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The concentration of major air pollutants during the movement control order due to the COVID-19 pandemic in the Klang Valley, Malaysia

Mohd Talib Latif[a,b,*], Doreena Dominick[c,d], Nor Syamimi Sufiera Limi Hawari[a], Anis Asma Ahmad Mohtar[a], Murnira Othman[e]

[a] Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia
[b] Department of Environmental Health, Faculty of Public Health, Universitas Airlangga, 60115 Surabaya, Jawa Timur, Indonesia
[c] Centre for Atmospheric Chemistry, University of Wollongong, Wollongong, NSW 2522, Australia
[d] School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW 2522, Australia
[e] Institute for Environment and Development (LESTARI), Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia

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ABSTRACT

The COVID-19 pandemic forced many governments across the world to implement some form of lockdown to minimalize the spread of the virus. On 18th March 2020, the Malaysian government put into action an enforced movement control order (MCO) to reduce the numbers of infections. This study aims to investigate the concentrations of air pollutants during the MCO in the Klang Valley. The concentrations of air pollutants were recorded by the continuous air quality monitoring system (CAQMS) operated by the Department of Environment. The results showed that there were significant reductions ($p < 0.05$) of PM_{10}, $PM_{2.5}$, NO_2 and CO during the MCO compared with the same periods in 2019 and 2018. The highest percentage of reduction during the MCO was recorded by NO_2 with a percentage reduction of between −55 % and −72 %. O_3 concentrations at several stations showed an increase due to the reductions of its precursors such as NO. Further investigation using diurnal patterns of air pollutant concentrations both before and during the MCO showed that NO_2 and CO were both reduced significantly during the rush hours, indicating the reduction in motor vehicles on the roads as a consequence of the MCO influenced the levels of these pollutants.

1. Introduction

The pandemic due to Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) or COVID-19 is a tragedy for the human race in this decade. In January 2020, the World Health Organization (WHO) declared the COVID-19 outbreak to be a Public Health Emergency of International Concern as the number of cases of infection was continuing to rise. The number of cases reached approximately 65 million with an estimated 1,507,018 deaths worldwide by the early of December 2020 (WHO, 2020). The COVID-19 pandemic started in Wuhan, China in late 2019 then spread rapidly across the globe, affecting almost all countries in the world (Dantas et al., 2020; Dong et al., 2020). The countries with the most infections include the USA, India, Brazil, Mexico, Spain, Russia, Germany, France, Italy, the United Kingdom and China (Gozali, 2020; WHO, 2020). Despite meteorological factors, air pollution might be one of the environmental drivers that exacerbated the risk of death due to COVID-19 as it may be possible for the virus to be transmitted via aerosols, adsorbed onto particulate matter or be airborne (Comber et al., 2020; Prather et al., 2020; van Doremalen et al., 2020). Sanità di Toppi et al. (2020) reported that COVID-19 virus was detected in aerosols up to three hours after aerosolization.

As a way of trying to slow down the morbidity and mortality rates of COVID-19, most of the severely affected countries enacted lockdown, where measures such as practising social distancing, the prohibition of public mass gatherings, the cancellation of festivals or events and the restriction of travel within or outside of the country in question were enforced (Das et al., 2020; Zambrano-Monserrate et al., 2020). Factories, industrial sectors and all other forms of economic activity were also forced to cease functioning while restaurants, markets, bars, schools and universities have been closed. Globally, however, there has also been a realization that lockdown may give rise to some positive impacts, particularly on atmospheric air quality (Kumar et al., 2020; Wyche et al.,

* Corresponding author at: Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia.
E-mail address: talib@ukm.edu.my (M.T. Latif).

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2021). Based on monitoring undertaken by satellite technology, the implementation of lockdown across the globe has noticeably reduced severe air pollution rates (Ghahremanloo et al., 2021). This phenomenon can be clearly seen in some of the world's major cities as reported by Kanniah et al. (2020), Joshi et al. (2020), Saadat et al. (2020), Sharma et al. (2020) and Ramachandran et al. (2020).

Lockdown reduced the number of vehicles on the roads, especially in major urban areas. Consequently, nitrogen dioxide (NO_2) gas, which mainly originates from the combustion of the fuel used for vehicles, has been dramatically reduced due to the reduction in vehicle exhaust emissions (Baldasano, 2020; Cameletti, 2020; Dutheil et al., 2020; Kerimray et al., 2020; Krecl et al., 2020; Lal et al., 2020; Lian et al., 2020; Paital et al., 2020; Pei et al.2020; Sarfraz et al., 2020; Tobías et al., 2020; Wang & Su, 2020). Wuhan, China is considered the epicentre of the coronavirus crisis and was the first city to impose lockdown measures, starting from 23rd January 2020 (Chong et al., 2020; Leung et al., 2020; Wu et al., 2020). According to Cole et al. (2020), the lockdown in China has drastically reduced air pollutant concentrations, particularly NO_2 and particulate matter with an aerodynamic diameter smaller than 2.5 micrometres ($PM_{2.5}$) by about -63 % (from 38 μg m^{-3} to 24 μg m^{-3}) and 35 % (from 62 μg m^{-3} to 22 μg m^{-3}), respectively. Another study by Bao and Zhang (2020) reported that the reduction in air pollution in northern Chinese cities was significantly linked with the movement restrictions, as results showed a decreasing trend in air pollutants including NO_2 (24.67 %), particulate matter with an aerodynamic diameter smaller than 10 micrometres or PM_{10} (13.66 %), SO_2 (6.76 %), $PM_{2.5}$ (5.93 %) and CO (4.58 %). In India, Mahato et al. (2020) revealed that the air quality based on National Air Quality Index in the megacity of Delhi, India, improved by about 40 %–50 % in just four days after lockdown was introduced on 24th March 2020. The concentrations of PM_{10} and $PM_{2.5}$ have shown the maximum reductions (>50 %) in comparison to the pre-lockdown phase. Studies in other parts of the world such as in Sao Paolo, Brazil by Nakada and Urban (2020) showed there was a drastic reduction of NO (up to −77.3 %), NO_2 (up to −54.3 %) and CO (up to −64.8 %). The only pollutant that showed an increase (around 30 %) in the study was ozone (O_3), due to the decrease in nitrogen monoxide (NO) levels during the lockdown period.

In Malaysia, the government implemented the Movement Control Order (MCO) or partial lockdown on 18th March 2020 in response to the COVID-19 crisis. By the early of December 2020, there had been 70,236 confirmed positive cases and 376 deaths. Statistics have shown that the Klang Valley recorded the highest number of confirmed cases, representing more than 40 % of the total cases in Malaysia (Department of Statistics Malaysia, 2020). An earlier study by Kanniah et al. (2020) over Southeast Asia and Malaysia using aerosol optical depth (AOD) observations from the Himawari-8 satellite, column density from Aura-OMI and ground-level continuous air pollutant measurements showed significant reductions of air pollutants such as PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO during the MCO. A study by Ash'aari et al. (2020) shows that 63 % of Malaysian Department of Environment stations showed significant reductions for $PM_{2.5}$ and CO, while all stations showed significant reductions in NO_2 concentrations during the MCO in Malaysia.

The Klang Valley represents a large fraction of the anthropogenic sources that have caused the deterioration of air quality over recent years. However, the urban air quality in these "red zones" may show some significant and positive changes as a result of the Malaysian government's MCO. The MCO might not only break the COVID-19 chain but also drastically reduce environmental pollution due to the reduction of activities and emissions from sources which cause air pollution. The MCO may temporarily result in positive feedback from the environment, and experts should identify the best way to sustain any positive changes in air quality over the long term. Therefore, this study aims to evaluate the changes in air pollutant concentrations in the Klang Valley, the most populated area in Malaysia, before and during the MCO, using data recorded continuously by the Malaysian Department of Environment. A comparison was also made between data recorded during the MCO and data recorded during the same periods of time in 2019 and 2018. The potential meteorological influences were also investigated for comparative purposes between the three different years studied (2018–2020).

2. Methodology

2.1. Study area

The Klang Valley was selected to study the impact of MCO as it is situated in the most populated area in Malaysia. Kuala Lumpur, the capital of Malaysia; Putrajaya, the administrative area of the Malaysian government; and part of Selangor state are located in the Klang Valley region. Currently, the population of the Klang Valley is around eight million and the number of vehicles moving around the Kuala Lumpur area on a normal day prior to the MCO was approximately 45,441 vehicles per day (Ministry of Transport, 2019). During the MCO period, the government was only allowing workers listed as working in the essential sectors to go to work and travel between states in Malaysia. This included any movement within the Klang Valley. All industrial activity was stopped, except industries in essential sectors, which were allowed to continue to operate.

2.2. Air quality, meteorological and mobility data

Major air pollutant (PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2 and O_3) concentrations and meteorological (temperature, wind speed, wind direction, relative humidity and solar radiation) data during the MCO (between 18th March and 22nd April 2020) were recorded on an hourly basis by the Pakar Scieno TW Sdn Bhd on behalf of the Malaysian Department of Environment. Measurements were taken from six continuous air quality monitoring stations (CAQMS) in the Klang Valley. Mobility data (Google LLC, 2020) were used to represent the traffic volume and industrial activities at the Klang Valley. The monitoring stations used were Batu Muda, Petaling Jaya, Cheras, Shah Alam, Klang and Putrajaya (Fig. 1). Batu Muda and Petaling Jaya stations are surrounded by busy major roads and are affected by emissions from heavy traffic. Cheras and Shah Alam are located in residential areas and near to highways and road traffic. Klang is located near to a port and industrial areas as well as a coal-fired power plant, which means that Klang is also affected by emissions from heavy traffic. Putrajaya is an administrative area of the Malaysian government. This station is influenced by motor vehicle emissions, especially early in the morning and in the late afternoon due to the movement of government staff arriving for work and then leaving work and returning home. All these monitoring stations are located within school compounds and are affected by urban activities within the Klang Valley. In this study, hourly measurements were used and the air pollutant concentrations recorded at all six stations using similar instruments were also analysed for the time period from 18th March to 22nd April for the past two years (2018 and 2019) for a comparison with the year 2020. Meanwhile, temporal patterns of air pollutant concentrations recorded at the same stations were analysed for the period of 1st January to 22nd April 2020 (before and during the MCO). The changes in mobility in the Klang Valley (represented by Kuala Lumpur and the Selangor state) were analysed using daily measurements (Google LLC, 2020).

The hourly concentrations of PM_{10} and $PM_{2.5}$ were measured using a Thermo Scientific tapered element oscillating microbalance (TEOM) 1405-DF (USA) monitor, while the hourly concentrations of CO and O_3 were measured using a Thermo Scientific Model 48i (USA) CO analyser and Thermo Scientific Model 49i (USA) O_3 analyser, respectively. The hourly SO_2 concentrations were measured using a Thermo Scientific Model 43i (USA) SO_2 analyser, while the NO_2 concentrations were measured using a Thermo Scientific Model 42i (USA) NO_2 analyser. Relative humidity and temperature were recorded using a Climatronic AIO 2 Weather Sensor (Climatronic Corporation, USA) (PSTW, 2018a). Due to the constraints of obtaining precipitation data from the

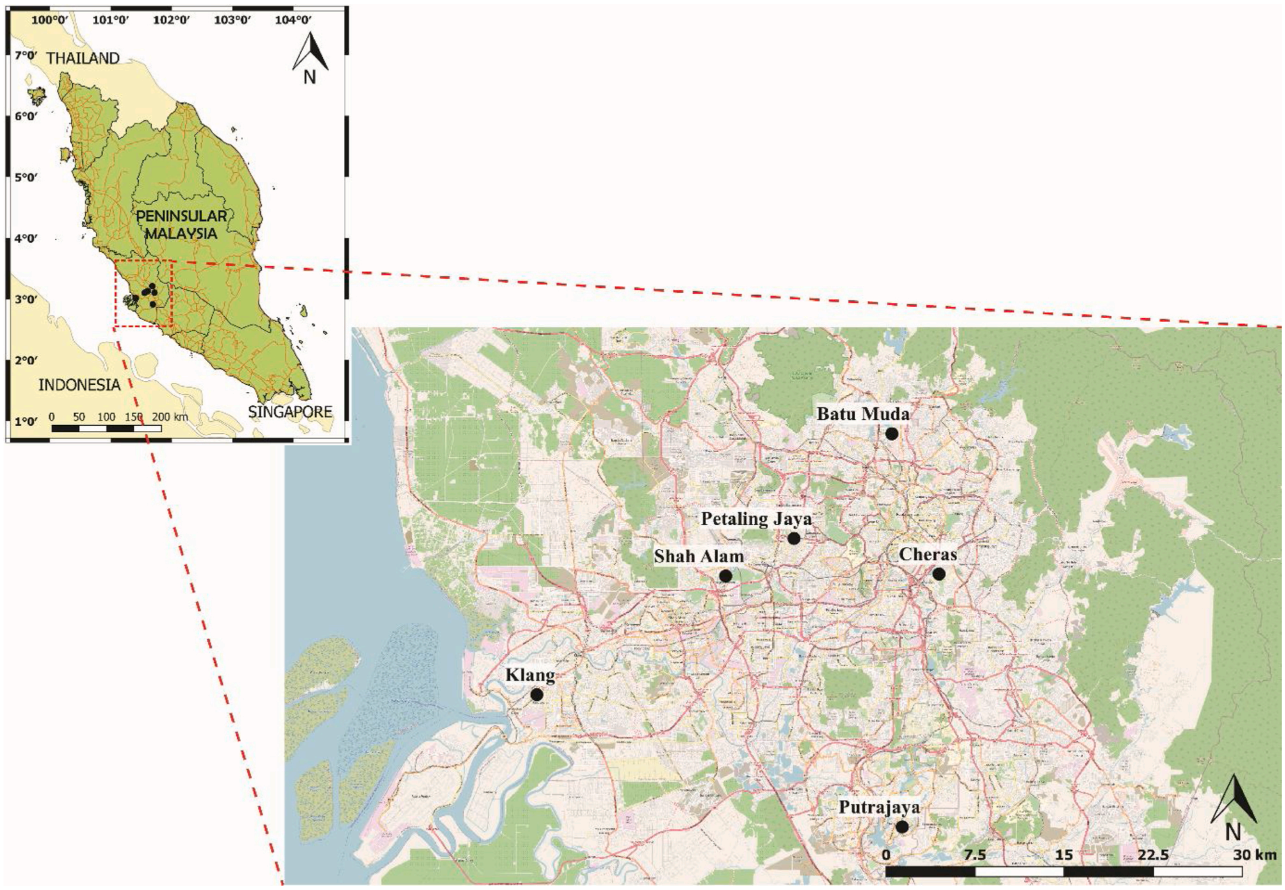

Fig. 1. Location of the sampling stations in the Klang Valley, Malaysia.

Malaysian Meteorological Department (MMD), satellite data from the National Aeronautics and Space Administration (NASA) were used to study the influence of precipitation on air quality in the Klang Valley. The Global Precipitation Measurement (GPM) data with a spatial scale of 0.1° and temporal scale of 30 min were downloaded and analysed for precipitation in the Klang Valley during the MCO and similar time frames in 2018 and 2019. The study by Mahmud et al. (2017) on the effectiveness of GPM satellite precipitation over Malaysia showed that in Peninsular Malaysia, the GPM data is able to depict spatial rainfall patterns varied by homogeneous rainfall with Spearman's correlation coefficient (*r*) ranging from 0.591 to 0.891.

2.3. QA/QC for air quality data

All air quality data from CAQMS went through quality assurance and quality control (QA/QC) procedures before submission to the Malaysian Department of Environment. Instruments for the detection of gases were manually calibrated once a fortnight. Flow verification for PM_{10} and $PM_{2.5}$ measurements using TEOM was conducted once a month, as stipulated in the standard operating procedures for all these instruments. The data removed during the QC checks was predominantly due to insufficient data (in turn due to negative values) and as a result of non-adherence to auto calibration targets. The second level QC checks were observed mainly due to outliers. Some of these observations were verified based on observed sources while others were rejected due to instrument failure (PSTW, 2018a, 2018b).

2.4. Percentage differences between MCO and non-MCO years

The percentage reductions between air pollutant concentrations recorded during the MCO in 2020 and the concentrations of air pollutants recorded in 2019 and 2018 were based on the Eq. (1):

$$\text{Percentage of difference } (\%) = \frac{A - B}{B} \text{ x } 100 \quad (1)$$

A = Concentration air pollutant recorded during the MCO in 2020.

B = The concentration of air pollutants recorded in the same period in 2019 or 2018.

For the differences between 2019 and 2018 in Eq. (1), the value of A is the concentration of air pollutants in 2019 and B is the concentration of air pollutants in 2018.

2.5. Statistical analysis

Descriptive and statistical analyses in this study were carried out using R statistical analysis version 3.6.3 (R Development Core Team, 2011). The main package used in R statistical analysis was the "Openair" Version 2.6 (Carslaw & Ropkins, 2012). Daily, diurnal and yearly plots of air pollutant datasets (2018–2020) at six study locations were assessed to examine temporal patterns. In addition to R statistical analysis, the Statistical Package for the Social Sciences (SPSS) software version 21 (IBM, USA) was used for one-way analysis of variance (ANOVA) and *t*-test. The data for ANOVA and *t*-test were normalised using the Inversed Distribution Function. The determination of normal distributions were then conducted by Kolmogorov-Smirnov and Shapiro-Wilk tests using SPSS. Variables with significance values that are greater than the alpha value ($p > 0.05$) were removed from the data set. In order to compare the spatiotemporal variation of air pollutants during the MCO and similar time frames in 2018 and 2019, Inverse Distance Weighting (IDW) was applied in the analysis as the IDW method is a practical and suitable method for spatial air quality modelling when the observation points are lower in number (Halim et al., 2020; Jumaah et al., 2019; Li et al., 2019; Peshin et al., 2017).

2.6. Bivariate polar plot

The bivariate polar plots were plotted to show the variation of air pollutant concentrations with wind speed and wind direction for polar coordinates. In a bivariate polar plot, wind speed is plotted as the distance from the origin and wind direction as the angle from the direction of the origin. The different colours in the polar plot are the average concentrations of the pollutant variable (Carslaw & Ropkins, 2012; Dotse et al., 2016; Uria-Tellaetxe & Carslaw, 2014). In this study, the bivariate polar plots for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2 and CO recorded in Petaling Jaya were presented to show the influence of wind speed and wind direction on the pollutant concentrations which then enabled the potential emission sources to be pin pointed during the MCO compared with 2019 and 2018. Petaling Jaya station was chosen because this station recorded the highest concentration of most air pollutants during the MCO.

2.7. Trajectory analysis

Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT version 4.9) was employed to calculate 72 h backward trajectories using a 6 h temporal resolution of the model to determine the origin of the air mass arriving at the Petaling Jaya station. The results of the backward trajectory for this station during the MCO were compared with the same periods in 2019 and 2018. HYSPLIT, which is used for backward trajectory analysis, was developed by the National Oceanic and Atmospheric Administration (NOAA)'s Air Resource Laboratory (ARL). The height level selected for model calculation was 500 m to ensure that the trajectories started in the atmospheric boundary layer (Eva & Lambin, 1998). The meteorological drivers used to compute the trajectories from 2018 to 2020 were obtained from the National Center for Environmental Prediction (NCEP) archive, which is maintained by ARL. In order to have an overview of the arrival of air masses to Petaling Jaya station from the 18th March to the 22nd April in 2018, 2019 and 2020, a clustering method in the HYSPLIT model was used to group the individual trajectories obtained based on curvature and length characteristics (Brankov et al., 1998).

3. Results and discussion

3.1. Concentrations of major air pollutants during the MCO

The average concentrations of hourly air pollutants with the addition of daily maximum O_3 concentration recorded during the MCO and the respective time period in the years 2019 and 2018 are presented in Table 1. During the MCO, the average concentrations of PM_{10} from all stations in the Klang Valley were between 21.4 and 30.6 µg m^{-3}. The concentrations of $PM_{2.5}$ were recorded as being between 16.1 and 22.8 µg m^{-3}. For both PM_{10} and $PM_{2.5}$, Cheras recorded the lowest average concentrations, while Klang recorded the highest. In terms of gas concentrations during the MCO, NO_2, SO_2 and CO were between 3.3 and 8.7 ppb, 0.6 and 1.1 ppb and 0.5 and 0.9 ppm, respectively. The average and maximum values of O_3 ranged from 17.2 to 29.3 ppb and 55.8 to 85.5 ppb, respectively. O_3 was clearly recorded as being at the lowest concentration at Petaling Jaya and NO_2 was recorded as having the highest concentration at Klang. One-way ANOVA analysis on hourly data showed there were significant differences ($p < 0.05$) between air pollutants (PM_{10}, CO, NO_2 and SO_2) measured at all six stations during the MCO and the same time periods in 2019 and 2018.

A comparison of the hourly concentrations of air pollutants during the MCO and the same periods in 2019 and 2018 are presented in Fig. 2 (**a**), (**b**) and Table 2. Fig. 2(**a**) is for stations located within and bordering the Kuala Lumpur administrative area (Batu Muda, Cheras and Petaling Jaya) and Fig. 2(**b**) is for stations located outside Kuala Lumpur (Shah

Table 1
Comparison between the average concentration of hourly data of major air pollutants recorded during MCO and at the same time in 2018 and 2019.

Station	PM_{10} (µg m^{-3})			$PM_{2.5}$ (µg m^{-3})			NO_2 (ppb)			SO_2 (ppb)			*O_3 (ppb)			CO (ppm)		
	2018	2019	2020	2018	2019	2020	2018	2019	2020	2018	2019	2020	2018	2019	2020	2018	2019	2020
Batu Muda	27.1	35.4	24.3	20.8	26.2	19.4	18.3	17.1	5.6	1.4	0.9	0.6	20.4 (100.3)	15.1 (79.2)	19.7 (68.7)	1.1	1.0	0.9
Cheras	35.1	35.4	21.4	23.4	27.5	16.1	18.3	18.4	5.1	0.7	1.0	0.6	24.4 (114.1)	29.0 (125.6)	24.8 (80.5)	0.9	0.9	0.6
Petaling Jaya	43.0	37.5	23.0	31.5	27.7	17.4	28.3	24.4	8.1	3.9	0.9	0.7	18.2 (93.4)	17.0 (90.6)	17.2 (55.8)	1.3	1.2	0.6
Shah Alam	39.7	41.4	23.8	29.1	31.2	17.8	20.9	16.8	7.3	1.4	1.2	1.0	26.7 (107.6)	33.9 (155.9)	29.3 (84.3)	1.1	0.9	0.7
Klang	51.6	36.6	30.6	28.3	30.6	22.8	25.2	19.1	8.7	2.0	0.8	1.1	21.2 (92.4)	15.4 (70.9)	24.9 (79.1)	1.0	1.2	0.6
Putrajaya	32.3	40.8	24.6	23.3	31.9	18.5	9.1	10.3	3.3	0.9	1.4	1.0	27.4 (100.7)	29.6 (124.8)	27.6 (85.5)	0.6	0.6	0.5

* Daily O_3 maximum value was included in the parenthesis.

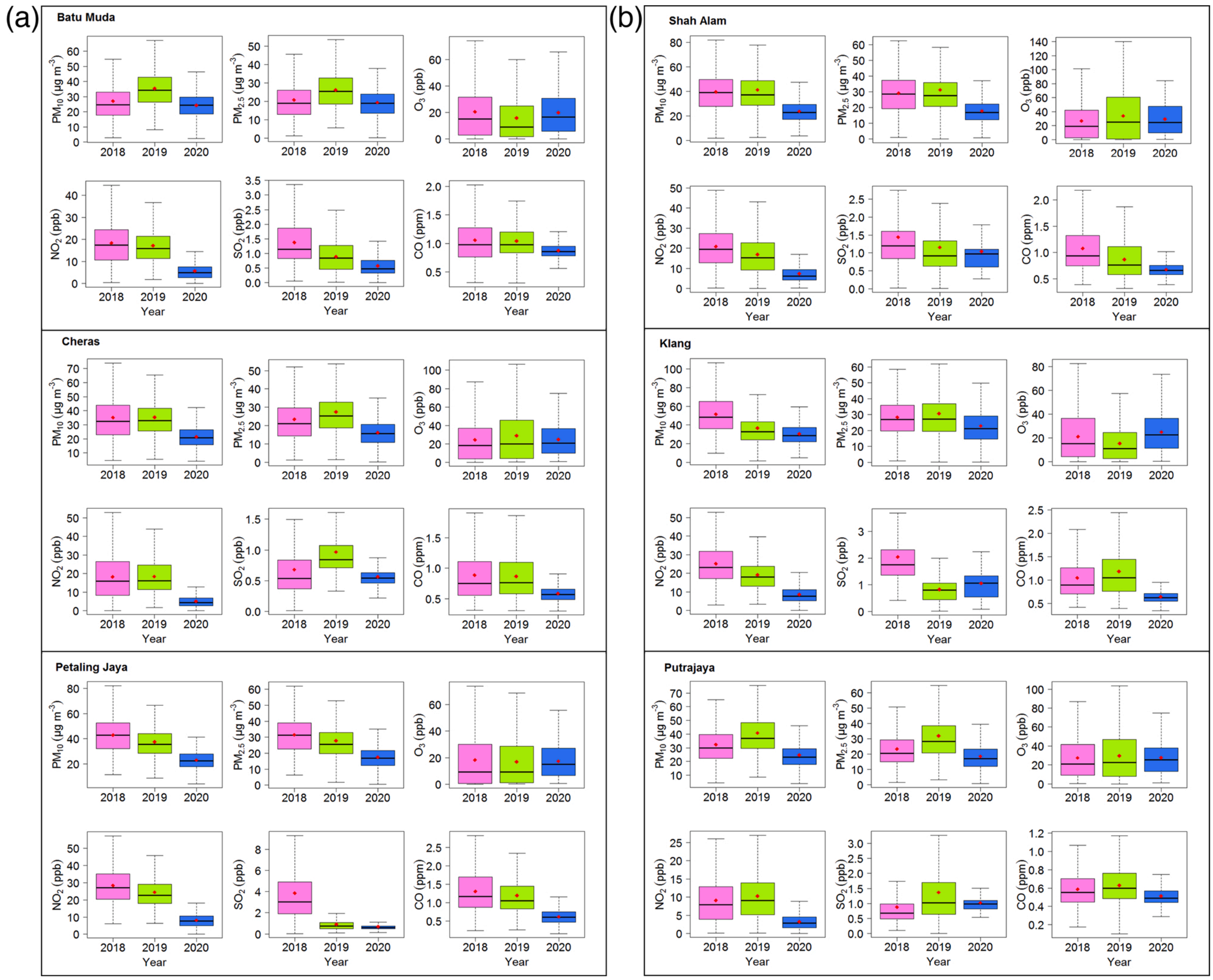

Fig. 2. **a**) Boxplot for air quality data at Batu Muda, Cheras and Petaling Jaya stations recorded during the Malaysian movement control order (MCO) (18th March 2020 to 22nd April 2020. Air quality data at the same time in 2019 (18th March 2019 to 22nd April 2019) and 2018 (18th March 2018 to 22nd April 2018) are used for comparison. **b**) Boxplot for air quality data at Shah Alam, Klang and Putrajaya stations recorded during the Malaysian movement control order (MCO) (18th March 2020 to 22nd April 2020). Air quality data at the same time in 2019 (18th March 2019 to 22nd April 2019) and 2018 (18th March 2018 to 22nd April 2018) are used for comparison.

Alam, Klang and Putrajaya). The spatiotemporal concentrations of PM_{10}, $PM_{2.5}$ and NO_2, and of SO_2, O_3 and CO recorded in 2018, 2019 and 2020 in the Klang Valley are presented in Supplementary 1(a) and Supplementary 1(b), respectively. Generally, the average concentrations of air pollutants recorded in the Klang Valley during the MCO were lower when compared with the same period in 2019 and 2018, except for O_3 and SO_2. Further ANOVA analysis using the Tukey's test for post-hoc analysis showed there were significant differences ($p < 0.05$) in NO_2 and CO concentrations recorded during the MCO and the similar periods in 2019 and 2018. The highest percentage reduction during the MCO compared with the same period in 2019 and 2018 was recorded for NO_2. The NO_2 reduction ranged from −55 % to −72 % between 2020 compared to 2019 and 2018, where Cheras recorded the highest percentage reduction. The second highest reduction was for CO with a range of between −13 % and −53 %. The reductions in PM_{10} and $PM_{2.5}$ ranged between −10 % and −46 %, and −7 % and −45 %, respectively. The results for PM_{10} and $PM_{2.5}$ in this study confirmed the previous findings by Kanniah et al. (2020) using AOD observations from Himawari-8 satellite as indicators for particulate matter which indicated a reduction of around 40–60 % of AOD within the urban environment. Lower regional transboundary emissions influence the satellite observations more compared to local ground-level measurements and may account for the differences in the percentages of particulate reduction using both methods.

The post-hoc analysis showed that SO_2 and O_3 did not show significant reductions at all stations. The change between SO_2 during the MCO and the similar period in 2019 and 2018 ranged between 28 % and −82 %. This also happened with O_3 with a change from 62 % to −14 %. From analysis of the observations made between 2019 and 2018, the SO_2 concentrations also recorded the highest differences with a range of 56 % to −76 %. Most of the stations showed an increase in average O_3 concentrations during the MCO compared to the same time period in 2019 and 2018. The average concentrations of O_3 recorded in Klang and Batu Muda during the MCO showed significantly increased O_3 ($p < 0.05$) compared with the similar period in 2019. Nevertheless, maximum O_3 concentrations recorded around midday during the MCO compared to the same period in 2019 and 2018 ranged between 12 % and −46 %. Shah Alam recorded the highest O_3 reduction. All stations recorded decreasing concentrations of the O_3 maximum during the MCO except for Klang (Table 2). One-way ANOVA analysis showed there were significant differences ($p < 0.05$) in daily O_3 maximum concentrations measured during the MCO and at the same periods in 2019 and 2018 at Shah Alam and Cheras stations.

The results from this study indicated that the concentrations of NO_2,

Table 2
Percentage of the average concentration differences between hourly air quality data recorded during MCO in 2020 compared with the same period in 2019 and 2018. The percentage of differences between 2019 and 2018 were used as a comparison.

Station	PM_{10}			$PM_{2.5}$			NO_2			SO_2			*O_3			CO		
	2019–2018	2020–2018	2020–2019	2019–2018	2020–2018	2020–2019	2019–2018	2020–2018	2020–2019	2019–2018	2020–2018	2020–2019	2019–2018	2020–2018	2020–2019	2019–2018	2020–2018	2020–2019
Batu Muda	31	−10	−31	26	−7	−26	−7	−69	−67	−35	−58	−35	−26 (−21)	−3 (−32)	31 (−13)	−2	−17	−16
Cheras	1	−39	−40	17	−31	−41	1	−72	−72	42	−17	−42	19 (10)	2 (−30)	−14 (−36)	−2	−34	−32
Petaling Jaya	−13	−46	−39	−12	−45	−37	−14	−71	−67	−76	−82	−25	−7 (−3)	−5 (−40)	2 (−38)	−9	−53	−49
Shah Alam	4	−40	−42	7	−39	−43	−19	−65	−56	−20	−27	−10	27 (45)	9 (−22)	−14 (−46)	−20	−37	−22
Klang	−29	−41	−16	8	−19	−25	−24	−66	−55	−60	−48	28	−28 (−23)	17 (−14)	62 (12)	13	−39	−46
Putrajaya	26	−24	−40	37	−21	−42	13	−64	−68	56	16	−25	8 (24)	1 (−15)	−7 (−31)	7	−13	−19

* Note: The percentage differences using daily O_3 maximum value was included in the parenthesis.

CO, PM_{10} and $PM_{2.5}$ were significantly reduced during the MCO. The reduction in the number of vehicles caused by the reduction of mobility due to the MCO in the Klang Valley (representing the state of Selangor and Kuala Lumpur) as shown in Supplementary 2 (Google LLC, 2020) has clearly reduced the concentrations of NO_2 and CO. The location of sampling stations near roads with heavy traffic led to the reduction of these two gases when there were low numbers of vehicles on the road. Motor vehicles, as well as industrial, construction and combustion activities, also contribute to the amount of particulate matter such as PM_{10} and $PM_{2.5}$ in ambient air. The lower numbers of motor vehicles and a limited number of industrial, construction and combustion activities would be expected to reduce the concentrations of PM_{10} and $PM_{2.5}$ in ambient air. These results support similar previous studies on the levels of NO_2, CO, PM_{10} and $PM_{2.5}$ in ambient air recorded during the lockdown in Malaysia from neighbouring countries including Singapore (Li & Tartarini, 2020) and Thailand (Stratoulias & Nuthammachot, 2020) and other parts of the world as suggested by Mahato et al. (2020), Menut et al. (2020) and Tobías et al. (2020).

The concentrations of SO_2 and O_3 did not follow the patterns of the concentrations of NO_2, CO, PM_{10} and $PM_{2.5}$. The average concentration of SO_2 recorded in the Klang Valley ranged between 0.7 and 3.9 ppb, which can be considered low compared with other gases (Table 1). A small change of SO_2 emissions in this area can contribute to a significant change in the SO_2 percentage. Even though there are signs of a reduction during the MCO compared with the same period of time in 2019 and 2018, the reduction was almost similar compared with the reduction between years without an MCO, i.e. between 2019 and 2018. The concentration of SO_2 during the MCO is expected to have originated from motor vehicles and other industrial activities as well as natural sources of SO_2. The variations in emissions, as well as wind direction and other meteorological factors, contribute to the amount of SO_2 in the ambient air in the Klang Valley. There are two power plants located near to the studied stations which are a coal-fired power plant (Klang station) and a gas turbine power plant (Putrajaya station). The power plants could be one of the reasons for the increase in SO_2 at the Klang station (28 %) during the MCO compared with the same period in 2019 and in Putrajaya during MCO compared with the same time period in 2018 (16 %). This result needs further detailed investigation which would involve detailed emission data from anthropogenic and natural sources, as well as the influence of local and regional meteorological factors.

Surface O_3 has been known as a secondary air pollutant that is influenced by its precursors such as NO_x and volatile organic compounds (VOCs) (Liu et al., 2020; Sillman, 1999). The reduction in O_3 during the MCO compared with the same period in 2019 was significant ($p < 0.05$) at the suburban stations outside the Kuala Lumpur city centre, which usually recorded high concentrations of O_3 on normal days, namely Cheras and Shah Alam (Ahamad et al., 2014; Banan et al., 2013; Latif et al., 2012). Other stations which are influenced by heavy traffic and industrial activities such as Batu Muda and Klang showed higher O_3 concentrations (at 31 % and 62 %, respectively) based on comparisons during the MCO and the same period in 2019. A similar increase in Klang (17 %) was also observed during the MCO and the same period in 2018 (Table 2).

The increasing and decreasing phenomena of O_3 at the sampling stations was to be expected due to the influence of O_3 precursors in the atmosphere. The limited emissions of NO_x, as represented by the NO_2 concentrations, reduced the concentrations of NO. The low rate of titration of NO to O_3 in these areas will automatically increase the O_3 concentration in ambient air as shown by other similar studies during the lockdown in tropical regions (Cazorla et al., 2020; Dhaka et al., 2020; Li & Tartarini, 2020; Stratoulias & Nuthammachot, 2020) and other parts of the world (Collivignarelli et al., 2020; Menut et al., 2020; Sicard et al., 2020; Siciliano et al., 2020; Tobías et al., 2020; Zoran et al., 2020). This phenomenon usually occurs in busy areas influenced by the emissions of NO from motor vehicles. The process of formation of O_3 is quite complicated and influenced by NO_x and other oxidants from other

(a)

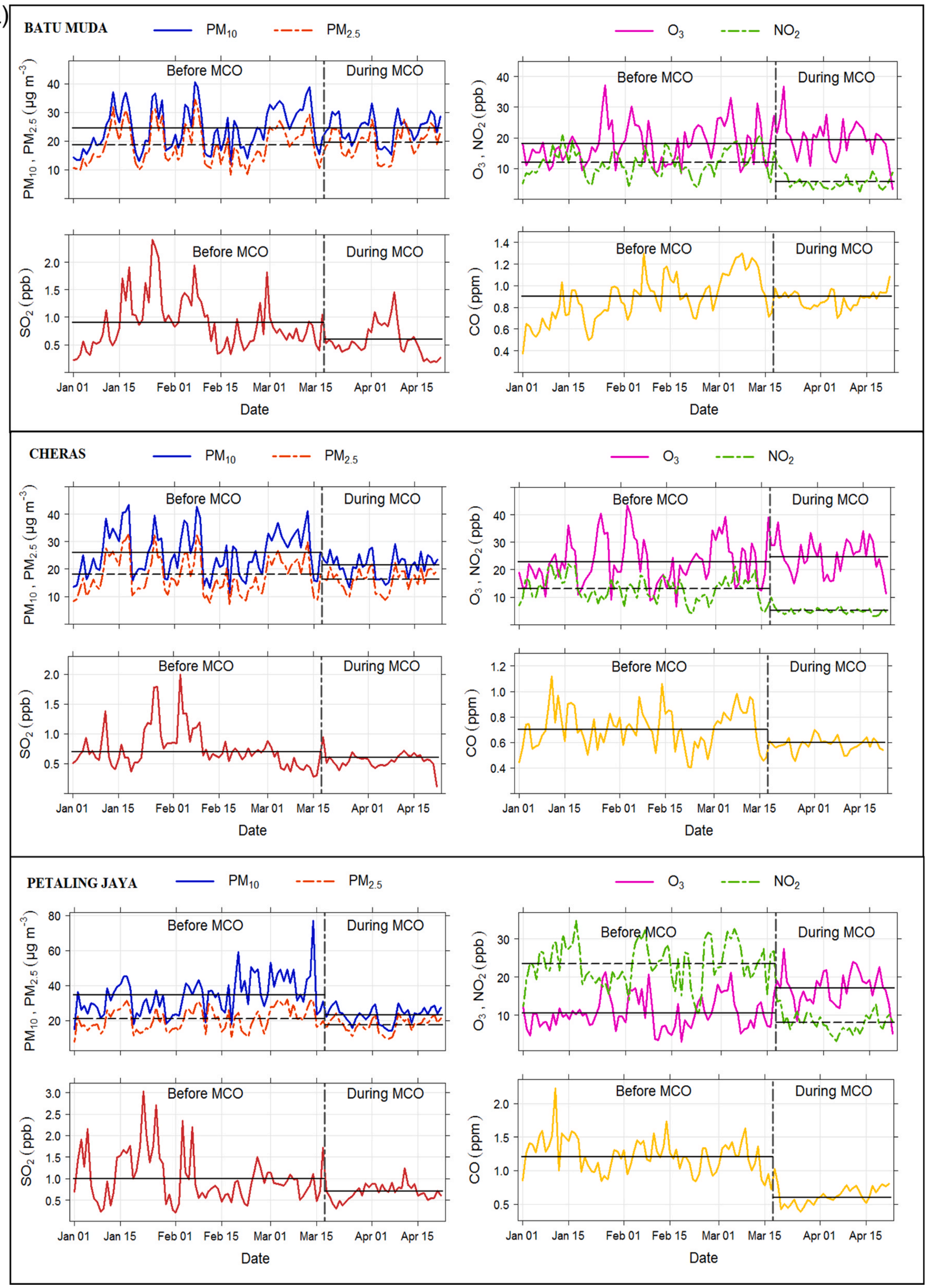

Fig. 3. (**a**) Time series of daily average concentration of major air pollutants before MCO (1st January 2020 to 17th March 2020) and during MCO (18th March 2020 to 22nd April 2020) for Batu Muda, Cheras and Petaling Jaya stations. The dashed vertical line is representing the first day of the MCO (18th March 2020). The horizontal line is representing the average value of the air pollutant before MCO and during MCO. (**b**) Time series of daily average concentration of major air pollutants before MCO (1st January 2020 to 17th March 2020) and during MCO (18th March 2020 to 22nd April 2020) for Shah Alam, Klang and Putrajaya stations. The dashed vertical line is representing the first day of the MCO (18th March 2020). The horizontal line is representing the average value of the air pollutant before MCO and during MCO.

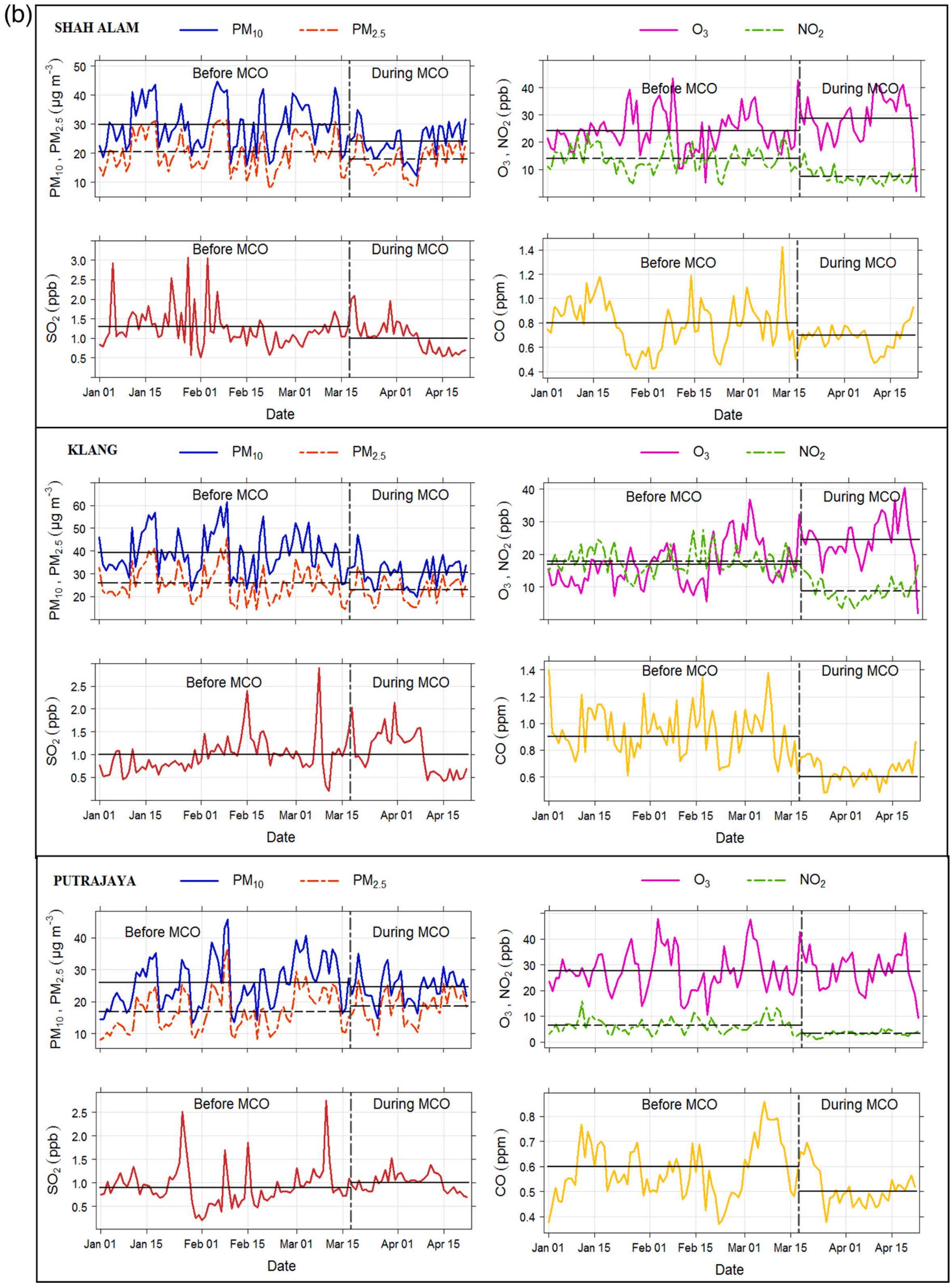

Fig. 3. (*continued*).

precursors ($RO_x = OH + OH_2 + RO_2$) from VOCs and CO in the atmosphere. The formation and destruction of O_3 are determined by the formation of $O(^3P)$ and interaction between O_3 and NO as illustrated in Eqs. (2)–(6) (Wang et al., 2017):

$$HO_2 + NO \rightarrow NO_2 + OH \tag{2}$$

$$RO_2 + NO \rightarrow NO_2 + RO \tag{3}$$

$$NO_2 + hv \rightarrow NO + O(^3P) \tag{4}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{5}$$

$$O_3 + NO \rightarrow NO_2 + O_2 \quad (6)$$

The reduction of the O_3 maximum around midday recorded at almost all stations may be due to the limited amounts of O_3 precursors available to form the O_3 maximum around midday.

3.2. Temporal patterns of major air pollutants

Time series of daily concentration of major air pollutants before the MCO (1st January 2020 to 17th March 2020) and during the MCO (18th March 2020 to 22nd April 2020) are presented in Fig. 3(**a**) and (**b**). The independent sample *t*-test ($p < 0.05$) results illustrated that all the six air pollutants measured at Cheras, Petaling Jaya and Shah Alam stations showed a significant difference during and before the MCO. In general, there were indications of PM_{10}, $PM_{2.5}$, NO_2 and CO reductions recorded at all stations during the MCO. The daily concentrations of NO_2 and CO were clearly significantly reduced ($p < 0.05$) after the MCO was implemented. The daily average of O_3 (Fig. 3(**a**) and (**b**)) and daily

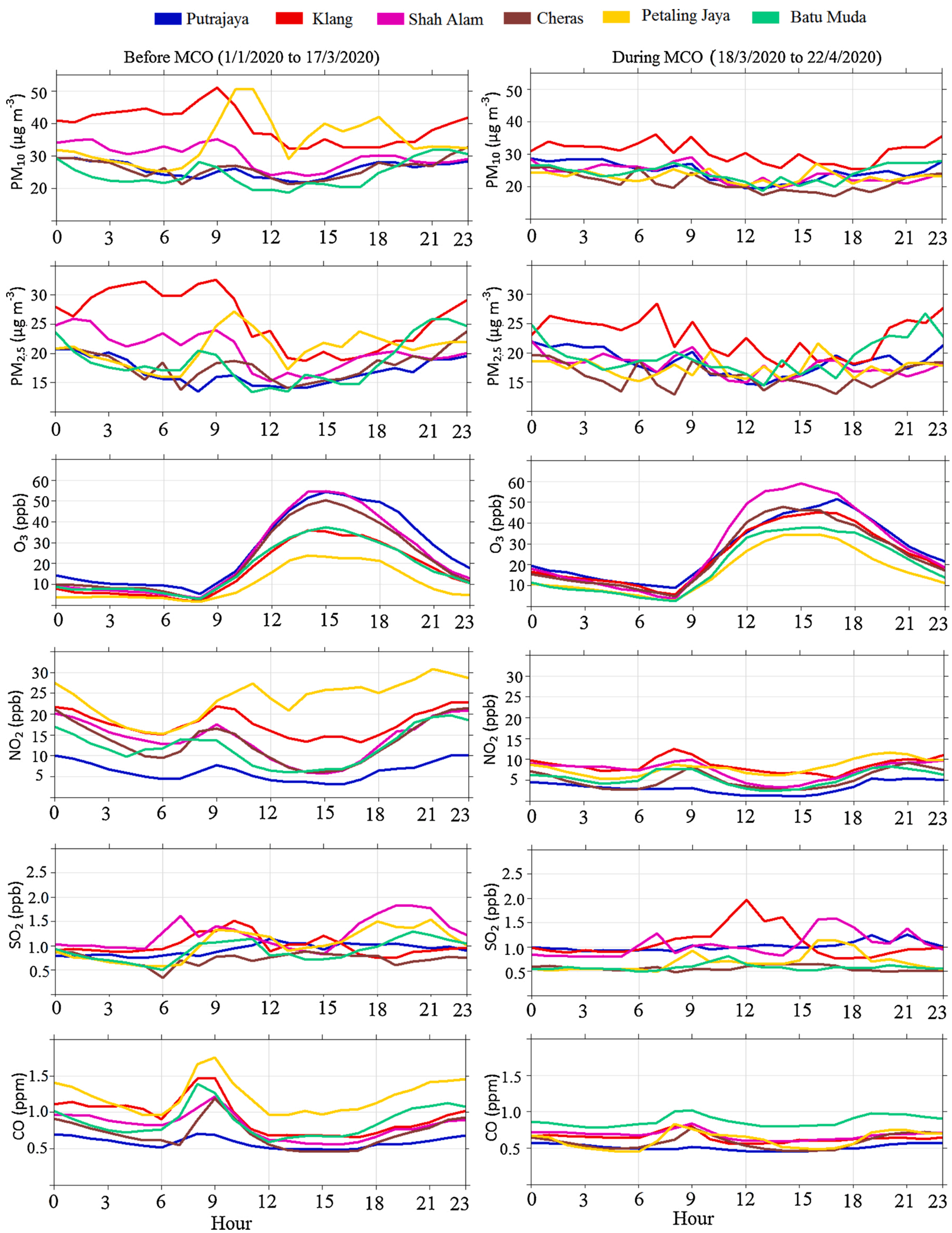

Fig. 4. Diurnal pattern of major air pollutants before MCO (1st January 2020 to 17th March 2020) and during MCO (18th March 2020 to 22nd April 2020).

maximum O_3 (Supplementary 3) showed similar patterns before and during the MCO. The results once again indicated that NO_2 and CO were the two major air pollutants which were clearly influenced by the reduction in motor vehicle emissions and other anthropogenic emissions during the MCO period. The same results were observed in other locations where the effect of lockdown was a reduction of NO_2 (Baldasano, 2020; Cameletti, 2020; Kerimray et al., 2020; Lian et al., 2020; Pei et al., 2020) and CO (Ghahremanloo et al., 2021; Kerimray et al., 2020). Other pollutants, such as PM and SO_2, are expected to originate from other sources such as soil dust, sea breezes, construction, coal-fired power plants and industrial activities, aside from the use of motor vehicles (Azhari et al., 2018; Keywood et al., 2003; Mohtar et al., 2018; Sulong et al., 2017). Therefore, PM and SO_2 concentrations were not necessarily reduced by the lower numbers of motor vehicles during the MCO. The lower concentrations of NO_2 as an O_3 precursor does not significantly follow the reduction of O_3 concentrations. The lower concentrations of NO as an O_3 titrant may once again increase the concentration of O_3 recorded at stations in the city centre and busy areas.

The diurnal patterns of major air pollutants are presented in Fig. 4. Overall, the concentrations of CO, NO_2, PM_{10}, $PM_{2.5}$ and SO_2 before the MCO were recorded at the highest concentrations between 7.00 a.m. and 11.00 a.m., while the lowest concentrations were observed around midday and increased again after 5.00 p.m. The concentrations of these pollutants were recorded as being higher at night and then dropping in the early morning. The MCO clearly reduced the concentrations of all these pollutants, particularly during the rush hours, at all stations. The changes in O_3 were observed to be similar for all locations studied both before and during the MCO, with a maximum concentration at around 3.00 p.m. that then rapidly decreased in the late afternoon. The maximum O_3 concentrations around midday at several stations were increased or almost similar during the MCO compared to the period of time before it. Stations located in the city centre and busy areas such as Petaling Jaya and Klang were found to show increasing concentrations of O_3 around midday during the MCO compared with the other stations. Lower concentration O_3 precursors such as NO_x were once again expected to contribute to the lower titration process of O_3 in the city centre and busy areas.

The high concentration of air pollutants during the rush hour in the morning shows the influence of motor vehicle emissions (Azmi et al., 2010). The diurnal pattern of NO_2 and CO during the MCO showed the flattened peak of their concentrations during the rush hour in the morning and late afternoon. This was followed by the lower concentration of these two gases at night. The patterns of lower concentrations during the rush hour and at night were hardly noticeable for PM_{10}, $PM_{2.5}$ and SO_2. The concentrations of O_3 were recorded at the highest level around midday due to the intensity of UV radiation that can separate O radicals from O_3 precursors, such NO_2 and VOCs. The low concentrations of NO_2 also mean lower concentrations of NO, which is usually directly emitted by motor vehicles and behaves as the main titrator for O_3, especially in urban and suburban areas. A similar result was obtained by Tobías et al. (2020) where O_3 was observed to have increased during lockdown in Barcelona, Spain, suggesting that contributing factors were a decrease in NO_x and NO concentrations resulting in an increase of temperatures from February to April which in turn led to an increased O_3 concentration.

3.3. Influence of meteorological factors

The time period chosen in this study was during the inter-monsoon season in Malaysia which occurs from March until May. During this period, the wind is weak and comes from a different direction than usual and thunderstorm events frequently occur in the evening (Malaysian Meteorological Department, 2020). The Klang Valley is located on the western coast of the Malaysian Peninsula and has maximum rainfall cycles during the inter-monsoon period (Jamaluddin et al., 2018). Strong local convection and precipitation are the other characteristics of the inter-monsoon season in the Klang Valley region (Ooi et al., 2017). Apart from traffic emissions and industrial emissions, meteorological factors are also one of the key subjects to be examined to understand the distribution and concentration of air pollution (Wang et al., 2006).

In order to investigate the influence of meteorological factors on the concentrations of air pollutants during the MCO, parameters such as precipitation, relative humidity, temperature and solar radiation were compared with the precipitation, relative humidity, temperature and solar radiation data recorded during the same time periods in 2019 and 2018. The results in Supplementary 4, Supplementary 5, Supplementary 6 and Supplementary 7 show the readings of precipitation, relative humidity, temperature and solar radiation during the MCO (c) and the same periods in 2019 (b) and 2018 (a) where the readings from all stations used in the study are averaged out. In general, precipitation, relative humidity, temperature and solar radiation during the MCO ranged between 0.22 and 76.37 mm day^{-1}, 68.36 and 87.35 %, 27.0 and 29.9 °C, 37.26 and 188.79 W m^{-2}, respectively The range of meteorological factors represents the conditions between the end of the northeast monsoon and the inter-seasonal monsoon in Peninsular Malaysia. There were no significant differences ($p > 0.05$) between the meteorological parameters recorded during the MCO compared with the same parameters recorded in 2019 and 2018. The influence of precipitation, relative humidity, temperature and solar radiation during the MCO compared with the similar data recorded in the previous years can therefore be considered as minimal.

3.4. Bivariate polar plot analyses and backward trajectory

The bivariate polar plot for Petaling Jaya station (Fig. 5) distinctly shows a reduction of air pollutant concentrations during the MCO compared with the same time periods in 2019 and 2018, except for SO_2 and O_3. Overall, all pollutants showed high concentrations at a low wind speed (< 3 ms^{-1}) during the MCO and at the same time period in 2019 and 2018. The results illustrated the influence of local emission sources such as motor vehicles and industrial activities. Lower concentrations of PM_{10} and $PM_{2.5}$ were observed during the MCO compared with the same time periods in 2019 and 2018, where the high concentrations of PM_{10} and $PM_{2.5}$ dominated from the southwest and west directions. This direction is associated with major roads, industrial activities and a coal-fired power plant on the west coast of Peninsular Malaysia.

NO_2 and CO recorded almost similar concentration patterns during the MCO and in 2019 and 2018. These two gases also showed clear reductions during the MCO compared with their concentrations during the same periods in 2019 and 2018, as the high concentrations came from northern and north-western regions, where a busy highway and roads with high numbers of motor vehicles are located. The lower numbers of motor vehicles resulted in reduced concentrations of NO_2 and CO. A similar pattern was also recorded with SO_2 concentrations in 2018 but there were no clear comparisons of SO_2 concentrations during the MCO. It is hard to differentiate between the concentrations of O_3 during the MCO and its concentrations during the same time periods in 2019 and 2018. In general, there was an indication of an increase in O_3 from areas north of the station and a reduction in southern areas during the MCO compared with the concentrations during the same periods in 2019 and 2018. These results indicated that the reduced number of motor vehicles during the MCO led to the increase in O_3. This may have been due to the reduction of titration of O_3 by NO in the environment during the MCO.

Further investigation of the Petaling Jaya station, using the backward trajectories analysis by HYSPLIT (Fig. 6), showed that all of the air masses originated from the northeast of the Malaysian Peninsula. The backward trajectories during the MCO in 2020 had almost the same patterns as the backward trajectories recorded in 2019 and 2018. The wind coming from the South China Sea may be influenced by natural and anthropogenic sources after it has passed through mainland areas on the eastern coast and central region of the Malaysian Peninsula.

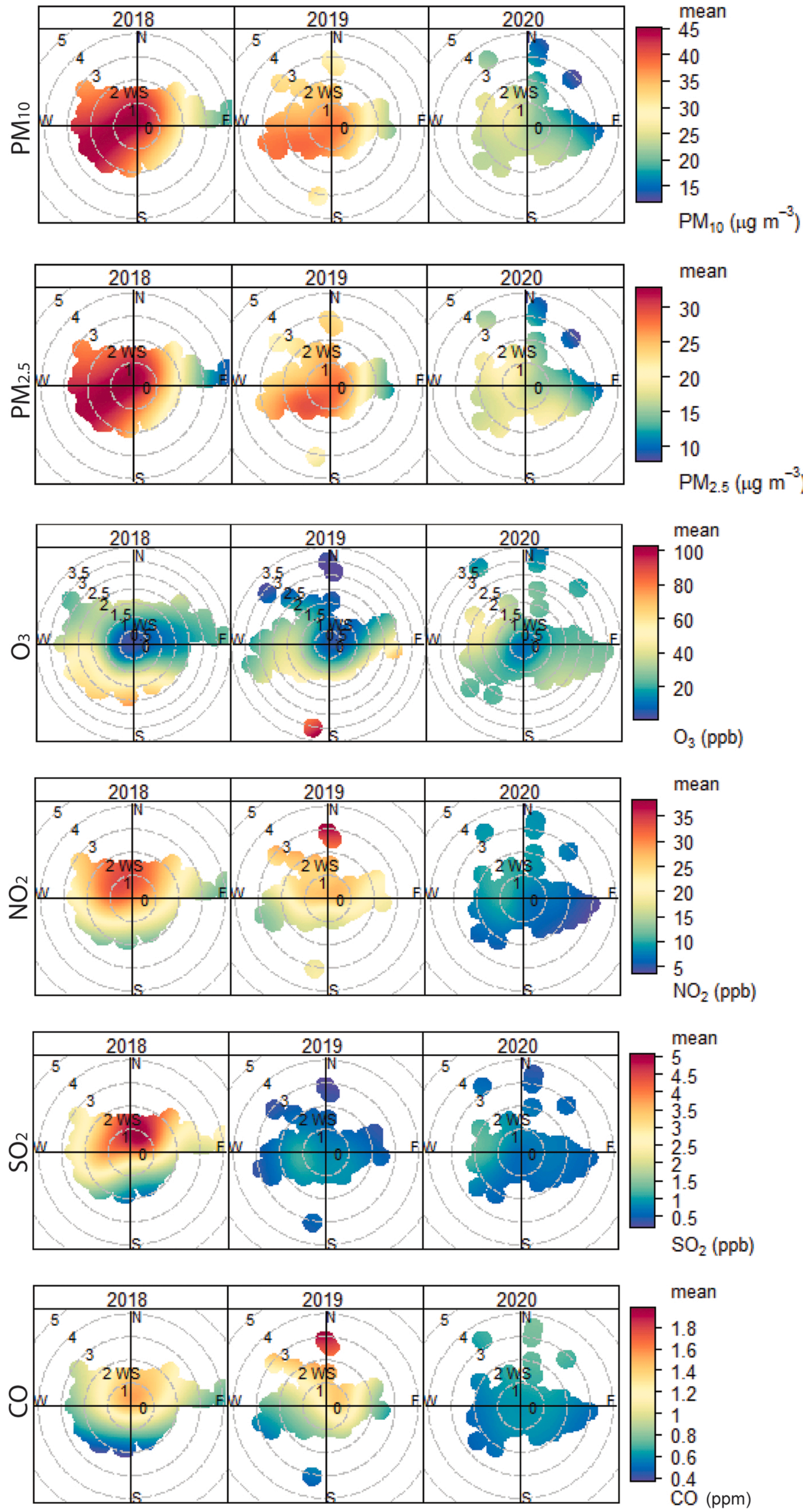

Fig. 5. Bivariate polar plot at Petaling Jaya station during MCO compared to a similar period in 2019 and 2018.

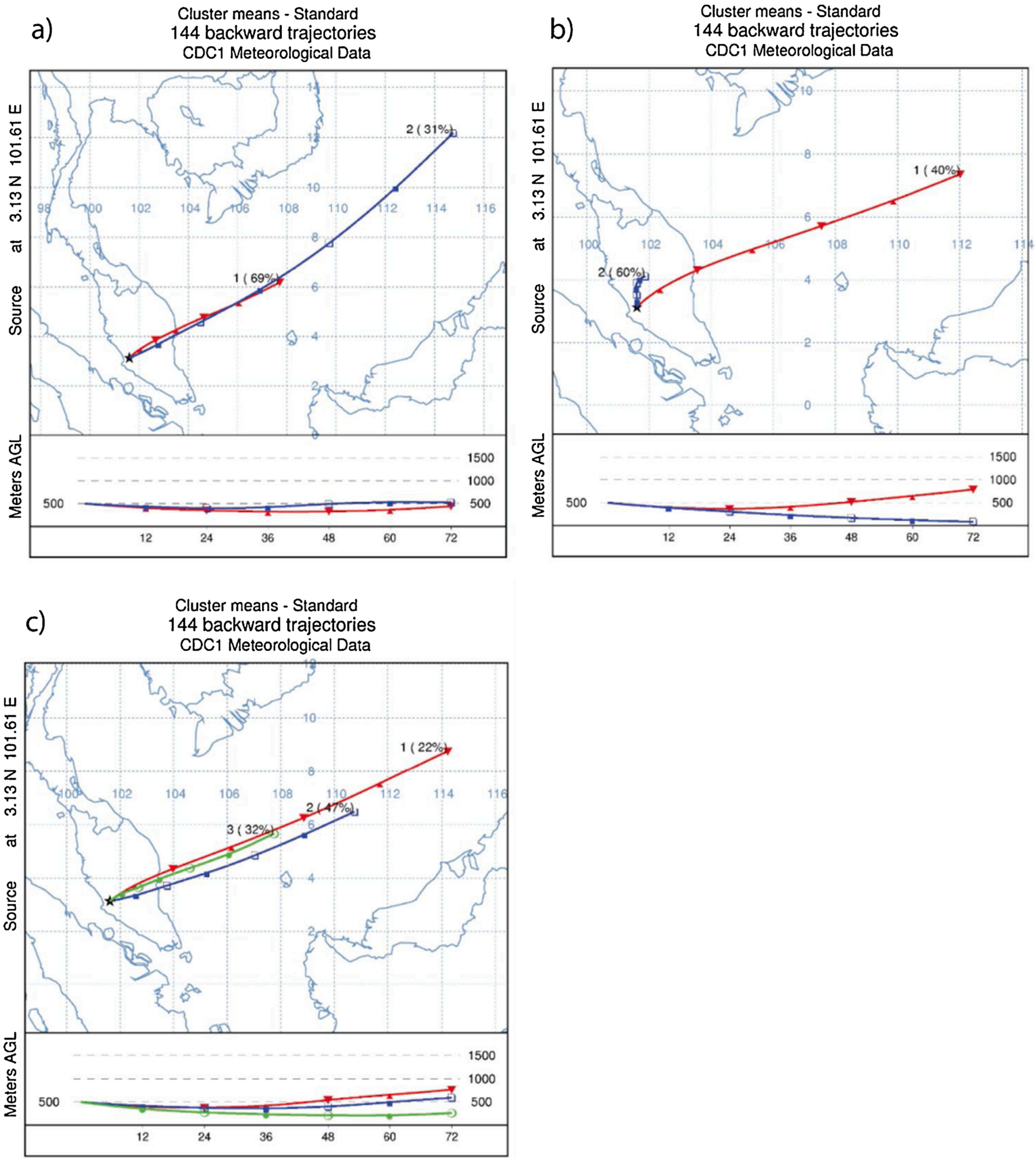

Fig. 6. Backwards trajectories to Petaling Jaya station during (c) MCO and similar periods in (b) 2019 and (a) 2018.

4. Conclusion

This study investigated the concentrations of major air pollutants recorded during the MCO in the Klang Valley, Malaysia. The results indicated that there were significant reductions ($p < 0.05$) in the levels of major air pollutants such as PM_{10}, $PM_{2.5}$, NO_2 and CO during the MCO compared with the same periods in 2019 and 2018. The highest reduction was recorded for NO_2, of between −55 % and −72 %. There were fluctuations of O_3 and SO_2 concentrations during the MCO compared with the concentrations from the same period in 2019 and 2018, based on the location of the stations. The lower concentrations of NO during the MCO influenced the increase in O_3 concentration due to the limitation of titration processes.

The diurnal pattern of air pollutants showed that air pollutants such as NO_2 and CO were clearly influenced by motor vehicle emissions. The maximum concentrations of O_3 at around midday showed an increase at several stations influenced by motor vehicles when compared with the concentrations before the MCO. This study shows that the concentrations of air pollutants in the Klang Valley were reduced during the MCO in line with the lower numbers of motor vehicles on the roads. Clean ambient air can ultimately be achieved through the reduction of emissions from motor vehicles and other anthropogenic activities which originate from local sources. Limitations of people's mobility in urban environments such as in the Klang Valley will help the government to reduce the concentrations of major air pollutants significantly. Several initiatives to limit the number of motor vehicles such as by encouraging people to use public transport and sharing cars for their mobility are really important to reduce air pollution. Government and private sectors also need to take the initiative to encourage workers to work from home to reduce emissions in urban areas. Emissions control through working from home can be conducted to reduce local and regional air pollutants during air quality episodes such as haze, which occurs in Southeast Asia in the Klang Valley almost every year. Fundamentally, more detailed studies need to be conducted on how to reduce surface O_3 in ambient air within urban and sub-urban area in the Klang Valley with emphasise on its precursors' chemical interactions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2020.102660.

References

Ahamad, F., Latif, M. T., Tang, R., Juneng, L., Dominick, D., & Juahir, H. (2014). Variation of surface ozone exceedance around Klang Valley, Malaysia. *Atmospheric Research, 61*, 434–445.

Ash`aari, Z. H., Aris, A. Z., Ezani, E., Kamal, N. I. A., Jaafar, N., Jahaya, J. N., et al. (2020). Spatiotemporal variations and contributing factors of air pollutant concentration in Malaysia during movement control order due to the pandemic COVID-19. *Aerosol and Air Quality Research, 20*, 2047–2061.

Azhari, A., Latif, M. T., & Mohamed, A. F. (2018). Road traffic as an air pollutant contributor within an industrial park environment. *Atmospheric Pollution Research, 9*, 680–687.

Azmi, S. Z., Latif, M. T., Ismail, A. S., Juneng, L., & Jemain, A. A. (2010). Trend and status of air quality at three different monitoring stations in the Klang Valley, Malaysia. *Air Quality, Atmosphere, & Health, 3*, 53–64.

Baldasano, J. M. (2020). COVID-19 lockdown effects on air quality by NO2 in the cities of Barcelona and Madrid (Spain). *The Science of the Total Environment, 741*, 40353.

Banan, N., Latif, M. T., Juneng, L., & Ahamad, F. (2013). Characteristics of surface ozone concentrations at stations with different backgrounds in the Malaysian Peninsula. *Aerosol and Air Quality Research, 13*, 1090–1106.

Bao, R., & Zhang, A. (2020). Does lockdown reduce air pollution? Evidence from 44 cities in northern China. *The Science of the Total Environment, 731*, Article 139052.

Brankov, E., Rao, S. T., & Porter, P. S. (1998). A trajectory-clustering-correlation methodology for examining the long-range transport of air pollutants. *Atmospheric Environment, 32*, 1525–1534.

Cameletti, M. (2020). The effect of corona virus lockdown on air pollution: Evidence from the City of Brescia in Lombardia Region (Italy). *Atmospheric Environment, 239*, Article 117794.

Carslaw, D., & Ropkins, K. (2012). Openair - an R package for air quality data analysis. *Environmental Modelling & Software, 27–28*, 52–61.

Cazorla, M., Herrera, E., Palomeque, E., & Saud, N. (2020). What the COVID-19 lockdown revealed about photochemistry and ozone production in Quito, Ecuador. *Atmospheric Pollution Research*. Article in press.

Chong, K. C., Cheng, W., Zhao, S., Ling, F., Mohammad, K. N., Wang, M. H., et al. (2020). Monitoring disease transmissibility of 2019 novel coronavirus disease in Zhejiang, China. *International Journal of Infectious Diseases, 96*, 128–130.

Cole, M., Elliott, R., & Liu, B. (2020). *The impact of the Wuhan Covid-19 lockdown on air pollution and health: A machine learning and augmented synthetic control approach.* Discussion Papers 20-09. Department of Economics, University of Birmingham.

Collivignarelli, M. C., Abbà, A., Bertanza, G., Pedrazzani, R., Ricciardi, P., & Miino, M. C. (2020). Lockdown for CoViD-2019 in Milan: What are the effects on air quality? *The Science of the Total Environment, 732*, Article 139280.

Comber, L., O Murchu, E., Drummond, L., Carty, P. G., Walsh, K. A., De Gascun, C. F., et al. (2020). Airborne transmission of SARS-CoV-2 via aerosols. *Reviews in Medical Virology*, e2184.

Dantas, G., Siciliano, B., França, B. B., da Silva, C. M., & Arbilla, G. (2020). The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. *The Science of the Total Environment, 729*, Article 139085.

Das, A., Ghosh, S., Das, K., Basu, T., Dutta, I., & Das, M. (2020). Living environment matters: Unravelling the spatial clustering of COVID-19 hotspots in Kolkata megacity. *India. Sustain. Cities Soc.*, Article 102577

Department of Statistics Malaysia. (2020). *-19 current situation in Malaysia*. https://ukkdosm.github.io/covid-19.

Dhaka, S. K. C., Kumar, V., Panwar, V., Dimri, A. P., Singh, N., Patra, P. K., et al. (2020). PM2.5 diminution and haze events over Delhi during the COVID-19 lockdown period: An interplay between the baseline pollution and meteorology. *Scientific Reports, 10*, 13442.

Dong, E., Du, H., & Gardner, L. (2020). An interactive web-based dashboard to track COVID-19 in real time. *The Lancet Infectious Diseases, 20*, 533–534.

Dotse, S.-Q., Dagar, L., Petra, M. I., & De Silva, L. C. (2016). Influence of southeast asian haze episodes on high PM_{10} concentrations across Brunei Darussalam. *Environmental Pollution, 219*, 337–352.

Dutheil, F., Baker, J. S., & Navel, V. (2020). COVID-19 as a factor influencing air pollution? *Environmental Pollution, 263*(A), Article 114466.

Eva, H., & Lambin, E. F. (1998). Remote sensing of biomass burning in tropical regions: Sampling issues and multisensor approach. *Remote Sensing of Environment, 64*, 292–315.

Ghahremanloo, M., Lops, Y., Choi, Y., & Mousavinezhad, S. (2021). Impact of the COVID-19 outbreak on air pollution levels in East Asia. *The Science of the Total Environment, 754*, Article 142226.

Google, L. L. C. (2020). *COVID-19 community mobility report* [Website Link].

Gozali, P. (2020). *Singapore's COVID-19 cases highest in Southeast Asia*. https://www.aa.com.tr/en/asia-pacific/singapore-s-covid-19-cases-highest-in-southeast-asia/1830924.

Halim, N. D. A., Latif, M. T., Mohamed, A. F., Maulud, K. N. A., Idrus, S., Azhari, A., et al. (2020). Spatial assessment of land use impact on air quality in mega urban regions, Malaysia. *Sustainable Cities Society, 63*, Article 102436.

Jamaluddin, A. F., Tangang, F., Chung, J. X., Juneng, L., Sasaki, H., & Takayabu, I. (2018). Investigating the mechanisms of diurnal rainfall variability over Peninsular Malaysia using the non-hydrostatic regional climate model. *Meteorology Atmospheric Phyics, 130*, 611–633.

Joshi, A., Agrawal, S., & Chauhan, P. (2020). Reduction of atmospheric effects in satellite images during the COVID-19 induced lockdown. *Journal of Indian Society Remote Sensing, 48*, 1613–1625.

Jumaah, H. J., Ameen, M. A., Kalantar, B., Rizeei, H. M., & Jumaah, S. J. (2019). Air quality index prediction using IDW geostatistical technique and OLS-based GIS technique in Kuala Lumpur, Malaysia. *Geomaterialia Natural Hazards Risk, 10*, 2185–2199.

Kanniah, K. D., Kamarul Zaman, N. A. F., Kaskaoutis, D. G., & Latif, M. T. (2020). COVID-19's impact on the atmospheric environment in the Southeast Asia region. *The Science of the Total Environment, 736*, Article 139658.

Kerimray, A., Baimatova, N., Ibragimova, O. P., Bukenov, B., Kenessov, B., Plotitsyn, P., et al. (2020). Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan. *Science Total Environment, 730*, Article 139179.

Keywood, M. D., Ayers, G. P., Gras, J. L., Boers, R., & Leong, C. P. (2003). Haze in the Klang Valley of Malaysia. *Atmospheric Chemistry and Physics, 3*, 591–605.

Krecl, P., Targino, A. C., Oukawa, G. Y. C., & Junior, R. P. C. (2020). Drop in urban air pollution from COVID-19 pandemic: Policy implications for the megacity of São Paulo. *Environmental Pollution, 265*, Article 114883.

Kumar, P., Hama, S., Omidvarborna, H., Sharma, A., Sahani, J., Abhijith, K. V., et al. (2020). Temporary reduction in fine particulate matter due to 'anthropogenic emissions switch-off' during COVID-19 lockdown in Indian cities. *Sustainable Cities Society, 62*, Article 102382.

Lal, P., Kumar, A., Kumar, S., Kumari, S., Saikia, P., Dayanandan, A., et al. (2020). The dark cloud with a silver lining: Assessing the impact of the SARS COVID-19 pandemic on the global environment. *The Science of the Total Environment, 732*, Article 139297.

Latif, M. T., Huey, L. S., & Juneng, L. (2012). Variations of surface ozone concentrations across the Klang valley, Malaysia. *Atmospheric Environment, 61*, 434–445.

Leung, K., Wu, J. T., Liu, D., & Leung, G. M. (2020). First-wave COVID-19 transmissibility and severity in China outside Hubei after control measures, and second-wave scenario planning: A modelling impact assessment. *Lancet, 395*, 1382–1393.

Li, J., & Tartarini, F. (2020). Changes in air quality during the COVID-19 lockdown in Singapore and associations with human mobility trends. *Aerosol and Air Quality Research, 20*, 1748–1758.

Li, S., Wang, H., Hu, H., Wu, Z., Chen, K., & Mao, Z. (2019). Effect of ambient air pollution on premature SGA in Changzhou city, 2013–2016: A retrospective study. *BMC Public Health, 19*, 705.

Lian, X., Huang, J., Huang, R., Liu, C., Wang, L., & Zhang, T. (2020). Impact of city lockdown on the air quality of COVID-19-hit of Wuhan city. *The Science of the Total Environment, 742*, Article 140556.

Liu, Y., Song, M., Liu, X., Zhang, Y., Hui, L., Kong, L., et al. (2020). Characterization and sources of volatile organic compounds (VOCs) and their related changes during ozone pollution days in 2016 in Beijing, China. *Environmental Pollution, 257*, 113599.

Mahato, S., Pal, S., & Ghosh, K. G. (2020). Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Science Total Environment, 730*, Article 139086.

Mahmud, M. R., Hashim, M., & Reba, M. N. M. (2017). How effective is the new generation of GPM satellite precipitation in characterizing the rainfall variability over Malaysia? *Asia Pacific Journal Atmospheric Science, 53*, 375–384.

Malaysian Meteorological Department. (2020). *Iklim Malaysia*. http://www.met.gov.my/pendidikan/iklim/iklimmalaysia.

Menut, L., Bessagnet, B., Siour, G., Mailler, S., Pennel, R., & Cholakian, A. (2020). Impact of lockdown measures to combat COVID-19 on air quality over western Europe. *The Science of the Total Environment, 741*, Article 140426.
Ministry of Transport. (2019). *Transport Statistics Malaysia 2018*. Putrajaya: Ministry of Transport.
Mohtar, A. A. A., Latif, M. T., Baharudin, N. H., Ahamad, F., Chung, J. X., Othman, M., et al. (2018). Variation of major air pollutants in different seasonal and conditions in an urban environment in Malaysia. *Geoscience Letters, 5*, 1–21.
Nakada, L. Y. K., & Urban, R. C. (2020). COVID-19 pandemic: Impacts on the air quality during the partial lockdown in São Paulo state, Brazil. *The Science of the Total Environment, 730*, Article 139087.
Ooi, M., Chan, A., Subramaniam, K., Morris, K., & Oozeer, M. (2017). Interaction of urban heating and local winds during the calm intermonsoon seasons in the tropics. *Journal of Geophysical Research Atmospheres, 122*, 11499–11523.
Paital, B., Das, K., & Parida, S. K. (2020). Inter nation social lockdown versus medical care against COVID-19, a mild environmental insight with special reference to India. *The Science of the Total Environment, 728*, Article 138914.
Pei, Z., Han, G., Ma, X., Su, H., & Gong, W. (2020). Response of major air pollutants to COVID-19 lockdowns in China. *The Science of the Total Environment, 743*, Article 140879.
Peshin, S. K., Sharma, A., Sharma, S. K., Naja, M., & Mandal, T. K. (2017). Spatio-temporal variation of air pollutants and the impact of anthropogenic effects on the photochemical buildup of ozone across Delhi-NCR. *Sustainable Cities Society, 35*, 740–751.
Prather, K. A., Marr, L. C., Schooley, R. T., McDiarmid, M. A., Wilson, M. E., & Milton, D. K. (2020). Airborne transmission of SARS-CoV-2. *Science, 370*, 303.
PSTW. (2018a). *Standard operational procedure for continuous air quality monitoring (CAQM). operation, scheduled maintenance, troubleshooting*. Calibration And Verification. Pakar Scieno TW Sdn. Bhd.
PSTW. (2018b). *Standard operational procedure for continuous air quality monitoring (CAQM) data validation*. Pakar Scieno TW Sdn. Bhd.
R Development Core Team, R. (2011). *R: A language and environment for statiscal computing*. Austria: R foundation for statistical computing Vienna.
Ramachandran, S., Rupakheti, M., & Lawrence, M. G. (2020). Aerosol-induced atmospheric heating rate decreases over South and East Asia as a result of changing content and composition. *Scientific Reports, 10*, 20091.
Saadat, S., Rawtani, D., & Hussain, C. M. (2020). Environmental perspective of COVID-19. *The Science of the Total Environment, 728*, Article 138870.
Sanità di Toppi, L., Sanità di Toppi, L., & Bellini, E. (2020). Novel coronavirus: How atmospheric particulate affects our environment and health. *Challenges, 11*, 1–12.
Sarfraz, M., Shehzad, K., & Shah, S. G. M. (2020). The impact of COVID-19 as a necessary evil on air pollution in India during the lockdown. *Environmental Pollution, 266*(Part 1), Article 115080.
Sharma, S., Zhang, M., Anshika, Gao, J., Zhang, H., & Kota, S. H. (2020). Effect of restricted emissions during COVID-19 on air quality in India. *The Science of the Total Environment, 728*, 1–10.
Sicard, P., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paoletti, E., et al. (2020). Amplified ozone pollution in cities during the COVID-19 lockdown. *The Science of the Total Environment, 735*, Article 139542.
Siciliano, B., Dantas, G., da Silva, C. M., & Arbilla, G. (2020). Increased ozone levels during the COVID-19 lockdown: Analysis for the city of Rio de Janeiro, Brazil. *The Science of the Total Environment, 737*, Article 139765.
Sillman, S. (1999). The relation between ozone, NOx and hydrocarbons in urban and polluted rural environments. *Atmospheric Environment, 33*, 1821–1845.
Stratoulias, D., & Nuthammachot, N. (2020). Air quality development during the COVID-19 pandemic over a medium-sized urban area in Thailand. *The Science of the Total Environment, 746*, Article 141320.
Sulong, N. A., Latif, M. T., Khan, M. F., Amil, N., Ashfold, M. J., Wahab, M. I. A., et al. (2017). Source apportionment and health risk assessment among specific age groups during haze and non-haze episodes in Kuala Lumpur, Malaysia. *The Science of the Total Environment, 601–602*, 556–570.
Tobías, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M. C., et al. (2020). Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. *The Science of the Total Environment, 726*, 1–4.
Uria-Tellaetxe, I., & Carslaw, D. C. (2014). Conditional bivariate probability function for source identification. *Environmental Modelling & Software, 59*, 1–9.
van Doremalen, N., Bushmaker, T., Morris, D. H., Holbrook, M. G., Gamble, A., Williamson, B. N., et al. (2020). Aerosol and surface stability of SARS-CoV-2 as sompared with SARS-CoV-1. *The New England Journal of Medicine, 382*, 1564–1567.
Wang, Q., & Su, M. (2020). A preliminary assessment of the impact of COVID-19 on environment – A case study of China. *The Science of the Total Environment, 728*, Article 138915.
Wang, T., Xue, L., Brimblecombe, P., Lam, Y. F., Li, L., & Zhang, L. (2017). Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. *The Science of the Total Environment, 575*, 1582–1596.
Wang, Y., Zhuang, G., Sun, Y., & An, Z. (2006). The variation of characteristics and formation mechanisms of aerosols in dust, haze, and clear days in Beijing. *Atmospheric Environment, 40*, 6579–6591.
WHO. (2020). *Coronavirus disease (COVID-2019): Situation report - 10*. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200130-sitrep-10-ncov.pdf?sfvrsn=d0b2e480_2.
Wu, J., Gamber, M., & Sun, W. (2020). Does Wuhan need to be in lockdown during the Chinese Lunar New Year? *International Journal of Environment Research Public Health, 17*(3), 1002.
Wyche, K. P., Nichols, M., Parfitt, H., Beckett, P., Gregg, D. J., Smallbone, K. L., et al. (2021). Changes in ambient air quality and atmospheric composition and reactivity in the South East of the UK as a result of the COVID-19 lockdown. *The Science of the Total Environment, 755*, Article 142526.
Zambrano-Monserrate, M. A., Ruano, M. A., & Sanchez-Alcalde, L. (2020). Indirect effects of COVID-19 on the environment. *The Science of the Total Environment, 728*, Article 138813.
Zoran, M. A., Savastru, R. S., Savastru, D. M., & Tautan, M. N. (2020). Assessing the relationship between surface levels of $PM_{2.5}$ and PM_{10} particulate matter impact on COVID-19 in Milan, Italy. *The Science of the Total Environment, 738*, Article 139825.