sinar Harian article dated 31st July 2019, the Malaysian Meteorological Department states that the country will face air pollution or haze starting 31st July 2019, possibly due to forest fires that occurred in Sumatra, Indonesia. Deputy Director General (Operations) of the Malaysian Meteorological Department, Muhammad Helmi Abdullah said, Sumatra is located in the southwest of Malaysia and the movement of the wind to this country was from that direction and according to him, the wind was also affected by the low wind pressure factor in the South China Sea (Ismail, 2019).

There was no specific article that mentioned when the haze episode in 2019 ends but there was one newspaper's article written by Sinar Harian dated 21st September 2019 mentioned that the hazy weather that hit the region of the country was expected to improve within the week due to the monsoon transition phase (Hussain, 2019). To determine the specific date when the haze episodes ended, the data from CAQM were referred. Based on the CAQM data obtained from DOE, the haze ended on 24th September 2019. This can

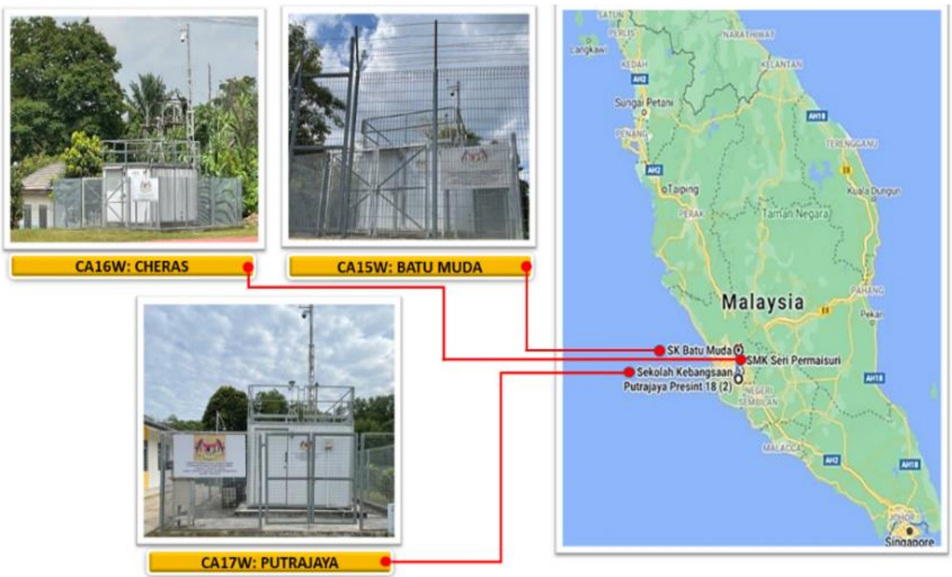

Fig. 2: Map location of air quality monitoring Stations in Kuala Lumpur and Putrajaya

Table 1: Summary table of air quality monitoring stations in Kuala Lumpur and Putrajaya

Monitoring Station	Location and Coordinates	Area Category	The Surroundings
	Kuala Lumpur		
Batu Muda (CA15W)	Batu Muda Primary School (3.212903, 101.683606)	Urban	Includes both residential and industrial areas such as IKS Industrial Park and Spring Crest Industrial Park. A nearby major road is Duta-Ulu Klang Expressway (DUKE)
Cheras (CA16W)	Seri Permaisuri Secondary School (3.107590, 101.716767)	Urban	Includes both residential and industrial areas such as Trisegi Industrial Area and a nearby major road is Kuala Lumpur Middle Ring Road 2 (MRR2), Maju Expressway (MEX) and Sungai Besi Expressway (SBE/BESRAYA)
	Putrajaya		
Putrajaya (CA17W)	Putrajaya Presint 18(2) Primary School (2.915463, 101.690535)	Urban	Includes both residential and government administration building areas such as Ministry of Youth and Sports, Ministry of Transport Malaysia, Putrajaya Energy Commission etc., A nearby road is Lebuh Wadi Ehsan

be seen by the reduction of the concentration level of all the pollutants on that day.

In this paper, the entire period of sampling is in the year 2019 from January to December. It was categorised into three episodes; first is the pre-haze episode from 1st January to 30th July, second is the haze episode from 31st July to 24th September and third is the post-haze episode from 25th September until 31st December 2019.

2.2 Details of the study areas

Kuala Lumpur and Putrajaya have been selected as the study area since Kuala Lumpur and Putrajaya is two important cities where many important activities take place such as the government administration, tourism, health care, and economic activities. Site coding for each monitoring station is generally given by the Department of Environment (DOE) itself: Batu Muda (CA15W), Cheras (CA16W), and Putrajaya (CA17W). Fig. 2 and Table 1 show the precise locations and coordinates, as well as the surroundings of the stations, which are visualised and summarised, accordingly.

2.3 Physical and meteorological factors

Secondary physical and meteorological data were obtained from the continuous ambient air quality monitoring (CAQM) stations by the Malaysian Department of Environment (DOE). The level and status of air quality were continuously monitored for 24 hours a day, which is operated from the remote station of the automated air quality control located in the Batu Muda (3.212903, 101.683606) and Cheras (3.107590, 101.716767) in Kuala Lumpur as well as in Putrajaya (2.915463, 101.690535). The monitoring sites in Malaysia were formerly run by a private company called Alam Sekitar Sdn Bhd (ASMA).

Currently, Pakar Scieno TWS Sdn Bhd, a new private company, has taken over this operation and operates the sites and data on behalf of the Malaysian DOE. The data were measured directly by instrumentation. The data obtained from CAQM were physical: particulate matter ($PM_{2.5}$ & PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and level ozone (O_3); as well as meteorological: temperature (T), relative humidity (RH), wind speed (WS), and wind direction (WDir).

2.4 Sampling procedures

The $PM_{2.5}$ and PM_{10} were measured based on beta ray attenuation (BAM 1020, Teledyne, USA) with a resolution of 0.1 μg/m^3 (Khan et al., 2020). CO was controlled with the lowest detection of 0.2 ppm using non-dispersive infrared absorption (API M300, Teledyne, USA), while SO_2 was measured using the fluorescence theory (APIM100A, Teledyne, USA) and the lowest detection was 0.4 ppb. With a lower detection level of 0.4 ppb and <0.6 ppb, respectively, NO_2 and O_3 were calculated using chemiluminescence (API 200A and Analyzer 400A, Teledyne, USA) (Khan et al., 2015). Auto-calibration was scheduled regularly for each instrument. During the calibration phase, zero air calibration, as well as regular cylinder gas, were injected. To calibrate the instruments, a calibration standard gas (Linde Group, Germany) was used (Wang et al., 2020).

2.5 Data analysis

R-Studio was used to test the interpretation of data and the correlation of statistics. R-Studio is an Interactive Platform for Software Development (IDE) for R. It includes a console, a syntax-highlighting editor that supports direct execution of code and plotting tools. The original data was hourly. In this study, the hourly data were averaged into daily and monthly data using R-Studio. Summary statistics were calculated directly using code execution for the entire sampling duration, pre-haze episode, haze episode, and post-haze episode, including maximum, minimum, mean, and standard deviation. In addition, this program was used for diurnal graph plotting.

2.6 Hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) modelling

The source region or origin of the air mass and the levels of air pollution at one location caused by the transport of air pollutants from another location were determined by HYSPLIT model that was developed by NOAA. The back trajectories of HYSPLIT indicate whether local air pollution sources have caused high levels of air pollution or whether the air pollution problem was affected by the wind. A computer based HYSPLIT 4.9 compiler was used in the current study to measure the daily hourly trajectories and used to estimate the backward trajectory cluster for pre-haze, haze, and post haze episodes during 2019 at two stations in Kuala Lumpur (Batu Muda and Cheras station) and one station in Putrajaya.

3.0 Results and discussion

3.1 Summary statistics of the pollutant gases in the air (24-hour average)

Table 2 shows the summary statistics of the pollutant's gases in the air on a 24 h average. The average concentration of $PM_{2.5}$ during the entire episode at Batu Muda station was 28.349 μg/m^3 while the concentrations of PM_{10} were recorded as being an average of 35.688 μg/m^3. The highest average concentrations were recorded for $PM_{2.5}$, PM_{10}, NO_2, O_3 as well as CO during haze episode compared to the pre-haze and post-haze episode where the concentration level of $PM_{2.5}$, PM_{10}, NO_2, O_3, and CO during haze episode were 61.78 μg/m^3, 72.11 μg/m^3, 18.003 ppm, 21.180 ppm, and 1.2605 ppm, respectively. For the concentration level of SO_2, it can be seen that the level was higher during the pre-haze episode which was 0.8405 ppm compared to haze and post-haze episodes where the values were 0.5656 ppm and 0.7380 ppm, respectively. Although the average concentration value for the air pollutants was higher during the haze episode, the maximum value for each of the pollutants recorded was different where the maximum value for $PM_{2.5}$ (138.416 μg/m^3), PM_{10} (151.529 μg/m^3), and CO (1.8161 ppm) were recorded during a haze episode, SO_2 (2.4090 ppm) during the pre-haze episode while NO_2 (29.497 ppm) and O_3 (37.750 ppm) were recorded at its maximum during the post-haze episode. This is due to the point sources that triggered the pollutants to be increased at a specific period.

For Cheras Monitoring Station in Table 3, it can be observed that the average concentration for each of the air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO) was higher during the haze episode where each of them recorded 59.54 μg/m^3, 70.41 μg/m^3, 0.8746 ppm, 17.623 ppm, 26.51 ppm, and 0.9485 ppm, respectively compared to pre-haze episode (23.22 μg/m^3, 31.10 μg/m^3, 0.8650 ppm, 16.119 ppm, 24.762 ppm, and

Table 2: Summary statistics of the pollutant gases in the air (24-h average) at Batu Muda Station, Kuala Lumpur

Entire Episode	No. of data	Minimum	Maximum	Average	Std. Deviation
PM_{10} (µg/m^3)	365	8.185	151.529	35.688	21.626
$PM_{2.5}$ (µg/m^3)	365	5.573	138.416	28.349	20.211
SO_2 (ppm)	365	0.0525	2.4090	0.7708	0.3924
NO_2 (ppm)	365	4.558	29.497	16.599	4.3569
O_3 (ppm)	365	2.788	37.750	16.289	6.2853
CO (ppm)	365	0.3920	1.8161	0.9792	0.2524
Pre-Haze Episode (1/1-30/7)					
PM_{10} (µg/m^3)	211	10.33	51.53	31.03	9.1543
$PM_{2.5}$ (µg/m^3)	211	6.334	42.815	23.280	7.8292
SO_2 (ppm)	211	0.0525	2.4090	0.8405	0.4446
NO_2 (ppm)	211	5.488	28.519	16.896	4.0838
O_3 (ppm)	211	2.788	33.518	14.934	5.3708
CO (ppm)	211	0.3920	1.4970	0.9199	0.1757
Haze Episode (31/7-24/9)					
PM_{10} (µg/m^3)	56	33.83	151.53	72.11	31.363
$PM_{2.5}$ (µg/m^3)	56	23.29	138.42	61.78	31.423
SO_2 (ppm)	56	0.1554	0.9472	0.5656	0.1827
NO_2 (ppm)	56	7.603	26.377	18.003	4.4324
O_3 (ppm)	56	8.574	37.425	21.180	6.8487
CO (ppm)	56	0.7699	1.8161	1.2605	.2321
Post-Haze Episode (25/9-31/12)					
PM_{10} (µg/m^3)	98	8.185	56.133	24.913	9.251833
$PM_{2.5}$ (µg/m^3)	98	5.573	52.768	20.161	8.450
SO_2 (ppm)	98	0.1517	1.5858	0.7380	0.3080
NO_2 (ppm)	98	4.558	29.497	15.158	4.5343
O_3 (ppm)	98	3.054	37.750	16.411	6.4328
CO (ppm)	98	0.4256	1.7343	0.9459	0.2955

0.7838 ppm) and post-haze episode (20.957 µg/m^3, 28.34 µg/m^3, 0.6565 ppm, 17.348 ppm, 18.371 ppm, and 0.8772 ppm). The maximum concentration value of $PM_{2.5}$ (135.530 µg/m^3), PM_{10} (151.47 µg/m^3), NO_2 (30.923 ppm), and CO (1.4784 ppm) were recorded during haze episodes while SO_2 (2.2885 ppm) and O_3 (53.077 ppm) were recorded during the pre-haze episode.

Similar to Cheras Station, Putrajaya Station in Table 4 also shows a similar trend where the average concentration level of pollutants gases during haze episode was the highest. The average concentration level of $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO during haze episode were 62.92 µg/m^3, 75.82 µg/m^3, 1.3285 ppm, 9.197 ppm, 26.820 ppm, and 0.8235 ppm while for pre-haze episode and post-haze episode were; pre-haze (25.18 µg/m^3, 33.57 µg/m^3, 1.1310 ppm, 8.447 ppm, 25.57 ppm and 0.6010 ppm); post-haze (20.728 µg/m^3, 28.83 µg/m^3, 0.8133 ppm, 9.104 ppm, 23.159 ppm, and 0.6474 ppm), respectively. It also can be observed that the maximum concentration value of particulate matters ($PM_{2.5}$, PM_{10}), and CO at Putrajaya station were recorded during haze episodes where the values were 145.39 µg/m^3, 164.37 µg/m^3, and 1.3787 ppm respectively while for SO_2 (4.7997 ppm), NO_2 (16.999 ppm), and O_3 (51.005 ppm), the maximum concentration values recorded were during the pre-haze episode. In non-haze days, Sulong et al. (2017) found that the source contribution of the air pollutants was due to the local emission, especially from traffic. A similar result was found by Rahman et al., (2011) where in Klang Valley, vehicular emission has been found to account for over 30% of the total particulate emission. In this study, the highest results of the air pollutants data were found due to the possibility the monitoring station is located near the

Table 3: Summary statistics of the pollutant gases in the air (24-hour average) at Cheras Station, Kuala Lumpur

Entire Episode	No. of data	Minimum	Maximum	Average	Std. Deviation
PM_{10} (µg/m^3)	365	14.56	151.47	36.39	21.026
$PM_{2.5}$ (µg/m^3)	365	9.564	135.530	28.187	19.520
SO_2 (ppm)	365	0.1372	2.2885	0.8105	0.3239
NO_2 (ppm)	365	5.678	30.923	16.680	4.0745
O_3 (ppm)	365	4.084	53.077	23.314	8.0691
CO (ppm)	365	0.2553	1.4784	0.8342	0.1890
Pre-Haze Episode (1/1-30/7)					
PM_{10} (µg/m^3)	211	14.99	77.65	31.10	8.8705
$PM_{2.5}$ (µg/m^3)	211	10.39	69.45	23.22	7.8750
SO_2 (ppm)	211	0.2288	2.2885	0.8650	0.3272
NO_2 (ppm)	211	5.678	27.923	16.119	4.1468
O_3 (ppm)	211	8.626	53.077	24.762	8.0508
CO (ppm)	211	0.2554	1.2561	0.7838	0.1891
Haze Episode (31/7-24/9)					
PM_{10} (µg/m^3)	56	26.30	151.47	70.41	33.212
$PM_{2.5}$ (µg/m^3)	56	19.63	135.53	59.54	31.547
SO_2 (ppm)	56	0.2468	1.6233	0.8746	0.3507
NO_2 (ppm)	56	9.186	30.923	17.623	4.3462
O_3 (ppm)	56	10.54	43.82	26.51	7.4654
CO (ppm)	56	0.5721	1.4784	0.9485	0.2062
Post-Haze Episode (25/9-31/12)					
PM_{10} (µg/m^3)	98	14.56	57.89	28.34	8.2980
$PM_{2.5}$ (µg/m^3)	98	9.564	49.530	20.957	7.5678
SO_2 (ppm)	98	0.1372	1.3100	0.6565	0.2435
NO_2 (ppm)	98	7.618	24.213	17.348	3.5650
O_3 (ppm)	98	4.084	30.060	18.371	6.1051
CO (ppm)	98	0.4957	1.1805	0.8772	0.1328

school where air quality data obtained was influenced by a high quantity of local traffic during schooling day (drop off and pick up the students using vehicles by parents or using public transport. Apart from local sources such as vehicles and industrial emissions as well as open burning, the higher concentration level during haze episode at Batu Muda station, Cheras station, and Putrajaya station compared to pre-haze and post-haze episodes were associated with biomass open burning and forest fires in Indonesia where most farmers usually burned the forest and peatland to clear, drain and do re-planting for industrial plantation purposes (Zainal, 2016). This activity becomes a norm for their country since this activity could save more money (Khan et al., 2020). Besides that, the haze usually occurs during the southwest monsoon season between June and September and becomes more severe during periods of dry weather (Alatas, 2019). The summary analysis of 24 h average data shows there were significant differences between pre-haze, haze, and post-haze episodes on air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, and CO) measured at Batu Muda, Cheras, and Putrajaya Station stations in 2019.

3.2 Diurnal variation graph of the air pollutant gases and meteorological factors

Fig. 3 to Fig. 8 illustrate the time variation between air pollutants gases ($PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3) and meteorological factors (temperature, relative humidity, and wind speed) throughout the year 2019. The data were presented on a monthly average and were divided into 3 episodes which were the pre-haze episodes started from 1st January to 30th July, the haze episodes (31st July to 24th September) and the post-haze episodes (25th September to 31st December 2019) at three different monitoring stations.

Table 4: Summary statistics of the pollutant gases in the air (24-h average) at Putrajaya Station, Putrajaya

Entire Episode	No. of data	Minimum	Maximum	Average	Std. Deviation
PM_{10} (µg/m^3)	365	13.28	164.37	38.78	22.9685
$PM_{2.5}$ (µg/m^3)	365	7.64	145.39	29.77	20.9454
SO_2 (ppm)	365	0.1829	4.7997	1.0760	0.5185
NO_2 (ppm)	365	1.506	16.999	8.739	2.8857
O_3 (ppm)	365	4.926	51.005	25.115	7.6080
CO (ppm)	365	0.2750	1.3787	0.6476	0.1523
Pre-Haze Episode (1/1-30/7)					
PM_{10} (µg/m^3)	211	13.28	78.05	33.57	9.8196
$PM_{2.5}$ (µg/m^3)	211	7.64	65.57	25.18	8.7524
SO_2 (ppm)	211	0.3010	4.7997	1.1310	0.5484
NO_2 (ppm)	211	1.506	16.999	8.447	2.8902
O_3 (ppm)	211	10.97	51.01	25.57	7.9750
CO (ppm)	211	0.2750	0.8582	0.6010	0.1109
Haze Episode (31/7-24/9)					
PM_{10} (µg/m^3)	56	26.90	164.37	75.82	36.2161
$PM_{2.5}$ (µg/m^3)	56	19.47	145.39	62.92	34.0046
SO_2 (ppm)	56	0.5133	2.2086	1.3285	0.4927
NO_2 (ppm)	56	2.871	16.938	9.197	2.7657
O_3 (ppm)	56	9.274	39.426	26.820	6.705
CO (ppm)	56	0.4903	1.3787	0.8235	0.2309
Post-Haze Episode (25/9-31/12)					
PM_{10} (µg/m^3)	98	15.05	59.68	28.83	8.7280
$PM_{2.5}$ (µg/m^3)	98	8.932	49.827	20.728	7.8611
SO_2 (ppm)	98	0.1829	1.6199	0.8133	0.3275
NO_2 (ppm)	98	3.046	15.976	9.104	2.8961
O_3 (ppm)	98	4.926	36.385	23.159	6.9298
CO (ppm)	98	0.4233	0.8352	0.6474	0.0871

Fig. 3 and Fig. 4 show the time variation of $PM_{2.5}$ and PM_{10} at all three monitoring stations which are Batu Muda, Cheras, and Putrajaya. From the figures, it can be seen that the concentration level of $PM_{2.5}$ and PM_{10} was at the highest during haze episode compared to other episodes (pre-haze and post-haze) which happens from the end of July to end of September. The result also found coherent to the finding from Abdullah et al. (2011) where the PM_{10} concentrations were higher, and they pointed out transboundary transport of air pollutants from biomass burning from neighbouring countries as one of the factors that contribute to the concentration of PM_{10}.

During the haze, it was observed that the emission level was higher compared to the non-haze period, indicating the emission of large quantities of gases and particulate matter during the fires of forests, such as greenhouse gases, photochemical reactions, and fine and coarse particulates that adversely affect the environment and health. Thus, the levels of PM_{10} and $PM_{2.5}$ rise steadily during the haze period. By observing the effects of the haze and non-haze periods, the results show the same trends as the preliminary study conducted. The concentration of PM_{10} over the haze period was higher than that of the Malaysia Ambient Air Quality Guidelines (MAAQG) (Rahman et al., 2015)., A study over the haze period found that there was an exceptionally high level of total suspended solid value (Yassen & Jahi, 2007). It was also observed that the PM_{10} concentrations were more consistent and the transboundary transport of biomass-burning air pollutants from surrounding countries was one of the factors contributing to the PM_{10} concentration (Abdullah et al., 2011).

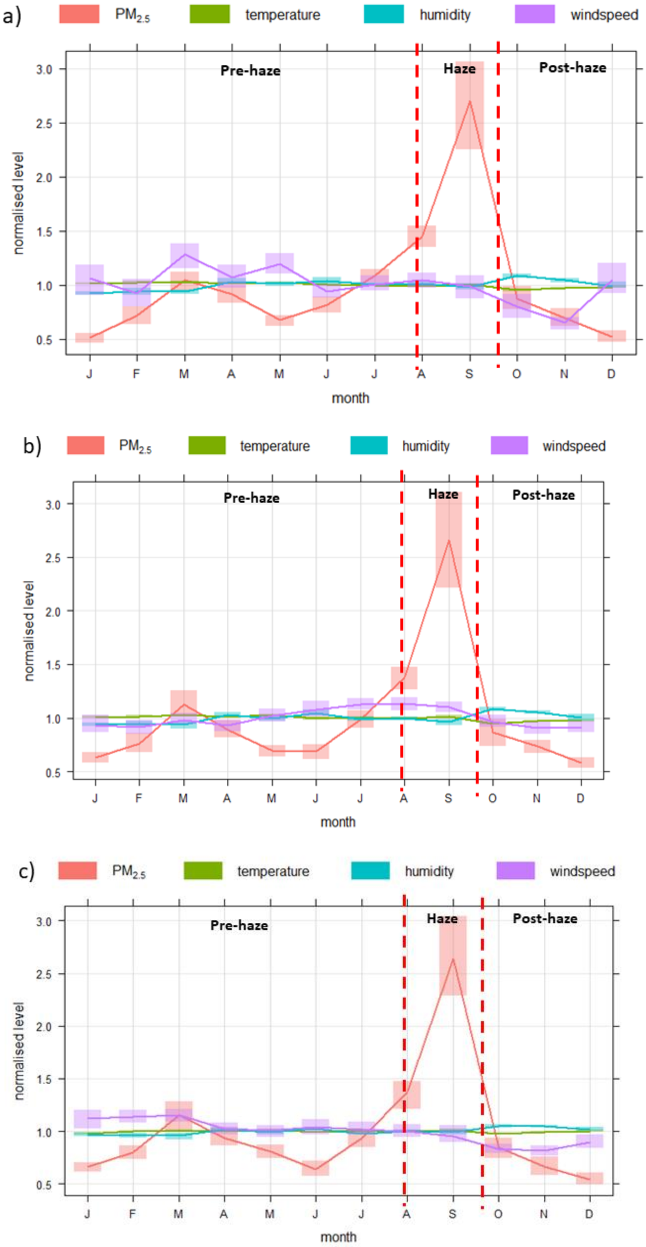

Fig. 3: Diurnal variation graph of particulate matter 2.5 ($PM_{2.5}$), temperature (T), relative humidity (RH), and windspeed (Ws) at a) Batu Muda Station, Kuala Lumpur, b) Cheras Station, Kuala Lumpur, and c) Putrajaya Station, WP. Putrajaya

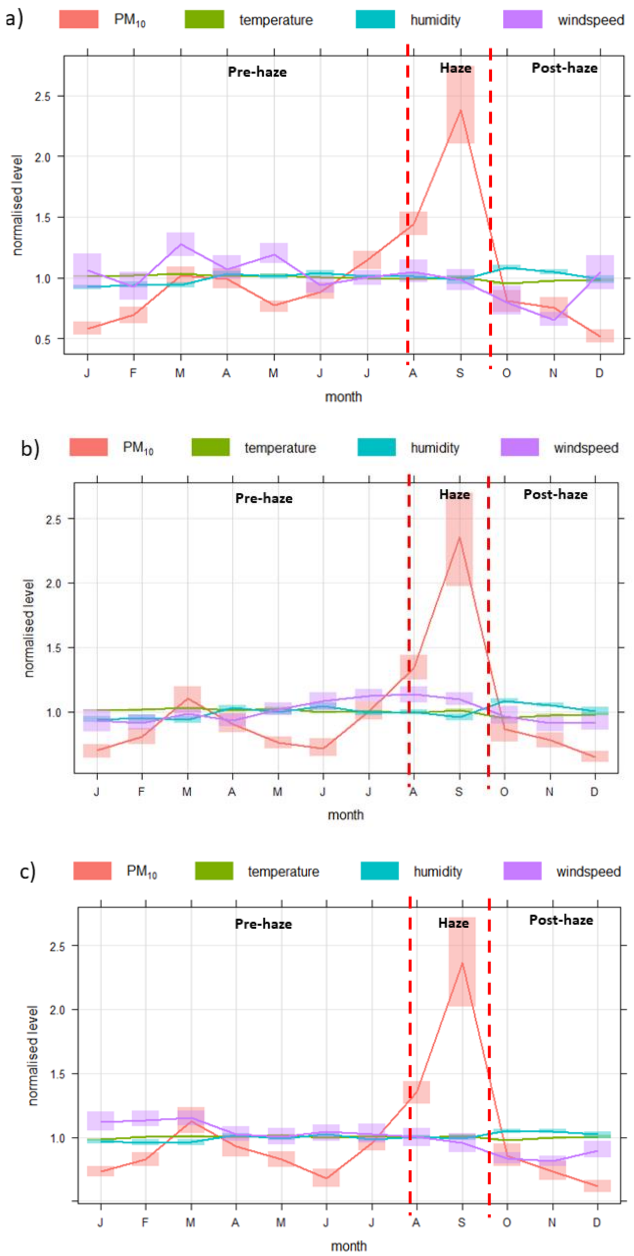

Fig. 4: Diurnal variation graph of particulate matter 10 (PM_{10}), temperature (T), relative humidity (RH), and windspeed (Ws) at a) Batu Muda Station, Kuala Lumpur, b) Cheras Station, Kuala Lumpur, and c) Putrajaya Station, WP. Putrajaya

Several studies had recorded excess deaths or global premature fatalities due to air pollution in urban and industrial areas (Anderson et al., 2012). The growth in population, manufacturing operations, and the number of vehicles in cities are also the key causes of urban air pollution. Jamhari et al. (2014) stated that in developing countries like Malaysia, which have a substantially growing number of motor vehicles, finer fractions of atmospheric aerosols, such as $PM_{2.5}$, were relevant. It may cause adverse health effects, such as increased mortality and morbidity in adults daily (Anderson et al., 2012).

Fig. 5 focuses on the time variation of CO. At all three monitoring stations, it can be seen that the concentration of CO was at the highest during haze episodes compared to pre-haze and post-haze episodes. Approximately two-thirds of the carbon monoxide in the atmosphere was responsible for anthropogenic emissions and the remaining one-third was responsible for natural emissions. It was generated by incomplete carbonaceous fuel combustion including wood, petrol, coal, kerosene, and natural gas (Khan et al., 2015). Other than that, CO was also produce through open burning activities and aircraft emissions. Vehicle

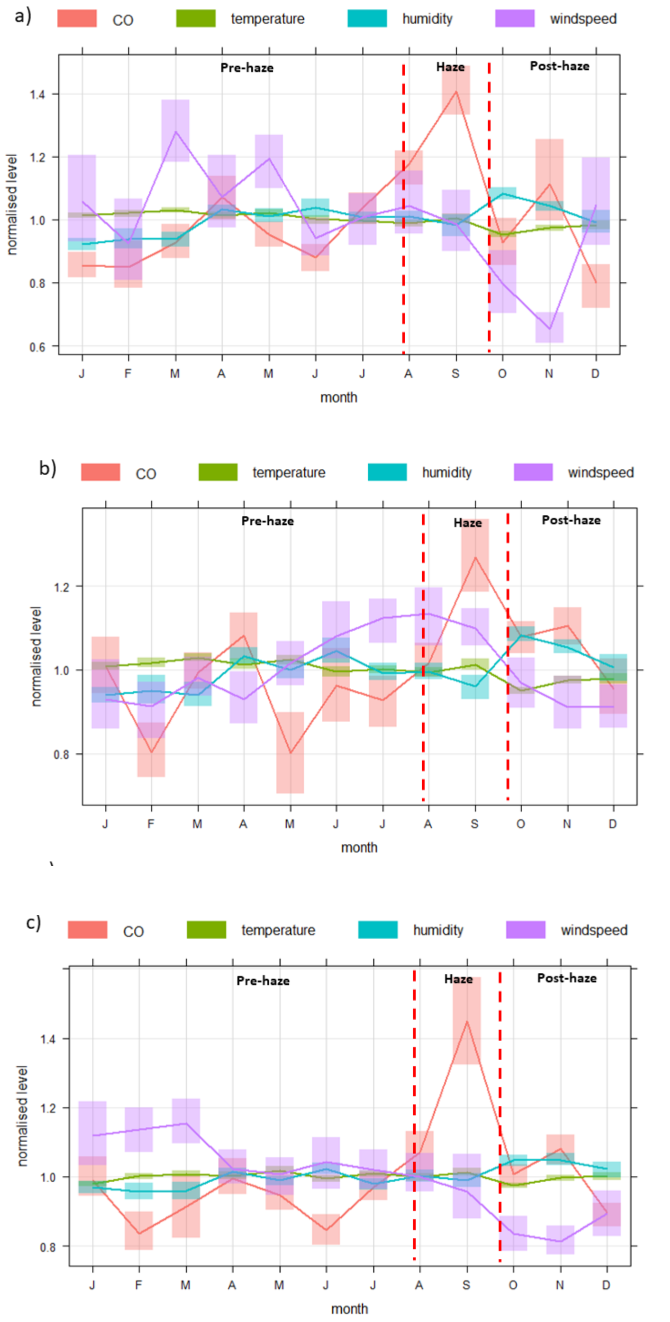

Fig. 5: Diurnal variation graph of carbon monoxide (CO), temperature (T), relative humidity (RH), and windspeed (Ws) at a) Batu Muda Station, Kuala Lumpur, b) Cheras Station, Kuala Lumpur, and c) Putrajaya Station

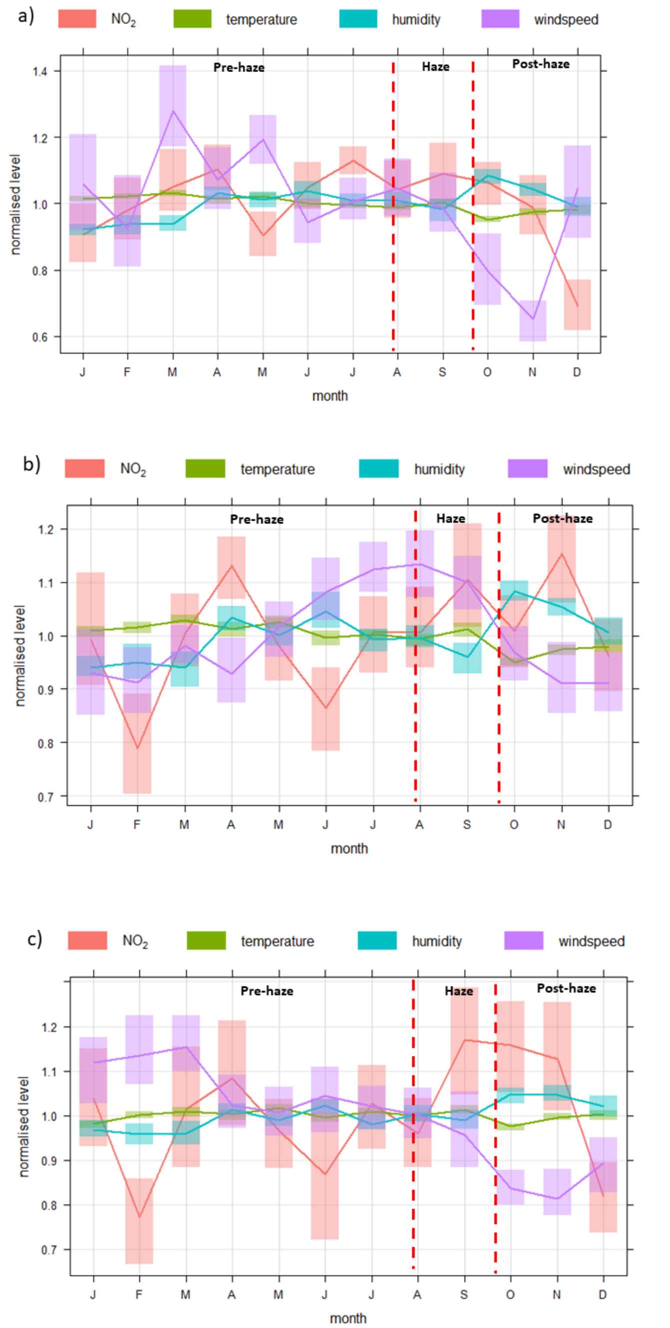

Fig. 6: Diurnal variation graph of nitrogen dioxide (NO_2), temperature (T), relative humidity (RH), and windspeed (Ws) at a) Batu Muda Station, Kuala Lumpur, b) Cheras Station, Kuala Lumpur, and c**)** Putrajaya Station, WP. Putrajaya

emissions were said to be the largest anthropogenic source of CO in Malaysia.

The increased number of vehicles registered from 28.18 million in 2017 to 31.2 million as of 31 December 2019 shows the increased number of vehicles on road (Wang et al., 2020), thus causing the emission of CO to increase. Due to its location as one of the most developed areas in terms of rapid urbanization, population growth, and industrial activities, the three locations were constantly exposed to the problem of air quality. This station is also in a school area, residential area, and is surrounded by major roads which experience heavy traffic, particularly during the morning rush hour. Traffic congestion, particularly during the morning peak between 7:00 am to 9:00 am, led to a higher amount of CO in the atmosphere (Mohamad et al., 2015). This phenomenon was considered to correlate directly with the number of motor vehicles at the three stations, which were located in the school area, residential areas,

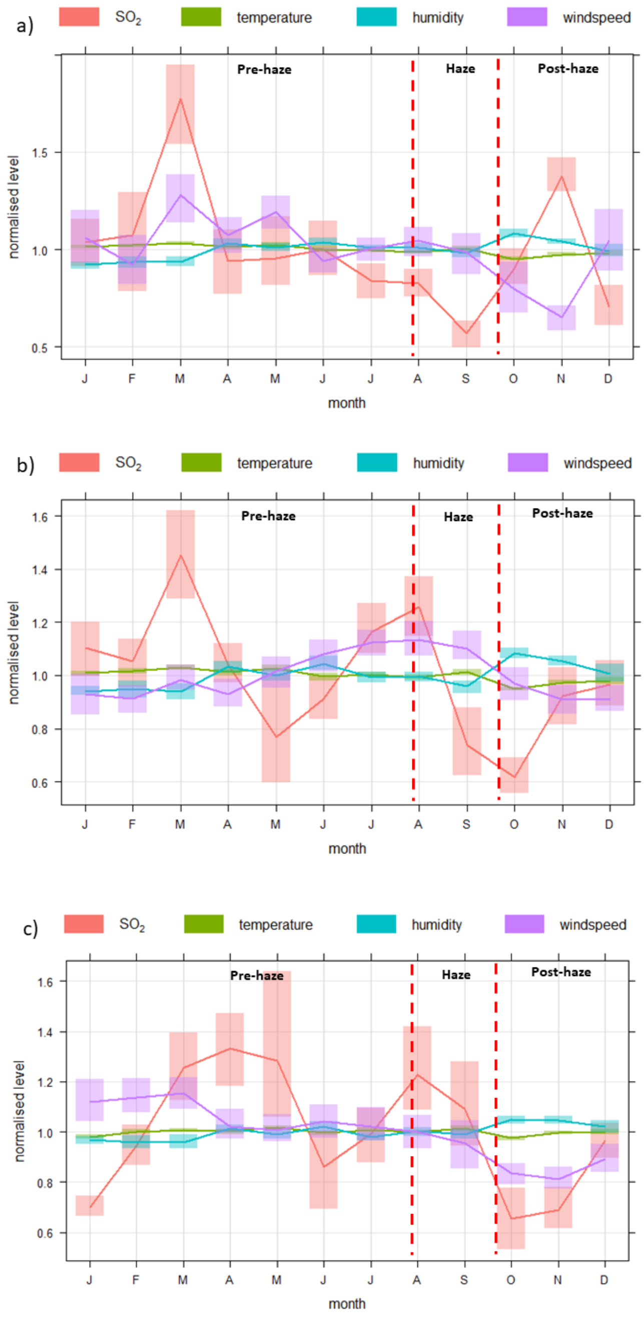

Fig. 7: Diurnal variation graph of sulphur dioxide (SO_2), temperature (T), relative humidity (RH), and windspeed (Ws) at a) Batu Muda Station, Kuala Lumpur, b) Cheras Station, Kuala Lumpur, and **c)** Putrajaya Station, WP. Putrajaya.

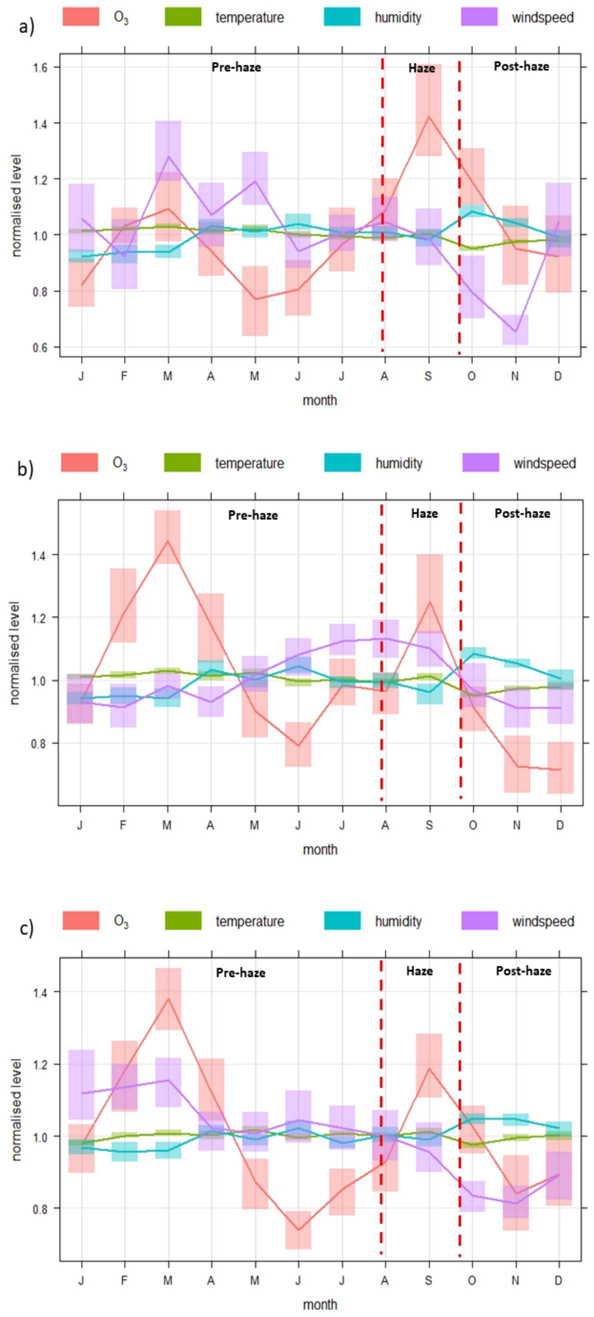

Fig. 8: Diurnal variation graph of ozone (O_3), temperature (T), relative humidity (RH), and windspeed (Ws)) at a) Batu Muda Station, Kuala Lumpur, b) Cheras Station, Kuala Lumpur, and **c)** Putrajaya Station, WP. Putrajaya.

and at these particular times, the number of motor vehicles increased significantly as people were going to work and children to school. In the latter part of the afternoon, CO concentration peaked from 5:00 pm in line with the evening rush hour when people started returning home from work (Azmi et al., 2010).

The late evening peak can also be attributed to meteorological conditions, particularly atmospheric stability, and wind speed (Azmi et al., 2010). Other than that, according to WHO, CO was also produced indoors by heating and cooking sources of combustion (Jabatan Pengangkutan Jalan Malaysi, 2020). In developing countries, the most important source of exposure to CO in indoor air emissions were defective devices, incorrectly installed, poorly maintained, or poorly ventilated cooking or heating devices that burn fossil fuels (WHO, 2010). Without properly functioning safety features, clogged chimneys, wood-burning fireplaces, decorative fireplaces, gas burners, and supplementary heaters could vent CO into indoor spaces (WHO, 2010). Incomplete oxidation during combustion may result in high indoor air concentrations of CO.

Meanwhile, Fig. 6 focuses on the time variation of NO_2. It can be seen that the concentration level of NO_2 at Batu Muda Station, Cheras Station, and Putrajaya Station are fluctuating throughout the entire episodes from January to December 2019. At Batu Muda Station, the maximum peak was during the pre-haze episode which was in between January to July while at Cheras Station, the peak occurred at each of the episodes which were in between March to April (pre-haze episode), September (haze episode) and in November (post-haze episode). At Putrajaya Station, the peak can be seen during the haze episode which was in September. In general, NO_2 was not released directly into the air. It forms when NO and other NOx react with other chemicals in the air to form NO_2. The presence of NO_2 in urban outdoor air was primarily caused by traffic. Nitric oxide (NO) emitted by motor vehicles or other processes of combustion such as from factories and coal-burning power plants, combines with oxygen in the atmosphere, producing NO_2 (United States Environmental Protection Agency, 2005).

According to EPA, the largest sources of emissions were cars, buses, and trucks, followed by power plants, diesel-powered heavy equipment for construction and other mobile engines, and industrial boilers (US EPA, 2017). In Malaysia, motor vehicles were responsible for over 49% of the NO_2 emitted into the atmosphere. It is estimated that a total of 203,235 metric tonnes of NO_2 emissions were released by motor vehicles in the country in 2008. Besides that, the country's power stations account for some 27% of total NO_2 emissions, with an estimated total release of 111,858 metric tonnes of NO_2 while 21% of the total NO_2 released contributed to the industrial sector (Salahudin et al., 2013). These values are estimated to increase significantly in the future due to the increased number of vehicles' registration based on the record in JPJ (Jabatan Pengangkutan Jalan Malaysia, 2020).

Fig. 7 shows the time series of SO_2 while Fig. 8 shows the time series of O_3 at all three monitoring stations (Batu Muda, Cheras, and Putrajaya). The concentration level of SO_2 was at the highest during pre-haze episodes compared to haze and post-haze episodes at all the monitoring stations (Batu Muda, Cheras, and Putrajaya). At Batu Muda Station, the concentration of SO_2 was the lowest during haze episodes while at Cheras and Putrajaya Stations, the minimum concentration level of SO_2 can be seen during post-haze episodes. The SO_2 was formed due to human activity or anthropogenic sources, such as the combustion of solid and fossil fuels accounts for over 80% of SO_2 emissions (Peavy et al., 1985). Human sources were the main contributors of sulphur oxides which include industrial processes and fuel combustion primarily from power stations. In Malaysia, 48% of total SO_2 emissions were generated in and around the country by power stations. This amounted to 78,416 metric tonnes of atmospheric SO_2 generated in total (Salahudin et al., 2013). The main operator that handles the power stations is Tenaga Nasional Berhad (TNB) which is linked to the national grid of electrical supply. There are 41 power stations in Malaysia used as main combustors with multiple resources which include oil, coal, gas, biomass, steam, and water.

Other than that, industrial processes were other significant contributors to the release of SO_2 into the environment which contributed 24% of total SO_2 emission which is approximately equal to 36,938 metric tonnes (Salahudin et al., 2013). The industrial sectors include the manufacturing, service sector, and transportation also contributed to the anthropogenic SO_2 in the atmosphere. Emission from motor vehicles contributes to about 8% or 12,865 metric tonnes (Salahudin et al., 2013). This was due to the low gasoline sulphur content, which was about 0.03 percent by mass. (Peavy et al., 1985). The daily trend at all three locations was nearly the same, and the results were considered to be influenced by these factors near the monitoring stations themselves.

At Batu Muda Station, the maximum peak of O_3 can be seen in between haze and post-haze episodes at the end of September and early October. For Cheras and Putrajaya Stations, both the stations show that the concentration level of O_3 was at the maximum during a pre-haze episode. O_3 trends demonstrated that the formation of this gas was influenced by sunlight through photochemical reactions (Atkinson, 2000) since O_3 was the major photochemical oxidant which makes up approximately 90 percent of the oxidant pool (Peavy et al., 1985). O_3 is an oxygen allotrope, much less stable than the diatomic allotrope O_2, which breaks down to O_2 in the lower atmosphere (Mishra, 2015).

O_3 is formed from dioxygen through the action of ultraviolet (UV) light and electrical discharges within the atmosphere of the earth. O_3 occurs in the upper atmosphere of the earth and at ground level. A naturally occurring gas in the upper atmosphere that filters the ultraviolet (UV) radiation of the sun is stratospheric ozone. Typically, this is known as good ozone because it decreases the harmful effects of ultraviolet (UV-B) radiation (Mohanakumar, 2008). According to Department for Environment, the atmospheric region is between 10 and 50 kilometres above the surface of the earth in the stratosphere. Solar wavelengths in the ultraviolet range between 180-240 nanometres are absorbed and separated by oxygen molecules (which are made of two oxygen atoms). Some of the resulting unattached pairs of oxygen atoms then recombine into triplets to form ozone.

Ground level or troposphere is a lower layer of the atmosphere that is known as bad ozone (Mohanakumar, 2008). It easily responds to other molecules, making it extremely toxic to living organisms. Michael et.al. (Jenkin & Clemitshaw, 2000) in their studies mentioned that ozone was not emitted directly into the air at ground level but was produced by chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOC). This occurs when the pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants, and other sources react chemically in the presence of sunlight. The reaction then will produce ozone.

Air pollutants gases were affected by meteorological factors such as temperature, relative humidity, and wind speed. As can be seen in Fig. 3 to Fig. 8, the concentration level of all the pollutant gases ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO) during the pre-haze, haze, and post-haze episodes at all three monitoring stations were directly proportional to the relative humidity and inversely proportional to the wind speed and temperature. The higher the concentration level of pollutants gases, the higher the relative humidity and the lower the wind speed and temperature.

The haze was closely related to temperature, wind speed, and relative humidity (Luan et al., 2018). Both primary and secondary contaminants were transported by windspeed from a point source to a non-point source (Dawson et al., 2007). The lower wind speed decreases particle dispersion, which allows the number of particles in the ambient air to increase (Alias et al., 2020). Karar & Gupta (2006) also noted that low windspeed allows the levels of pollution to increase. In contrast to high wind speed, the dispersion of dust particles by erosion and re-suspension was increased by higher wind speed, thereby flushing the contaminants out of the system.

The particle dispersion allows the particulate matter in ambient air to decrease (Alias et al., 2020). Winds move particles to other regions during different monsoon seasons, hundreds of kilometres away from their sources. (Csavina et al., 2014). This situation might explain the transboundary movement of particulate matter from one region to another, depending on prevailing wind conditions. In addition, Deng et al. (2016) found a high concentration of particulate matter, thus degrading the visibility of humans during haze events. As hygroscopic particles absorb substantial water at high relative humidity (RH), the light dispersion of aerosols depends on ambient RH, and this results in low visibility. On top of that, Gupta & David Cheong (2007) mentioned that in the tropics, where the weather was generally hot and humid due to high ambient RH, the percentage of water vapor retained in the air was also high (about 60%). The particles appear to coagulate, creating larger particles until gravity falls to the ground.

A study by Bhawar & Devara (2010) found that the water vapour condensation takes place on aerosols with increasing RH. Che et al. (2007) suggested that the aerosols can develop rapidly under high RH while the secondary aerosols play an important role in the growth of typical haze weather. Friedlander et al., (2000) and Khan et al. (2020) also stated that the hygroscopic ionic composition of aerosols rises under periods of higher RH, such as sulphate, nitrate, and water vapor, which are potential light dispersing species, resulting in reduced visibility.

3.3 Hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) modelling

The effect of haze is aggravated in people with pre-existing heart or lung disorders. Haze exposure can have various health implications, including acute symptoms such as cough, wheezing, shortness of breath, and a feeling of tiredness and weakness. However, the harmful health effects of a few minutes of haze exposure are temporary and usually do not lead to long-term health issues. The study used HYSPLIT to show the winding path at various altitudes to understand how wind movement causes haze formation during the selected period of the month.

The Southwest Monsoon (SWM) from June to September and the Northeast Monsoon (NEM) from December to March are two monsoon regimes in Peninsular Malaysia (Khan et al., 2016). During the SWM, the southwest wind dominates the wind pattern in Peninsular Malaysia, making the weather dry while strong north-east winds dominate during NEM in Peninsular Malaysia, causing wet weather.

Khan et al. (2016) reported that the RH was below 90% during SWM, while the temperature was found to vary within 26 °C to 32 °C range, making the rainfall events relatively short during this season. The accumulation of air particles and reactive gases in the ambient air over this area increases during the dry season, especially due to the burning of peat soil. The aerosol levels are alleged to be highly affected by changes in the monsoon seasons (Juneng et al., 2009).

Fig. 9 to Fig. 14 show the backward trajectories during pre-haze (January to July), haze (end of July to September), and post-haze (end of September to December) episodes of $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3. During the pre-haze episode, the source of the haze, mostly from Malaysia and a little part from Sumatera were observed.

The haze from Malaysia was caused by the human activities in Malaysia due to the open burning, vehicles emission, combustion from industry, and agricultural activities i.e., burning of paddy fields and peatlands for replanting. Fossil fuels from vehicles majorly contribute to air pollution. Vehicles emit more than half of nitrogen oxides in the air and become the main source of global warming emissions (Union of Concerned Scientists, 2014). Air pollution from vehicles is divided into two which is primary and secondary. Primary pollution is pollution that emits directly into the atmosphere while secondary pollution occurs when there is a chemical reaction between pollutants in the atmosphere (Australia State of Environment, 2016). Pollutants such as particulate matter, nitric oxide, carbon monoxide, lead, and organic compounds emitted from the vehicles causing a high level of pollution while manufacturing industries release a huge amount of carbon monoxide, hydrocarbons, organic compounds, and chemicals into the air thus depleting the air quality. Air emissions from industrial agriculture such as ammonia, hydrogen sulphide, particulate matter, volatile organic compounds, pesticides, and other airborne agriculture pollution impact climate and affect human health. Industrial farming operation contributes to the greenhouse gases while animal waste from all livestock emits an odour, and this odour consists of potentially harmful hydrogen sulphide.

During the haze episode, it indicated that forest burning due to agriculture activities in Sumatra, Indonesia was the main cause of the haze before it spread out to Malaysia.

Haze episodes in Malaysia occurred due to the local and transboundary impact. According to BBC News dated 16 September 2019 (BBC News, 2019), forest fires in Sumatra, Indonesia in 2019 were the main cause of the haze in Malaysia. Many farmers in Indonesia practice shifting agriculture, which is a traditional farming method that involves clearing tracts of forested land for cultivation using the slash-and-burn method. This practice has increased in recent decades as large-scale burning and is carried out to prepare land for the planting of commercial crops such as oil palm. On top of that, factors of El Niño and poor forest management were said to be some of the factors that uncontrolled forest fires in Indonesia (Koh & Ho, 2013). El Niño is a phenomenon caused by a continuous increase in the sea surface temperature of the Pacific Ocean. This climatic phenomenon affects weather patterns and results in less rainfall and storms. The hot and dry weather conditions triggered forest fires and strong winds during the southwest monsoon help to spread the haze produced by such fires throughout Southeast Asia (Grove, 2007).

During the post-haze episode, the haze spread from Sumatra, Indonesia to Malaysia before spreading further to Vietnam, Cambodia, Thailand, Laos, China, and Taiwan. This makes the air quality in those countries deteriorated while air quality in Indonesia and Malaysia gradually improved. The spreading of the haze is associated with meteorological effects such as temperature, relative humidity, and wind speed.

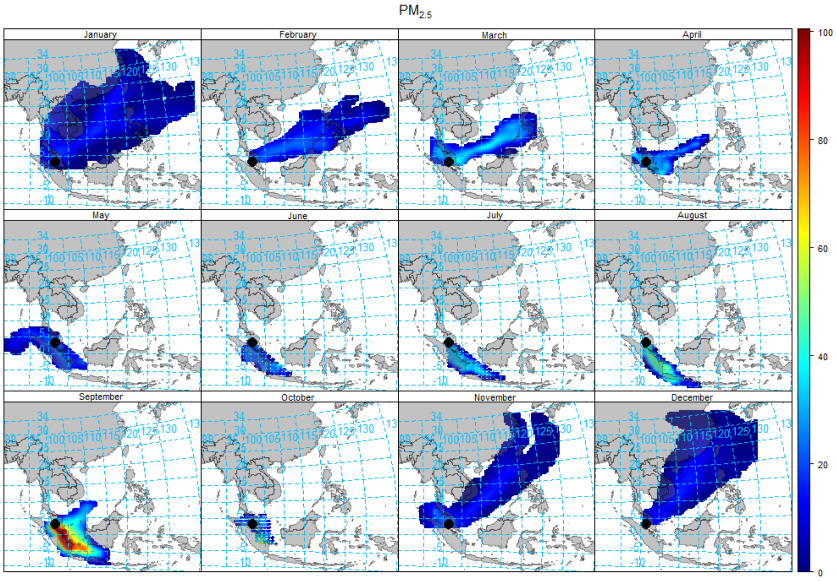

Fig. 9: Backward trajectories of particulate matter 2.5 ($PM_{2.5}$)

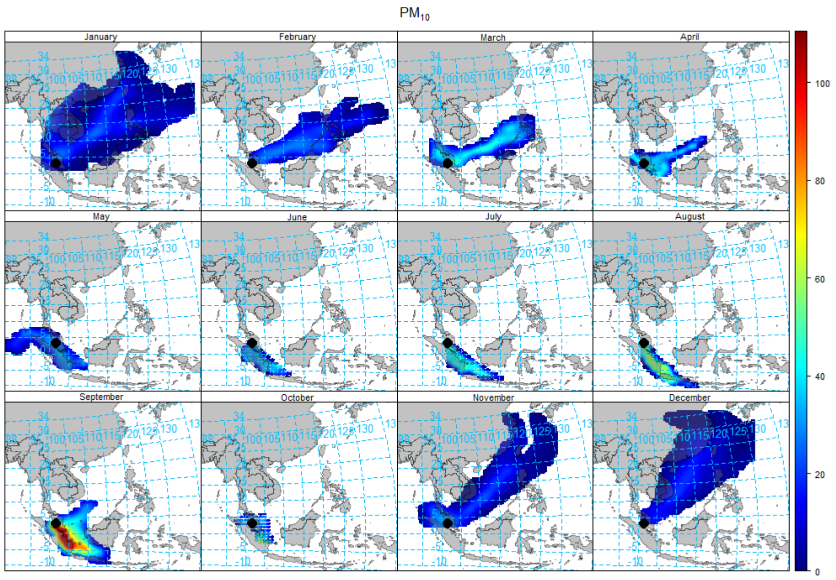

Fig. 10: Backward trajectories of particulate matter 10 (PM_{10})

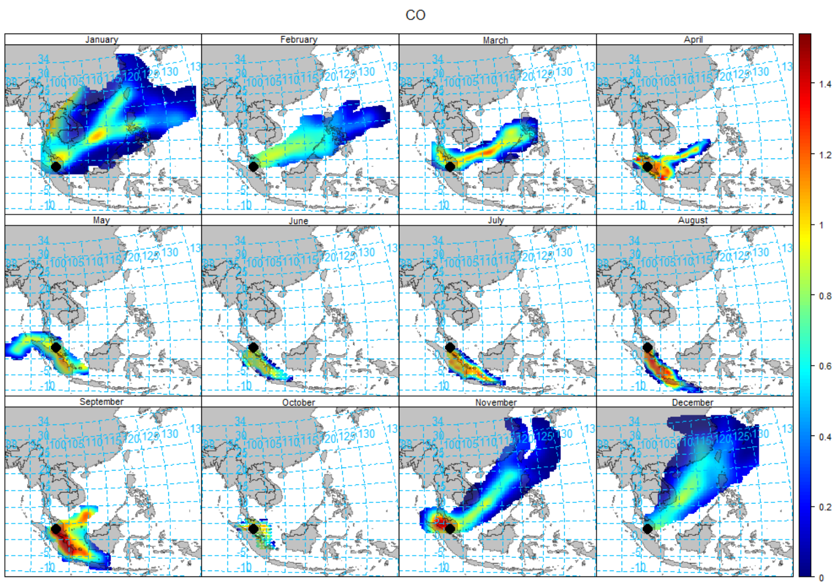

Fig. 11: Backward trajectories of carbon monoxide (CO)

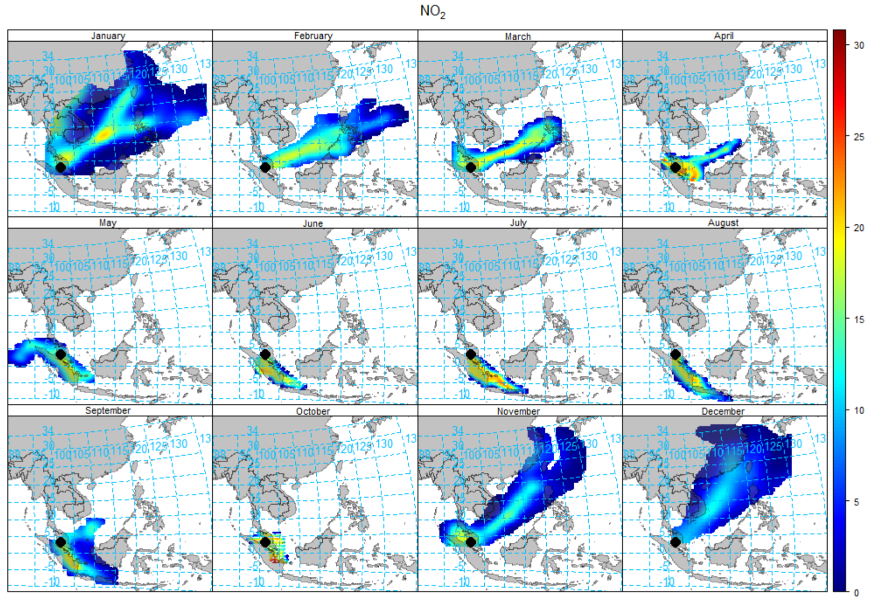

Fig. 12: Backward trajectories of nitrogen dioxide (NO_2)

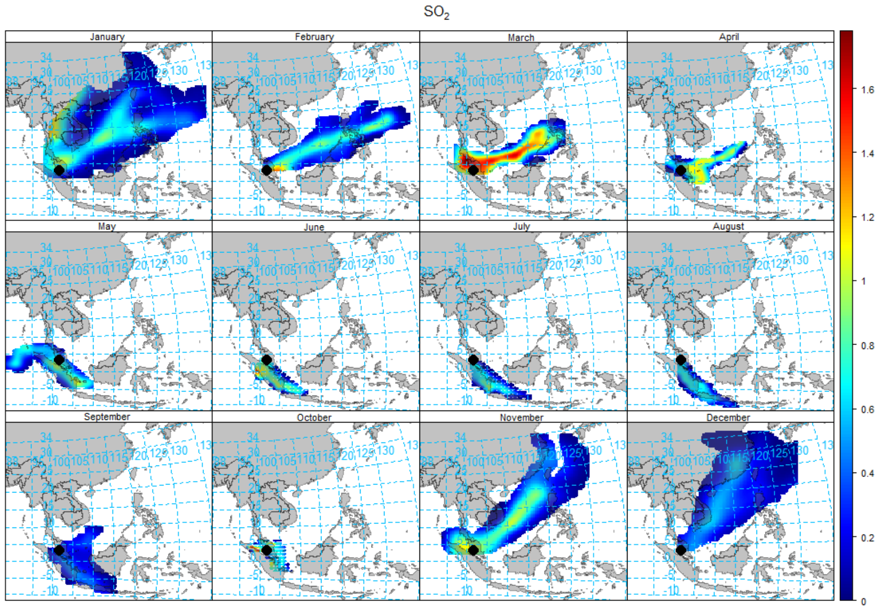

Fig. 13: Backward trajectories of sulphur dioxide (SO_2)

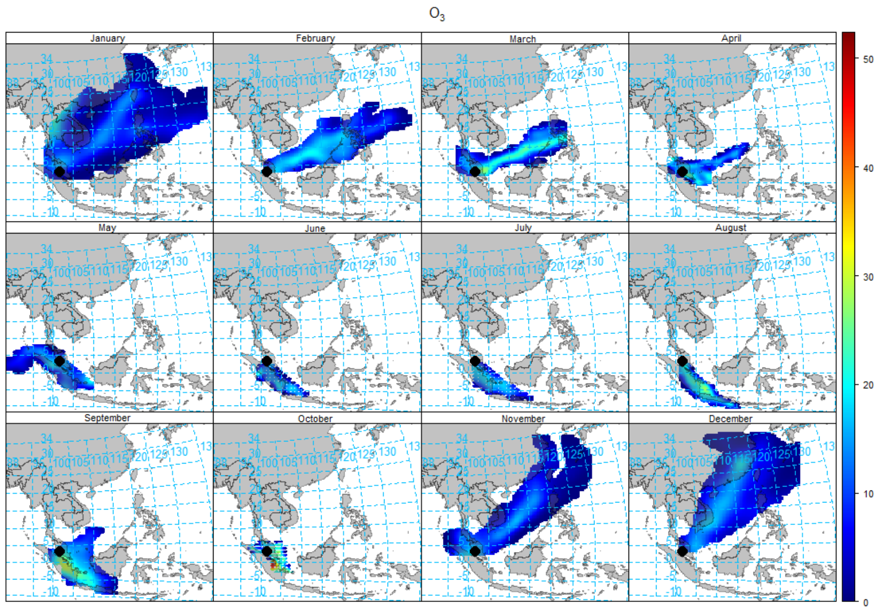

Fig. 14: Backward trajectories of ozone (O_3)

4.0 Conclusion

The observation data presented in this article represent Kuala Lumpur and Putrajaya region in the Central Malaysian Peninsular which includes Batu Muda Station and Cheras Station in Kuala Lumpur as well as Putrajaya Station in Wilayah Persekutuan Putrajaya. The 24 h average concentration of $PM_{2.5}$, PM_{10}, and CO during haze episode show the highest concentration where at Batu Muda station, the concentration of $PM_{2.5}$, PM_{10}, and CO was 61.78 µg/m^3, 72.11 µg/m^{3,} and 1.2605 ppm, respectively compared to pre-haze episode (23.280 µg/m^3, 31.03 µg/m^3, 0.9199 ppm) and post-haze episode (8.450 µg/m^3, 9.259 µg/m^3, 0.2955 ppm). The trend for this result was also similar to Cheras Station and Putrajaya Station which the concentration of $PM_{2.5}$, PM_{10}, and CO was the highest during haze episode where the concentration of $PM_{2.5}$, PM_{10}, and CO at Cheras Station was 59.54 µg/m^3, 70.41 µg/m^3, and 0.9485 ppm while at Putrajaya Station, the concentrations were 62.92 µg/m^3, 75.82 µg/m^3, and 0.8235 ppm, respectively. It was observed that the highest concentration of $PM_{2.5}$, PM_{10}, and CO during haze episodes at these locations were more impacted by the slash and burn method in Sumatera, Indonesia due to the releases of a large number of pollutant gases which then transported by wind and settles in Peninsular Malaysia as the wind from Sumatra passes Malaysia. For the concentration level of SO_2, NO_2, and O_3 in all three stations, the values have fluctuated throughout the entire episode. This was associated with the local sources such as vehicle emissions, industrial's emissions, and open burning by Malaysian citizens themselves. This condition became more severe due to the influence of meteorological factors such as temperature, relative humidity, wind speed, and wind direction that affects the concentration level of the pollutants. This study observed that the high level of relative humidity and low wind speed, as well as temperature, was associated with high levels of pollutants gases over the Kuala Lumpur and Putrajaya region. In conclusion, this finding is quite important as it can help the Malaysian government and NGOs to think about other alternatives that could help to reduce pollution as well as give awareness to Malaysian about the air quality in Malaysia.

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References

Abdullah, N. A., Shuhaimi, S. H., Toh, Y. Y., Shafee, A., & Maznorizan, M. (2011). The study of seasonal variation of PM_{10} concentration in Peninsula, Sabah and Sarawak. *Malaysian Meteorological Department*, *9*, 1–28.

Ahmed, M. J., Ali, M. K., Hossain, M., Siraj, S., & Ahsan, M. A. (2012). Determination of trace metals in air of Chittagong city-Bangladesh. *European Journal of Chemistry*, *3*(4), 416–420. https://doi.org/10.5155/eurjchem.3.4.416-420.645

Alatas, S. F. (2019). Against the grain: The political ecology of the haze | The Edge Markets. https://www.theedgemarkets.com/article/against-grain-political-ecology-haze

Alias, N. F., Khan, M. F., Sairi, N. A., Zain, S. M., Suradi, H., Rahim, H. A., Banerjee, T., Bari, M. A., Othman, M., & Latif, M. T. (2020). Characteristics, Emission Sources, and Risk Factors of Heavy Metals in $PM_{2.5}$ from Southern Malaysia. *ACS Earth and Space Chemistry*, *4*(8), 1309–1323. https://doi.org/10.1021/acsearthspacechem.0c00103

Anderson, J. O., Thundiyil, J. G., & Stolbach, A. (2012). Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health. *Journal of Medical Toxicology*, *8*(2), 166–175. https://doi.org/10.1007/s13181-011-0203-1

Atkinson, R. (2000). Atmospheric chemistry of VOCs and NOx. *Atmospheric Environment*, *34*(12), 2063–2101. https://doi.org/https://doi.org/10.1016/S1352-2310(99)00460-4

Australia State of Environment. (2016). Pollution types | Australia State of the Environment Report. https://soe.environment.gov.au/theme/ambient-air-quality/topic/2016/pollution-types

Azmi, S., Latif, M. T., Ismail, A., & Juneng, L. (2010). Trend and status of air quality at three different monitoring stations in the Klang Valley, Malaysia. *Air Quality, Atmosphere, & Health*, *3*, 53–64. https://doi.org/10.1007/s11869-009-0051-1

Barrientos. (2020). Indonesia Palm Oil Production by Year (1000 MT). https://www.indexmundi.com/agriculture/?country=id&commodity=palm-oil&graph=production

BBC News. (2019). Indonesia haze: Why do forests keep burning? https://www.bbc.com/news/world-asia-34265922

Bhawar, R. L., & Devara, P. C. S. (2010). Study of successive contrasting monsoons (2001–2002) in terms of aerosol variability over a tropical station Pune, India. *Atmospheric Chemistry and Physics*, *10*(1), 29–37. https://doi.org/10.5194/acp-10-29-2010

Che, H., Zhang, X., Li, Y., Zhou, Z., & Qu, J. J. (2007). Horizontal visibility trends in China 1981–2005. *Geophysical Research Letters*, *34*(24). https://doi.org/10.1029/2007GL031450

Csavina, J., Field, J., Félix, O., Corral-Avitia, A. Y., Sáez, A. E., & Betterton, E. A. (2014). Effect of wind speed and relative humidity on atmospheric dust concentrations in semi-arid climates. *Science of The Total Environment*, *487*, 82–90. https://doi.org/https://doi.org/10.1016/j.scitotenv.2014.03.138

Dawson, J. P., Adams, P. J., & Pandis, S. N. (2007). Sensitivity of $PM_{2.5}$ to climate in the Eastern US: a modeling case study. *Atmospheric Chemistry and Physics*, *7*(16), 4295–4309. https://doi.org/10.5194/acp-7-4295-2007

Deng, H., Tan, H., Li, F., Cai, M., Chan, P. W., Xu, H., Huang, X. & Wu, D. (2016). Impact of relative humidity on visibility degradation during a haze event: A case study. *Science of the Total Environment*, *569–570*, 1149–1158. https://doi.org/10.1016/j.scitotenv.2016.06.190

Forsyth, T. (2014). Public concerns about transboundary haze: A comparison of Indonesia, Singapore, and Malaysia. *Global Environmental Change*, *25*(1), 76–86. https://doi.org/10.1016/j.gloenvcha.2014.01.013

Friedlander, S. K. (2000). *Smoke, dust, and haze : fundamentals of aerosol dynamics*. Oxford University Press.

Grove, R. H. (2007). The Great El Niño of 1789-93 and its global consequences: Reconstructing an extreme climate event in world environmental history. *Medieval History Journal*, *10*(1–2), 75–98. https://doi.org/10.1177/097194580701000203

Gupta, A., & David Cheong, K. W. (2007). Physical characterization of particulate matter and ambient meteorological parameters at different indoor–outdoor locations in Singapore. *Building and Environment*, *42*(1), 237–245. https://doi.org/https://doi.org/10.1016/j.buildenv.2006.02.017

Hussain, H. (2019). Jerebu bakal pulih, ribut petir pula menyusul. Retrieved November 16, 2020, from https://www.sinarharian.com.my/article/48783/BERITA/Nasional/Jerebu-bakal-pulih-ribut-petir-pula-menyusul

Ismail, M. H. (2019). Malaysia berdepan jerebu bermula hari ini. https://www.sinarharian.com.my/article/40801/BERITA/Nasional/Malaysia-berdepan-jerebu-bermula-hari-ini

Jabatan Pengangkutan Jalan Malaysia. (2020). Online Statistic - JPJ Portal - Jabatan Pengangkutan Jalan. https://www.jpj.gov.my/en/web/main-site/statistik-dalam-talian

Jamhari, A. A., Sahani, M., Latif, M. T., Chan, K. M., Tan, H. S., Khan, M. F., & Mohd Tahir, N. (2014). Concentration and source identification of polycyclic aromatic hydrocarbons (PAHs) in PM_{10} of urban, industrial and semi-urban areas in Malaysia. *Atmospheric Environment*, *86*, 16–27. https://doi.org/https://doi.org/10.1016/j.atmosenv.2013.12.019

Jenkin, M. E., & Clemitshaw, K. C. (2000). Ozone and other secondary photochemical pollutants: Chemical processes governing their formation in the planetary boundary layer. *Atmospheric Environment*, *35*(16), 2499–2527. Elsevier Science Ltd. https://doi.org/10.1016/S1352-2310(99)00478-1

Juneng, L., Latif, M. T., Tangang, F. T., & Mansor, H. (2009). Spatio-temporal characteristics of PM_{10} concentration across Malaysia. *Atmospheric Environment*, *43*(30), 4584–4594. https://doi.org/https://doi.org/10.1016/j.atmosenv.2009.06.018

Kamaruzzaman, A., Saudi, A. S. M., Azid, A., Balakrishnan, A., Abu, I. F., & Amin, N. A. (2017). Assessment on air quality pattern: A case study in Putrajaya, Malaysia. *Journal of Fundamental and Applied Sciences*, *4*(1), 9–10. https://doi.org/10.4314/jfas.v9i4S.44

Karar, K., & Gupta, A. K. (2006). Seasonal variations and chemical characterization of ambient PM_{10} at residential and industrial sites of an urban region of Kolkata (Calcutta), India. *Atmospheric Research*, *81*, 36–53. https://doi.org/10.1016/j.atmosres.2005.11.003

Khan, M. F., Latif, M. T., Saw, W. H., Amil, N., Nadzir, M. S. M., Sahani, M., Tahir, N. M., & Chung, J. X. (2016). Fine particulate matter in the tropical environment: Monsoonal effects, source apportionment, and health risk assessment. *Atmospheric Chemistry and Physics*, *16*(2), 597–617. https://doi.org/10.5194/acp-16-597-2016

Khan, M. F., Hamid, A. H., Rahim, H. A., Maulud, K. N. A., Latif, M. T., Nadzir, M. S. M., Sahani, M., Qin, K., Kumar, P., Varkkey, H., Faruque, M. R. I., Guan, N. C., Ahmadi, S. P., & Yusoff, S. (2020). El Niño driven haze over the Southern Malaysian Peninsula and Borneo. *Science of the Total Environment*, *730*, 139091. https://doi.org/10.1016/j.scitotenv.2020.139091

Khan, M. F., Latif, M. T., Lim, C. H., Amil, N., Jaafar, S. A., Dominick, D., Nadzir, M. S. M., Sahani, M., & Tahir, N. M. (2015). Seasonal effect and source apportionment of polycyclic aromatic hydrocarbons in $PM_{2.5}$. *Atmospheric Environment*, *106*, 178–190. https://doi.org/10.1016/j.atmosenv.2015.01.077

Khan, Md Firoz, Sulong, N. A., Latif, M. T., Nadzir, M. S. M., Amil, N., Hussain, D. F. M., Lee V., Hosaini, P. N., Shaharom, S., Yusoff, N. A. Y. M., Hoque, H. M. S., Chung, J. X., Sahani, M., Tahir, N. M., Juneng, L., Maulud, K. N. A., Abdullah, S. M. S., Fujii, Y., Tohno, S., & Mizohata, A. (2016). Comprehensive assessment of $PM_{2.5}$ physicochemical properties during the Southeast Asia dry season (southwest monsoon). *Journal of Geophysical Research*, *121*(24), 14589–14611. https://doi.org/10.1002/2016JD025894

Koh, J., & Ho, S. (2013). Haze pollution | Infopedia. https://eresources.nlb.gov.sg/infopedia/articles/SIP_2013-08-30_185150.html

Laden, F., Neas, L. M., Dockery, D. W., & Schwartz, J. (2000). Association of fine particulate matter from different sources with daily mortality in six U.S. cities. *Environmental Health Perspectives*, *108*(10), 941–947. https://doi.org/10.1289/ehp.00108941

Luan, T., Guo, X., Guo, L., & Zhang, T. (2018). Quantifying the relationship between $PM_{2.5}$ concentration, visibility and planetary boundary layer height for long-lasting haze and fog–haze mixed events in Beijing. *Atmos. Chem. Phys.*, *18*(1), 203–225. https://doi.org/10.5194/acp-18-203-2018

Mabahwi, N. A. B., Leh, O. L. H., & Omar, D. (2014). Human Health and Wellbeing: Human Health Effect of Air Pollution. *Procedia - Social and Behavioral Sciences*, *153*, 221–229. https://doi.org/https://doi.org/10.1016/j.sbspro.2014.10.056

Martins, N. R., & Carrilho da Graça, G. (2018). Impact of $PM_{2.5}$ in indoor urban environments: A review. *Sustainable Cities and Society*, *42*, 259–275. https://doi.org/https://doi.org/10.1016/j.scs.2018.07.011

Mishra, A. K. (2015). Electrochemical Ozone Production. In *Nanocomposites in Wastewater Treatment*. CRC Press.

Mohamad, N. D., Ash'aari, Z. H., & Othman, M. (2015). Preliminary assessment of air pollutant sources identification at selected monitoring stations in Klang Valley, Malaysia. *Procedia Environmental Sciences*, *30*, 121–126.

Mohanakumar K. (2008). *Stratosphere Troposphere Interactions: An Introduction*. Springer Netherlands. https://doi.org/10.1007/978-1-4020-8217-7

Official Portal of Department of Environment. (2015). *Chronology of Haze Episodes n Malaysia*. https://www.doe.gov.my/portalv1/en/info-umum/info-kualiti-udara/kronologi-episod-jerebu-di-malaysia/319123

Peavy, H. S., Rowe, D. R., & Tchobanoglous, G. (1985). Environmental Engineering.

Nadason, M. (2015). Pertambahan Kenderaan Punca Sesak, Pencemaran. http://www.konsumerkini.net.my/v2/index.php/berita-terkini/rencana/1052-pertambahan-kenderaan-punca-sesak-pencemaran

Rahman, S. A., Hamzah, M. S., Wood, A. K., Elias, M. S., Salim, N. A. A., & Sanuri, E. (2011). Sources apportionment of fine and coarse aerosol in Klang Valley, Kuala Lumpur using positive matrix factorization. *Atmospheric Pollution Research*, *2*(2), 197–206. https://doi.org/10.5094/APR.2011.025

Rahman, S. R. A., Ismail, S. N. S., Raml, M. F., Latif, M. T., Abidin, E. Z., & Praveena, S. M. (2015). The assessment of ambient air pollution trend in Klang Valley, Malaysia. *World Environment*, *5*(1), 1–11.

Salahudin, S. N., Abdullah, M. M., & Newaz, N. A. (2013). Emissions : Sources, policies and development in Malaysia. *International Journal of Education and Research*, *1*(7), 1–12.

Sulong, N. A., Latif, M. T., Khan, M. F., Amil, N., Ashfold, M. J., Wahab, M. I. A., Chan, K. M., & Sahani, M. (2017). Source apportionment and health risk assessment among specific age groups during haze and non-haze episodes in Kuala Lumpur, Malaysia. *Science of the Total Environment*, *601–602*, 556–570. https://doi.org/10.1016/j.scitotenv.2017.05.153

Union of Concerned Scientists. (2014). Vehicles, Air Pollution & Human Health. https://www.ucsusa.org/resources/vehicles-air-pollution-human-health

United States Environmental Protection Agency (EPA). (2005). *Nitrogen Oxides (NOx), Why and How They Are Controlled*. http://www.epa.gov/ttn/catc

US EPA, O. (2017). 2017 National Emissions Inventory (NEI) Data. https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data

Wang, B., Eum, K.-D., Kazemiparkouhi, F., Li, C., Manjourides, J., Pavlu, V., & Suh, H. (2020). The impact of long-term $PM_{2.5}$ exposure on specific causes of death: exposure-response curves and effect modification among 53 million U.S. Medicare beneficiaries. *Environmental Health*, *19*(1), 20. https://doi.org/10.1186/s12940-020-00575-0

WHO. (2010). WHO guidelines for indoor air quality: selected pollutants. *Encyclopedia of Health*, 406–418. https://doi.org/10.1016/B978-0-12-384947-2.00550-X

Yassen, M. E., & Jahi, J. M. (2007). Investigation of Variations and Trends in TSP Concentrations in The Klang Valley Region, Malaysia. *Malaysian Journal of Environmental Management*, *8*, 57–68.

Zainal. (2016). *Root Problem of Forest Fire And Solutions in Completion (Study in The Riau Province)*.