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Air pollution impacts from COVID-19 pandemic control strategies in Malaysia

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ABSTRACT

Mitigation measures and control strategies relating to novel coronavirus disease 2019 (COVID-19) have been widely applied in many countries in order to reduce the transmission of this pandemic disease. A Movement Control Order (MCO) was implemented in Malaysia starting from the March 18, 2020 as a pandemic control strategy which restricted all movement and daily outdoor activities. To investigate the impact of MCO, air pollutants: particulate matter with an aerodynamic diameter less than 10 μm (PM_{10}), particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3) and carbon monoxide (CO) in nine major cities in Malaysia were measured before and during the implementation of the MCO. The non-carcinogenic health risk assessments of the air pollutants are also determined using the United States Environmental Protection Agency (USEPA) Health Risk Assessment method. Overall, NO_2 recorded an average percentage reduction of 40% with the highest reduction observed at Kota Kinabalu (62%). The largest reductions of PM_{10}, $PM_{2.5}$, SO_2, O_3 and CO were recorded at Kota Kinabalu (17%), Kuantan (9.5%), Alor Star (38%), Kota Bharu (15%), and Ipoh (27%) respectively. All cities had hazard quotient (HQ) values of <1 suggesting no non-carcinogenic health effects. The highest HQ was observed for $PM_{2.5}$ during the MCO period (4.53E-02) in Kuala Lumpur. An average hazard index (HI) value of 1.44E-01 (before the MCO) and 1.40E-01 (during the MCO) showed higher human health risks before the MCO than during the MCO. This study gives confidence to regulatory bodies that the reduction of human activities significantly reduces air pollution and increases human health and so good air pollution control strategies can provide crucial impacts, especially in reducing air pollution and improving human health.

1. Introduction

Anthropogenic air pollutants are of concern to human health, especially in urban areas where economic activities and rapid industrialization are associated with poor air pollution. Studies on air pollution and human health have been performed in order to explore links between air pollution and human health in terms of toxicity effects (Hanedar et al., 2013), DNA damage (Kalemba-Drozdz, 2015), reduced lung function (Panis et al., 2017), preterm delivery for pregnant women (Sun et al., 2019), mutagenic effects (Feretti et al., 2019), mortality and morbidity (Giallouros et al., 2020; Sarnat et al., 2008) and cardiopulmonary disease (Wang et al., 2018). There are also links between elevated risk of hospital admissions and severe air pollution episodes which indicates the crucial relationship between air pollution and human health.

Significant health affects due to the respiratory disease Coronavirus SARS-CoV-2 (COVID-19) have impacted almost all countries in the world; this epidemic is characterized as a pandemic due to its impact worldwide. COVID-19 was first identified in December 2019 near Wuhan, China. Up to the April 20, 2020, there was a total of 2,314,621 cases of COVID-19 in the world and the risk assessment was characterized as very high (WHO, 2020). The initial cause of this pandemic is Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) which affects the lower respiratory tract and acts in a similar way to pneumonia (Sohrabi et al., 2020). The symptoms of COVID-19 are fever, cough and dyspnoea (Ogen, 2020). COVID-19 was suggested to be spread by direct contact due to touching an infected person or a surface that an infected person has touched and droplets that contain the virus can remain stable for few days (Morawska and Cao, 2020). Due to the highly contagious nature of this virus, strict epidemic and pandemic control strategies have been implemented in China and other infected countries.

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In Malaysia, COVID-19 control strategies were implemented and named a movement control order (MCO) starting from the March 18, 2020 with phases 1, 2 and 3 (Nadzir et al., 2020). The MCO in Malaysia prohibits any government and private operations except for several important sectors. No educational activities by universities and schools are allowed, with day care and shopping complexes also being closed. Mass gathering are also prohibited and tourism and recreational activities are restricted. The MCO aims to reduce the transmission of COVID-19 nationally. A study on COVID-19 control measures in China found that the implementation of control measures successfully reduced the eventual epidemic size, suggesting strict monitoring and early detection of COVID-19 cases should remain in place until the end of April 2020 (Yang et al., 2020b). Moreover, the scenario of the lockdown event in China was studied to investigate the influence of emissions reduction due to reduced anthropogenic activities. A decrease in $PM_{2.5}$ was observed of between 5.35 and 30.79 $\mu g\ m^{-3}$ (Wang et al., 2020).

Previous studies (as shown in Table S1) critically investigated lockdown effects toward concentrations of air pollutants (Abdullah et al., 2020; Nakada and Urban, 2020; Tanzer-Gruener et al., 2020; Tobías et al., 2020; Venter et al., 2021; Yuan et al., 2021); air pollution relationship with COVID-19 cases (Accarino et al., 2021; Tello-Leal and Macías-Hernández, 2020); meteorology and air pollutants changes (Hossain et al., 2021; Sulaymon et al., 2021); traffic and mobility changes (Aloi et al., 2020); and the application of statistical and modelling (Bao and Zhang, 2020; He et al., 2020; Liu et al., 2020b) while this study focuses mainly on air pollutants effects in cities with the analysis related to population exposure to non-carcinogenic risks. The COVID-19 pandemic affected human activities, primarily when the MCO was implemented to reduce the chain of infection among the population in Malaysia. Thus, the aim of this study is to investigate the potential changes in concentrations of air pollutants caused by MCO in nine major cities in Malaysia, which had different types of economic activities and number of populations. Differences in air pollutant concentrations before and during the MCO period were evaluated in order to understand the impact of changes in emission on air pollution and human health, in particular on inhalation of non-carcinogenic pollutants for the city population. As the research related to the impact of reduced outdoor activities and COVID-19 pandemic mitigation measures in major cities in Malaysia have not been studied to present, therefore, this study may provide some background reference to the concentration of air pollution for the impact of “stay at home” strategy. In order to achieve this, the result of this study will provide insight into the implementation of policies aimed at reducing air pollution in a sector such as transportation, especially in the city.

2. Materials and method

2.1. Study area

In this study, nine major cities in Malaysia covering different regions, the North, Central, South, East Coast and West Malaysia, were chosen. The cities were Kuala Lumpur (Central); Seremban and Johor Bahru (South); Kuantan and Kota Bharu (East Coast); Kuching and Kota Kinabalu (East Malaysia); and Ipoh and Alor Star (North). Kuala Lumpur is the capital city of Malaysia known to have experienced an acceleration in economic development. Kuala Lumpur also has a high population and traffic density, thus investigation into the effects of the reduction of the number of vehicles on the roads during the MCO is one of the main interests. Kuala Lumpur has the highest population of the cities studied, 1.78 million, and the highest number of vehicles, 6.1 million (Road Transport Department Malaysia, 2020). Other cities have also experienced rapid development, especially industrial activities such as manufacturing, factories, processing, shipping and tourism. The locations of the selected cities in this study are shown in Fig. S1.

2.2. Data collection

The MCO in Malaysia started on the March 18, 2020 where almost all economic and daily activities were restricted in order to reduce the transmission of the COVID-19 disease. The concentrations of the air pollutants, PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3 and CO before the MCO (January 1 to March 17, 2020) were compiled and compared with the concentrations during the MCO period (March 18 until April 21, 2020).

The hourly air pollution dataset recorded at the Continuous Air Quality Monitoring Station (CAQMS) was obtained from the Malaysian Department of Environment (DOE). The instrument used for the measurements of PM_{10} and $PM_{2.5}$ was a Thermo Scientific Model TEOM 1450-DF while for SO_2, NO_2, CO and O_3 the instruments were Thermo Scientific Models 43i, 42i, 48i and 49i respectively. Each instrument was calibrated monthly to ensure the accuracy and precision. The concentration of each pollutant was determined at 10 min intervals and then calculated for 1 h averages.

The numbers of COVID-19 cases for each state in Malaysia are published daily by the Malaysian Ministry of Health (http://covid-19.moh.gov.my/) and were mapped using ArcGIS Version 10.5 (ESRI Inc, United States).

2.3. Air mass trajectories

Air mass trajectories for 5 days backward analysis for Kuala Lumpur was simulated for before MCO and during MCO using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPIT) developed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL). The longitude and latitude of the modelled backward trajectories was 3.1390 N, 101.6869 E with input meteorological data from Global Data Assimilation System (GDAS) 1.0 × 1.0 resolution global data.

2.4. Statistical analysis

A descriptive analysis was performed to explore the city-specific characteristics of air pollutants. Statistical analyses (*t*-test and one-way ANOVA) were used to investigate the relationship of air pollutant concentrations between cities and the effects of the MCO on air pollutants. SPSS V. 21 and Openair packages R software (Carslaw, 2015) were used for the statistical analyses in this study.

2.5. Health risk assessment

In this study, health risk assessments were performed for the non-carcinogenic risk to exposure by inhalation of ambient PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3 and CO based on the USEPA Risk Assessment Guidance for Superfund (USEPA, 2009). The exposure concentration (EC) was calculated as in Eq. (1):

$$EC = CA \times ET \times EF \times ED)/AT \quad (1)$$

where CA is the pollutant concentration ($\mu g\ m^{-3}$ or ppb), ET is exposure time (24 h), EF is the exposure frequency (30 days), ED is the exposure duration (1 year) and AT is the averaging time (ED × 365 days $year^{-1}$ × 24 h day^{-1}). The hazard quotients (HQ) for non-carcinogenic risk were calculated by dividing the EC with the reference exposure level (REL) which is a toxic threshold dose (Matooane and Diab, 2003). In this study, the Standard 2020 for air pollutants implemented under the Malaysia Ambient Air Quality

Standard was used, where REL values are 100 μg m^{-3} for PM_{10}, 35 μg m^{-3} for $PM_{2.5}$, 80 μg m^{-3} for SO_2, 70 μg m^{-3} for NO_2, 100 μg m^{-3} for O_3 and 10 μg m^{-3} for CO. HQ values of <1 suggest no significant risk of non-carcinogenic effects from air pollutants (Othman et al., 2020). Notation of all abbreviations is listed in Table S2.

3. Results and discussion

3.1. COVID-19 cases in Malaysia

As of April 20, 2020, a total of 5,425 cases of COVID-19 were reported in Malaysia and the fractions by states are shown in Fig. S2. The highest number of cases was recorded in Selangor state with 1,352 cases, of which 1,008 were in Kuala Lumpur. These numbers reflect the high population of these areas. During the study period (February 18 to April 20, 2020) there were 89 deaths in Malaysia reported due to COVID-19. The COVID-19 pandemic had significantly impacted almost all countries in the world.

The results show that the highest numbers of cases were recorded in the high-population city of Kuala Lumpur. The numbers of COVID-19 cases are suggested to increase in the weeks ahead. The relationship of COVID-19 cases and meteorological factors was studied by Liu et al. (2020a) where the results indicated that COVID-19 transmission may be favoured by low temperatures, mild diurnal temperature ranges and low humidity, while a study by Ma et al. (2020) found significant positive relationship between daily temperature and the daily mortality from COVID-19 and a negative relationship between COVID-19 mortality and relative humidity. Moreover, as exposure to high air pollution concentration can cause several health problems, such as cardiovascular disease, heart problem and respiratory diseases, especially in city areas, it is one of the possible causes of infection with COVID-19 disease. As reported by Conticini et al. (2020) and Ogen (2020) exposure to atmospheric pollution can cause cilia, and the upper airways defence may be weakened, which explains the higher prevalence and lethality of COVID-19. Zhu et al. (2020) who studied the association between air pollution and COVID-19 cases, had found that there is a statistically significant relationship between air pollution and COVID-19 infection, suggesting that further laboratory analysis is crucial to the investigation of the air pollution-related mechanism and the COVID-19 pandemic.

3.2. Characteristics of air pollutants before and during MCO

Fig. 1a to Fig. 1f illustrate the daily 24 h average concentrations of six criteria air pollutants in Kuala Lumpur, Alor Star, Ipoh, Seremban, Johor Bahru, Kuantan, Kota Bharu, Kuching and Kota Kinabalu. The measurements were divided into two periods, before the MCO (January 1, 2020 to March 17, 2020) and during the MCO (March 18 to April 21, 2020). A descriptive summary of each pollutant is given in Table S3. The calculated average daily, weekday and monthly concentrations are illustrated in Fig. 2 to Fig. 4.

3.2.1. PM_{10} and $PM_{2.5}$

PM_{10} and $PM_{2.5}$ had similar trends with no clear decreasing concentrations after the MCO was implemented in all cities (Fig. 1a and b). Moreover, peaks in concentrations were observed in Alor Star, Ipoh and Kota Kinabalu in the early part of the MCO while Kota Bharu had the highest peak during the MCO on April 7, 2020. A similar trend of PM_{10} and $PM_{2.5}$ concentrations were determined for Kuala Lumpur and Seremban city. The highest mean of PM_{10} was recorded at Kota Bharu with a mean concentration of 26.7 μg m^{-3} (range 4.98–74.6 μg m^{-3}) before the MCO and a mean concentration of 25.0 μg m^{-3} (range 3.95–203 μg m^{-3}) during the MCO. For $PM_{2.5}$, the highest mean was recorded at Kuala Lumpur for both before and during MCO period with a mean concentration of 18.6 μg m^{-3} and range of 0.26–133 μg m^{-3} for before the MCO period and a mean concentration of 19.3 μg m^{-3} and range of 0.24–172 μg m^{-3} during the MCO (Table S3). A reduction in PM_{10} concentrations during the MCO was recorded at all cities except Alor Star (which showed an increase of 11.2%) while for $PM_{2.5}$ a reduction in concentrations was recorded for Kuantan (9.5% reduction), Kuching (4.6% reduction) and Kota Kinabalu (3.4% reduction). Statistical analysis (a *t*-test) showed that there were significant differences ($r < 0.05$) in PM_{10} and $PM_{2.5}$ concentrations before and during the MCO period at all cities. We also examined the impact of MCO on the level of air quality using the difference in differences (DiD) model. For this analysis, 2019 data was used as a control group, while MCO was used as a treatment group. The result is shown in Table S4. Negative values of DiD suggested that there were reduction of air pollutant concentration after MCO was implemented. Cities such as Kota Kinabalu, Kuantan and Kuching recorded negative DiD values for PM_{10} while only Kuching had a negative DiD value for $PM_{2.5}$ that suggested a decrease in concentration during MCO.

PM_{10} and $PM_{2.5}$ concentrations were found to have peak concentrations at almost midnight in Alor Star, Ipoh, Kota Bharu and Kota Kinabalu while for Kota Bharu, a steady increase in concentrations was observed in the early morning followed by decreases until around 18:00 (Fig. 2a and b). Two clear peaks between 12:00 and 18:00 were observed for Kota Kinabalu before the MCO period with maximum values of 60 μg m^{-3} (PM_{10}) and 40 μg m^{-3} ($PM_{2.5}$). When comparing PM_{10} and $PM_{2.5}$ concentrations between months, a clear reduction was observed only for Alor Star, Ipoh, Johor Bahru and Kota Kinabalu in April 2020 which is in the MCO period. PM_{10} and $PM_{2.5}$ concentrations were also analysed for their variations during days in the week where, during the MCO, higher concentrations were observed on Wednesday in Alor Star and on Saturdays for Kota Bharu for both PM_{10} and $PM_{2.5}$. Higher PM_{10} concentrations for all days were observed before the MCO compared to during the MCO in Kuantan, Kuching, Kota Kinabalu and Johor Bahru, while for $PM_{2.5}$, higher concentrations were observed during the MCO compared to before the MCO for Alor Star and Kota Bharu for all days of the week.

Slightly higher $PM_{2.5}$ concentrations during the MCO compared to before the MCO suggested contributions from regional sources, e.g. transport of air masses and the resuspension of dust. Five day trajectories of air masses arriving in Kuala Lumpur during the MCO showed the contribution of two wind directions, one from the South China Sea and one from Northern Peninsular Malaysia while before the MCO period, air masses were from the South China Sea (Fig. S3). From these trajectories, it can be seen that regional sources can be factors in air pollutant variation, especially for fine particulates. Moreover, during the MCO, lorries used for the transportation of food and crucial supplies were not prohibited and thus the concentrations of both PM_{10} and $PM_{2.5}$ may have originated from these transportation activities and the resuspension of dust for Kuala Lumpur city. Amato et al. (2009) reported that dust resuspension, particularly road dust, plays a significant role in PM concentrations for urban areas. On the contrary, a reduction in $PM_{2.5}$ concentrations was suggested by Bao and Zhang (2020), He et al. (2020), Liu et al. (2020a), Sulaymon et al. (2021) and Wang et al. (2020) during the COVID-19 outbreak where lockdown had been implemented in China. Reductions in PM_{10} and $PM_{2.5}$ were reported to be 31% and 43% during the lockdown period in India which suggested the effects of lockdown and restricted human activities were substantial (Sharma et al., 2020) while reductions of up to 58% in $PM_{2.5}$ concentrations in Malaysia were thought to be linked to the restrictions of activities in Malaysia such as mass

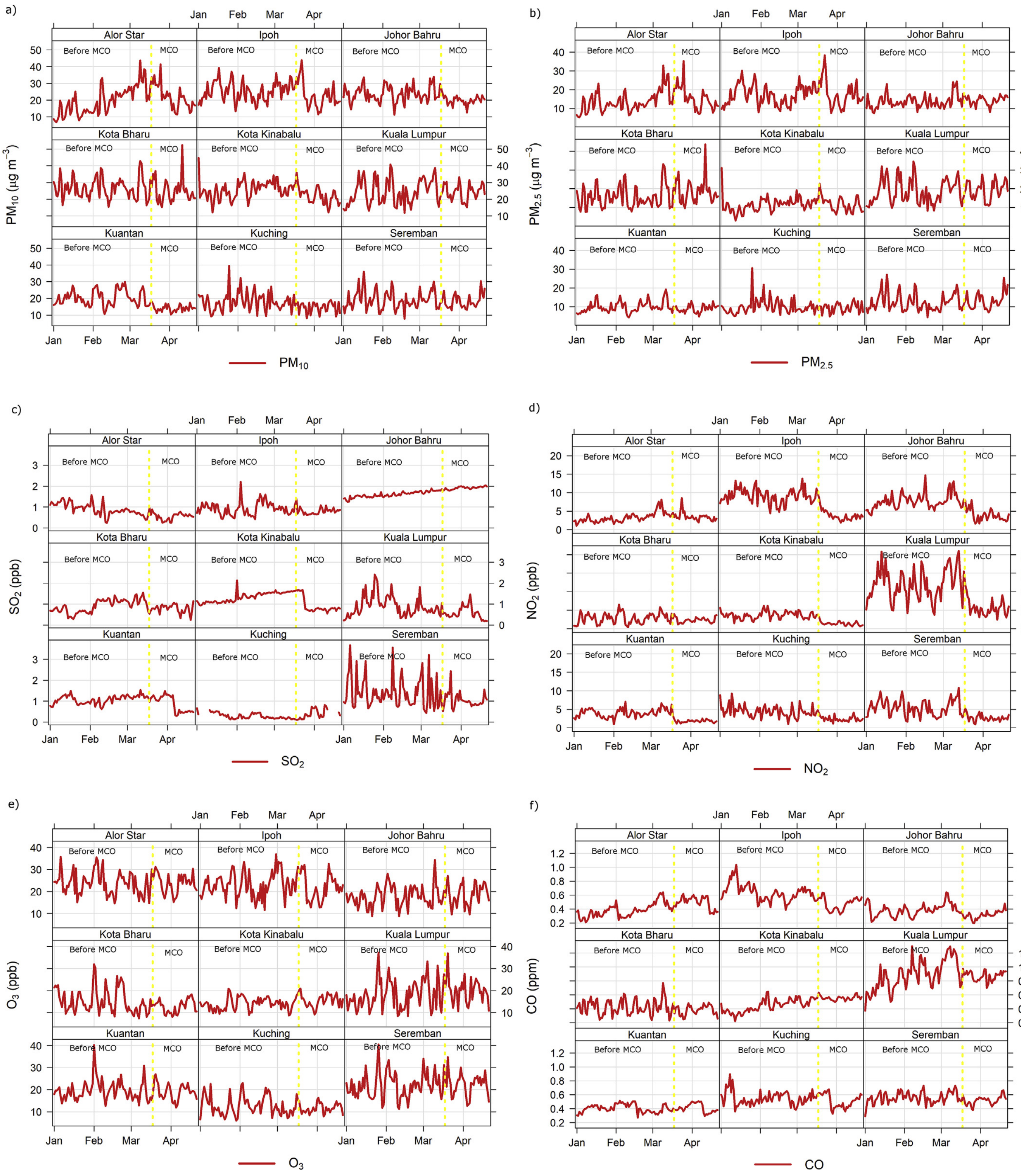

Fig. 1. Daily 24 h averages of a). PM_{10}, b). $PM_{2.5}$, c). SO_2, d). NO_2, e). O_3 and f). CO concentration of major cities in Malaysia.

gatherings and the closure of government and private agencies (Abdullah et al., 2020). Higher drop of PM_{10} and $PM_{2.5}$ concentration during the pollution control measures for APEC Meeting in Beijing, China was recorded by Li et al. (2017) compared to this study where the control measures had provided short-term enhancement in air quality. PM_{10} and $PM_{2.5}$ can significantly reduce with continually upgrading the quality of gasoline with additional systematic design of series of policies to mitigate PM pollution (Yang et al., 2020a).

3.2.2. SO_2

SO_2 showed increasing concentrations from the beginning of the

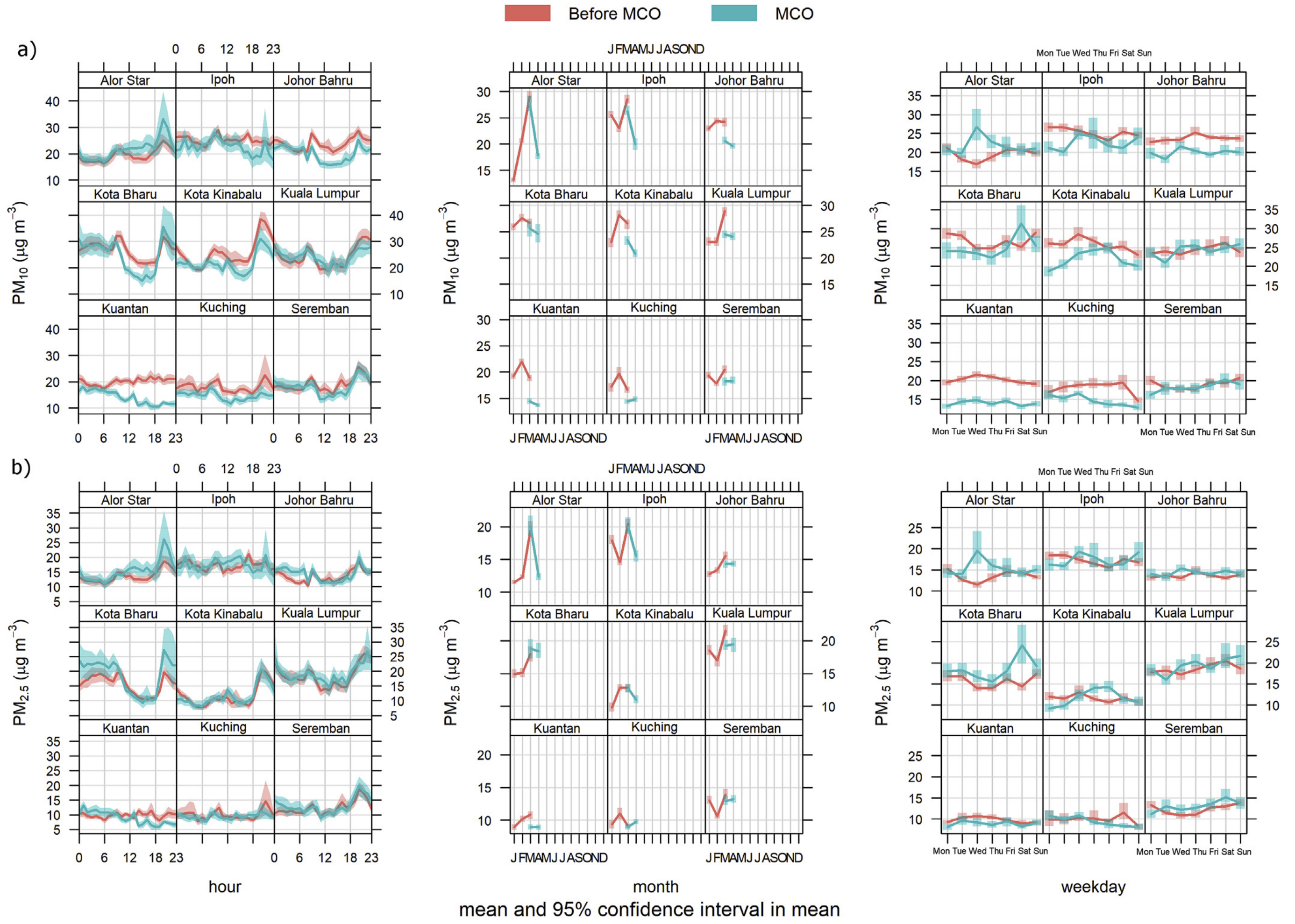

Fig. 2. Variation of a). PM_{10} and b). $PM_{2.5}$ before MCO and during MCO calculated for hourly, weekday and monthly concentration.

year 2020 until the early part of the MCO and then decreasing concentrations after the first few days of the MCO in Kota Kinabalu city (Fig. 1c). A similar trend was also recorded at Kuantan with a sudden drop in SO_2 concentrations in the middle of the MCO period. The opposite trend was exhibited at Johor Bahru where a steady increase in SO_2 concentrations was recorded from the beginning of 2020 which continued during the MCO period. Kuala Lumpur and Seremban both had fluctuating concentrations before the MCO while during the MCO no clear reduction of concentration was observed. As listed in Table S3, the highest mean concentration of SO_2 both before and during the MCO was from Johor Bahru with concentrations of 1.60 ppb and 1.88 ppb respectively. The average daily SO_2 concentrations during the MCO were 0.9 times lower (an average reduction of 39%) than before the MCO at all cities (except Johor Bahru and Kuching), with significant differences ($r < 0.05$) between concentrations before and during the MCO. The result of the DiD model (Table S4) suggested that Seremban, Kota Kinabalu, Alor Star, Kuantan had reduced SO_2 concentration after MCO had been established.

Hourly SO_2 average concentrations were observed to be higher before the MCO compared to during the MCO at Alor Star, Ipoh, Kota Kinabalu, Kuala Lumpur and Seremban (Fig. 3a). A clear distinction of hourly average SO_2 concentrations before and during the MCO were observed at Seremban, where the highest concentration before the MCO was recorded between 06:00 to 12:00. Johor Bahru had higher hourly SO_2 concentrations during the MCO compared to before the MCO but the other cities had the opposite pattern, with higher hourly SO_2 concentrations before the MCO compared to during the MCO period. Monthly concentrations of SO_2 showed decreases at Kota Kinabalu, Kuantan and Seremban while other cities had either increases or constant trends in the monthly concentrations of SO_2.

SO_2 concentrations were expected to decrease due to reduced industrial activities in Malaysia during the MCO, while the increase in concentrations at Johor Bahru suggest that the nearby coal-fired power plant influenced SO_2 concentrations as they were observed to be higher here for both before MCO and during MCO compared to other cities. SO_2 concentration can further transported to other places from industries and power plant that have massive emission of SO_2 (Shen et al., 2017). Sharma et al. (2020) reported that increased SO_2 concentrations in 2020 during the lockdown may be due to coal-fired powered plant contributions while Tobías et al. (2020) suggested the rising SO_2 concentrations were from shipping emissions. Mahato et al. (2020) reported only small changes in SO_2 concentrations compared to other air pollutants after the lockdown event in Delhi, India during the COVID-19 pandemic. This was likely to be due to the location of Delhi as it is inland and would generally experience low SO_2 concentrations. Compared to other studies, higher reduction of SO_2 than this study was observed (Nakada and Urban, 2020; Sulaymon et al., 2021; Tobías et al., 2020; Yuan et al., 2021) which suggested that the different levels of SO_2 during the regular day without lockdown could be unlikely due to

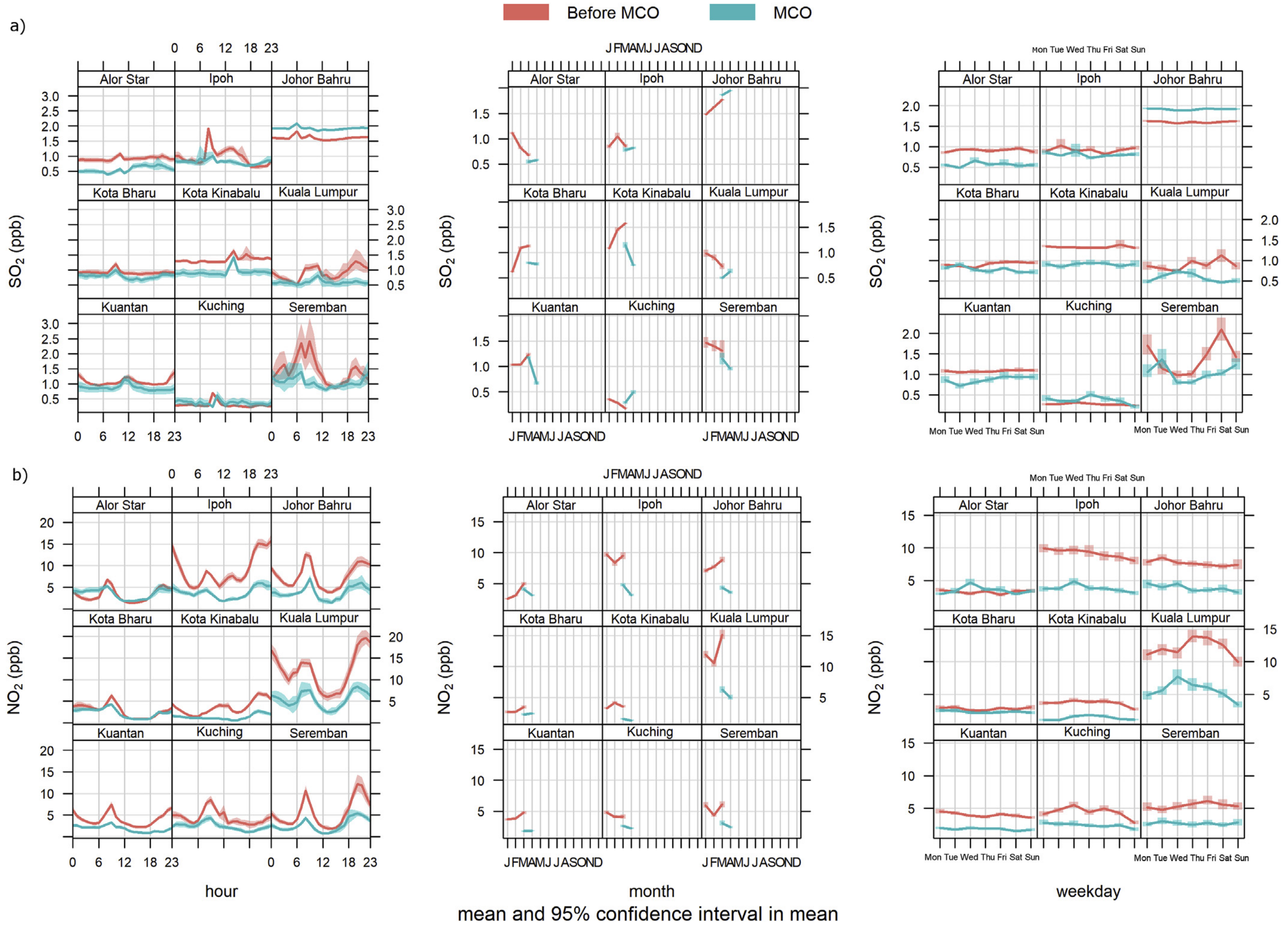

Fig. 3. Variation of a). SO_2 and b). NO_2 before MCO and during MCO calculated for hourly, monthly and weekday concentration.

different intensity and source of SO_2 concentration, which in turns provide different percentages of reduction. Furthermore, the effect of strengthened air pollution regulation during the APEC Meeting and the Victory-day Parade in Beijing; and World Internet Conference in Jiaxing which had reported reduction of 56.5% and 7.1% which suggested effectiveness of stringent regulation to reduced air pollution (Li et al., 2017; Shen et al., 2017).

3.2.3. NO_2

All cities showed decreasing concentrations of NO_2 during the MCO, except for Alor Star which had peak concentrations during the MCO (Fig. 1d). Some cities, for instance Kota Bharu, Kota Kinabalu, Kuantan and Kuching, showed small variations in concentrations with no obvious peak in concentrations either before or during the MCO. Kuala Lumpur had fluctuations in NO_2 before the MCO with a minimum value of 0.01 ppb and maximum value of 42.9 ppb, while during the MCO the minimum value was 0.008 ppb and maximum value was 22.2 ppb (Table S3). The result from DiD model (as shown in Table S4) had negative values for all cities except for Kota Bharu, Johor Bahru and Alor Star, which indicated no significant impact of MCO towards NO_2 concentration in these cities.

The calculated hourly and weekday trends of NO_2 clearly showed that higher concentrations were observed before the MCO compared to during the MCO, except for Alor Star and Kota Bharu (Fig. 3b). Almost all cities had peak concentrations between 06:00 and 12:00 while another peak was observed at night (18:00 to 23:00) for Ipoh, Johor Bahru, Kota Kinabalu, Kuala Lumpur, and Seremban. Decreases in the calculated average monthly concentrations of NO_2 were observed in Alor Star, Ipoh, Johor Bahru, Kuala Lumpur and Seremban. Higher NO_2 concentration during lockdown were observed by Bao and Zhang (2020), Nakada and Urban (2020), Sulaymon et al. (2021) and Tobías et al. (2020) compared to the MCO period in this study indicating that NO_2 concentration may depend on the specific sources and local contribution.

Significant decreases in NO_2 concentrations after the implementation of the MCO were caused by the reduced number of motor vehicles on the roads as human activities were reduced. Reduced concentrations of NO_2 were clearly observed in Kuala Lumpur and Seremban. These cities are close to each other and usually have high numbers of motor vehicles used to commute between these cities on a normal day. Moreover, a significant peak of NO_2 was observed on the March 13 for Kuala Lumpur and Seremban, a date that marked the beginning of a school holiday in Malaysia and thus unusual traffic movements were suggested to be due to family activities such as visiting home towns and tourism activities. A similar result was obtained by Tobías et al. (2020) where peak concentrations before the lockdown and significant variations in NO_2 were suggested to be due to reduced emissions from combustion process, road traffic, power generation and shipping. A study by Dantas et al. (2020) reported a reduction of NO_2 concentrations in the city of Rio de Janeiro, Brazil where NO_2

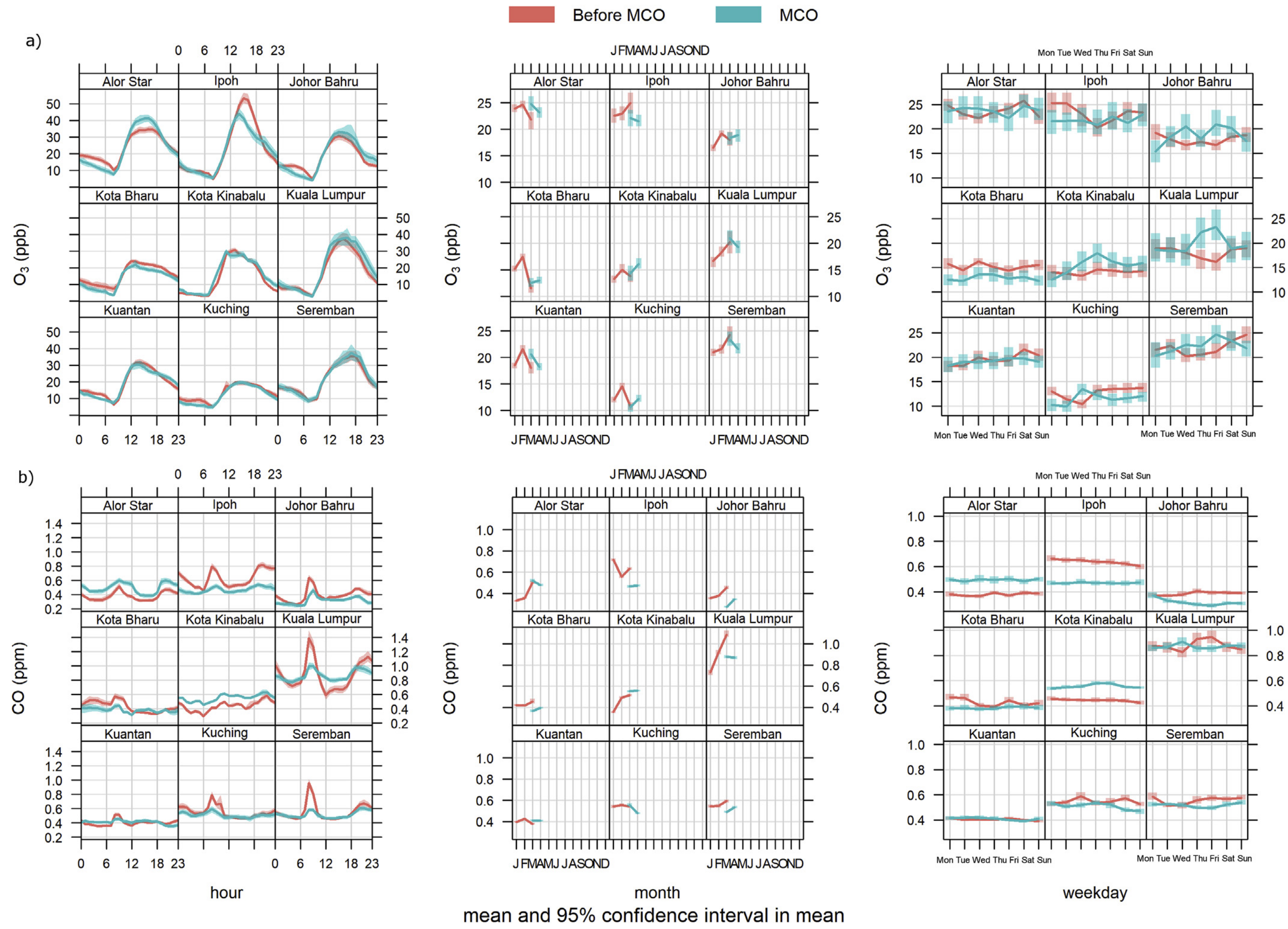

Fig. 4. Variation of a). O_3 and b). CO before MCO and during MCO calculated for hourly, monthly and weekday concentration.

was suggested to be decreased due to the decrease of 80% of the vehicle movements and other factors, for instance transport of air masses and meteorological parameters. Ogen (2020) assessed the levels of NO_2 over Europe using TROPOMI data which indicated that high NO_2 concentrations are often associated with downward airflows providing increased NO_2 near to the earth's surface and this combined with topographic structures and atmospheric conditions means NO_2, along with other air pollutants, was not dispersed.

3.2.4. O_3

The mean concentrations of O_3 before the MCO in the studied cities were in the sequence Alor Star > Ipoh > Seremban > Kuantan > Kuala Lumpur > Johor Bahru > Kota Bharu > Kota Kinabalu > Kuching while the sequence during the MCO was Alor Star > Seremban > Ipoh > Kuala Lumpur > Kuantan > Johor Bahru > Kota Kinabalu > Kota Bharu > Kuching (Table S3). No clear trend in O_3 concentrations was observed during either period (before and during the MCO) for all cities (Fig. 1e). However, similar trends of O_3 were observed for Kuala Lumpur and Seremban where the highest peak concentration was observed at the end of January 2020 before the MCO period and another peak was seen in the early part of the MCO. Only Ipoh, Kuantan, Kota Bharu and Kuching had reduced O_3 concentrations after the implementation of the MCO with an average percentage reduction of 0.8%. The *t*-test indicated that no significant difference ($r > 0.05$) was observed for O_3 concentrations before and during the MCO period, while DiD model result (Table S4) indicated that only Kuala Lumpur and Ipoh had reductions of O_3 during the MCO period.

Hourly average of O_3 concentrations clearly showed similar trends before and during the MCO in all cities, with increasing concentrations after 06:00 until 12:00 and then rapid decreases after 12:00 for all cities except for Seremban which had highest peak concentrations in the late afternoon (17:00) (Fig. 4a). For weekday average concentrations, only Kota Bharu had higher O_3 concentrations before the MCO on all days of the week compared to before the MCO. Monthly average concentrations showed decreases during the MCO in April for Alor Star, Kuala Lumpur, Kuantan, and Seremban while other cities had increasing or stable O_3 concentrations during the MCO period.

This study found that O_3 concentrations were not affected by the MCO and this is suggested to be due to the continuous production of O_3 via photochemical reactions. O_3 is a component of photochemical smog and formed through a reaction involving NOx and VOCs in the presence of sunlight where both NOx and VOCs are suggested to originate from traffic (Zhang et al., 2011). With the reduction in O_3 precursors such as NOx, O_3 concentration will increase with the added effect of titration ($NO + O_3 = NO_2 + O_2$) (Mahato et al., 2020). Agreeing with the result from this study, Li et al. (2017) had also had found that higher O_3 concentration after regulatory approached to reduced air pollutants in Beijing. Comparisons of O_3 concentrations before and after seasonal holidays conducted in China and Taiwan showed higher O_3 concentrations were observed during the holiday period due to the NO titration effect (Chen et al., 2019; Tan et al., 2009; Xu et al., 2017). A study by Tan et al. (2009) on the holiday effect in China reported higher O_3 concentrations during the Chinese New Year holiday compared to non-Chinese New Year holiday periods which was thought to be due to factors such as carry forward emissions, NO titration and the effect of dust storms.

3.2.5. CO

The average mean concentration of CO in all cities before the MCO period was 0.53 ppm which is about 0.94 times higher compared to the mean concentration during the MCO period (Table S3). Significant differences in CO concentrations before and during the MCO for all cities were seen using a *t*-test ($r < 0.05$) with an average reduction of 1.2%. The CO concentrations in Kuala Lumpur recorded a large range, between 0.55 ppm and 1.57 ppm during the MCO while range concentrations between 0.07 ppm and 2.75 ppm were observed before the MCO, with a small reduction of 1.1% after the MCO was implemented. The two highest peaks were observed in the second week of February 2020 and March 2020 for 24 h average CO concentrations in Kuala Lumpur with concentrations above 1.2 ppm while several other peaks were also observed during the January 1, 2020 to the April 17, 2020 (Fig. 1f). Based on Table S4, the negative value of DiD was only observed for Kuala Lumpur and Kuching (significance at 1%), which suggested a reduced CO concentration with not a much difference for CO concentration during the MCO period compared to the previous year.

For hourly CO variation, peak concentrations were observed between 06:00 to 12:00 before the MCO in Seremban, Kuala Lumpur, Johor Bahru, Kuching, Alor Star and Ipoh. Moreover, only Alor Star and Kuching had higher hourly concentrations during the MCO compared to before the MCO (Fig. 4b). For weekday averages, all days in the week had similar concentrations with no obvious peaks. Monthly variations of CO indicated decreasing monthly concentrations for Alor Star and Kuching during the MCO. Before the MCO, Kuala Lumpur recorded a rapid increase in concentrations from January 2020 to March 2020.

The reduced concentrations of CO can be attributed to restricted movement after the MCO was implemented, particularly due to reduced vehicle emissions. CO emissions are strongly related to local emission sources, particularly road traffic where higher CO concentrations have been recorded in high traffic areas (Azhari et al., 2018; Jang et al., 2017). A study by Mahato et al. (2020) recorded a reduction in CO of 36.84% in the megacity of Delhi, suggested to be due to closed roads, manufacturing industries and power plants during the COVID-19 lockdown. Furthermore, the CO concentrations before and during the Chinese New Year holiday in Taiwan reduced during the holiday. CO was mainly related to mobile sources with strong relationships with population number and number of motor vehicles suggesting possible impacts of urbanization on the air pollutants concentration (Tan et al., 2013). CO concentration was also observed to be reduced after implementation of strict pollution control measures where traffic restriction and reduced industrial emission provided reduction of 41.7% (Shen et al., 2017).

3.3. Correlation matrix

The relationships between air pollutants in each city during the period of study are illustrated in Fig. 5. Overall, strong correlations were observed between PM_{10} and $PM_{2.5}$ for all cities with $r = 0.93$ for Alor Star, $r = 0.95$ for Ipoh, $r = 0.88$ for Johor Bahru, $r = 0.94$ for Kota Bharu, $r = 0.98$ for Kota Kinabalu, $r = 0.92$ for Kuala Lumpur, $r = 0.84$ for Kuantan, $r = 0.93$ for Kuching and $r = 0.95$ for Seremban. Other correlations were observed for CO and NO_2 with $r > 0.60$ in Alor Star, Ipoh, Kota Bharu, Kuala Lumpur, Kuching and Seremban. A correlation matrix between air pollutants before MCO and during MCO are presented in Fig. S4. Strong positive correlations were observed between $PM_{2.5}$ and PM_{10}, and between CO and NO_2 ($r > 0.8$) while moderate relationships ($r = 0.5$) were observed between CO and $PM_{2.5}$ and NO_2 with $PM_{2.5}$ for the dataset before the MCO. There were also moderate positive correlations between CO and PM_{10}, $PM_{2.5}$ and NO_2 and between NO_2 with PM_{10} and $PM_{2.5}$ for the dataset during the MCO.

Correlations of $PM_{2.5}$ and PM_{10} for before and during the MCO clearly indicate that $PM_{2.5}$ is significantly associated with PM_{10}. Moreover, a strong correlation between CO and NO_2 suggested that these two pollutants were produced from the same source such as traffic emissions and the incomplete combustion of fuel. CO and NO_2 were observed to have a moderate relationship with both PM_{10} and $PM_{2.5}$, suggesting these pollutants have similar sources.

3.4. Health risk assessment

The hazard quotient (HQ) values for non-carcinogenic exposure to air pollutants are reported in Table 1. Overall, higher HQ values for all pollutants were observed before the MCO compared to during the MCO except for $PM_{2.5}$ and O_3. The total HQ value is indicated by the hazard index (HI) which recorded a reduction of 11% for PM_{10} and SO_2, 81% for NO_2 and 3% for O_3 and an increase of 3% for $PM_{2.5}$ and 10% for O_3 during the MCO. Among all pollutants, the highest HQ values were observed for $PM_{2.5}$ at Kuala Lumpur both before the MCO (4.37E-02) and during the MCO (4.53E-02) while Kuala Lumpur also recorded the highest total HQ value for air pollutants with values of 7.43E-02 (before the MCO) and 1.19E-01 during the MCO. The sequence of non-carcinogenic exposure was $PM_{2.5} > PM_{10} > O_3 > NO_2 > CO > SO_2$ before the MCO while during the MCO it was $PM_{2.5} > PM_{10} > O_3 > NO_2 > CO > SO_2$.

The results for HQ and HI were lower than the acceptable limit of 1.0, indicating that there is no significant non-carcinogenic risk from air pollutant exposure either before or during the MCO. Higher HQ values for $PM_{2.5}$ compared to other pollutants clearly indicate the greater non-carcinogenic risk posed by fine particles, while the population of Kuala Lumpur are exposed to a higher risk from air pollutants compared to other cities. Non-carcinogenic health risks in Kuala Lumpur showed a HI value of 0.28 for an adult during a non-haze day in Kuala Lumpur while the inhalation of Cr was shown to pose a health risk to the population in Kuala Lumpur (Sulong et al., 2017). A study by Othman et al. (2020) had higher HQ values for O_3 rather than $PM_{2.5}$ in outdoor air which is inconsistent with this study. This could be due to the strong outdoor sources such as traffic and human activities. Studies on human health risks are usually performed based on inhalation, ingestion and dermal routes for metals and exposure calculations can be different based on exposure duration, time, frequency and body weight. Moreover, calculation of the excess risk of the population described by Sharma et al. (2020) was attempted but due to low 24 h concentrations of all air pollutants compared to the Standard 2020 for air pollutants implemented under the Malaysia Ambient Air Quality Standard, no excess health risk of air pollutants was suggested.

With the result of this study, clear policies on vehicle emission and improving of current standard of fuel are needed for example in city of Kuala Lumpur with high population thus mitigating the emission of fine PM and health risk area crucial.

4. Conclusion and policy implication

In this study, the impact of the MCO due to the COVID-19

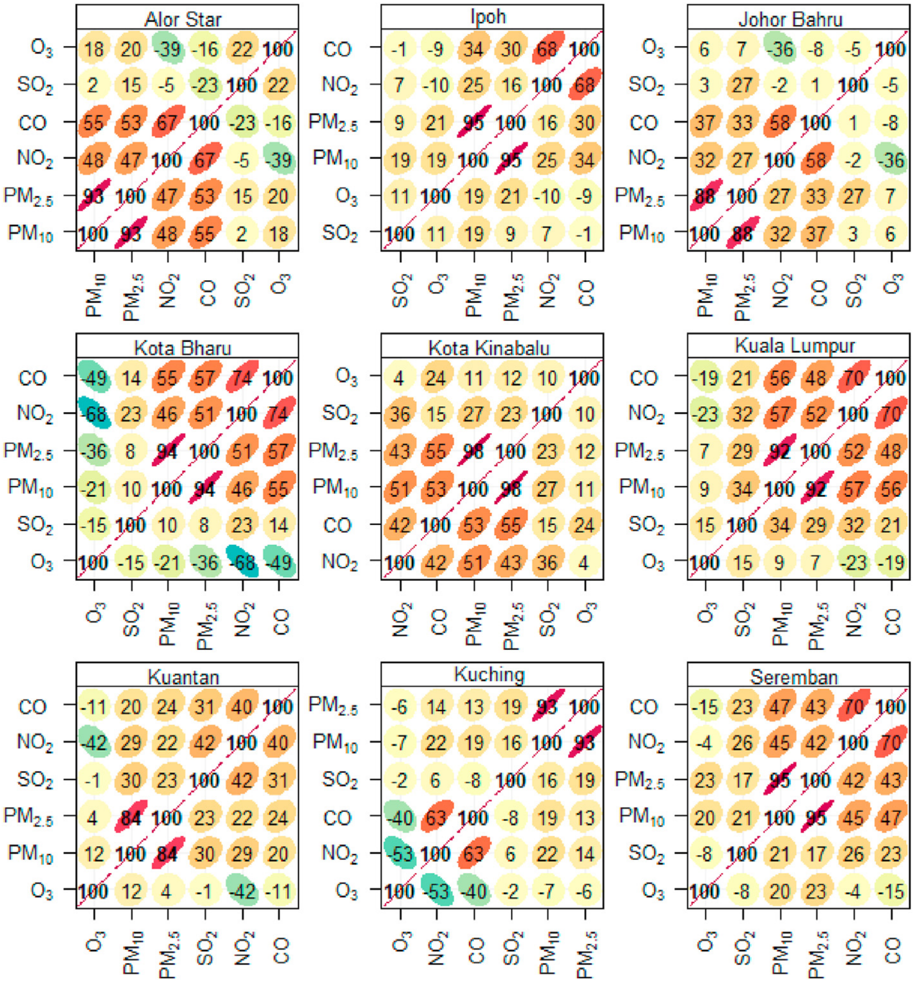

Fig. 5. Correlation matrix of air pollutants in major cities in Malaysia.

Table 1
Hazard quotient value of PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3 and CO before and during MCO.

	PM_{10}		$PM_{2.5}$		SO_2		NO_2		O_3		CO	
	Before MCO	During MCO	Before MCO	During MCO	Before MCO	During MCO	Before MCO	During MCO	Before MCO	During MCO	Before MCO	During MCO
Kuala Lumpur	2.00E-02	1.99E-02	4.37E-02	4.53E-02	2.40E-03	1.53E-03	6.72E-03	1.14E-02	2.98E-02	3.27E-02	8.29E-03	8.19E-03
Alor Star	1.61E-02	1.79E-02	3.17E-02	3.62E-02	2.45E-03	1.51E-03	2.61E-02	7.34E-03	3.90E-02	3.90E-02	3.48E-03	4.61E-03
Ipoh	2.07E-02	1.85E-02	4.04E-02	4.06E-02	2.48E-03	2.15E-03	1.88E-02	7.81E-03	3.81E-02	3.57E-02	5.93E-03	4.33E-03
Seremban	1.56E-02	1.50E-02	2.89E-02	3.08E-02	3.80E-03	2.77E-03	1.11E-02	5.49E-03	3.60E-02	3.67E-02	5.18E-03	4.80E-03
Johor Bahru	1.95E-02	1.64E-02	3.19E-02	3.36E-02	2.58E-03	5.06E-03	8.71E-03	8.03E-03	2.93E-02	3.06E-02	3.58E-03	3.01E-03
Kuantan	1.65E-02	1.14E-02	2.31E-02	2.09E-02	2.88E-03	2.40E-03	8.18E-03	3.72E-03	6.58E-04	3.14E-02	3.77E-03	3.77E-03
Kota Bharu	2.19E-02	2.05E-02	3.66E-02	4.34E-02	2.45E-03	2.10E-03	5.77E-03	4.81E-03	2.50E-02	2.10E-02	3.95E-03	3.58E-03
Kuching	1.48E-02	1.20E-02	2.33E-02	2.22E-02	7.27E-04	9.96E-04	9.02E-03	4.91E-03	2.07E-02	1.89E-02	5.08E-03	4.71E-03
Kota Kinabalu	2.17E-02	1.79E-02	2.86E-02	2.61E-02	3.58E-03	2.42E-03	7.58E-03	2.86E-03	2.32E-02	2.53E-02	4.14E-03	5.18E-03
Total HQ	1.67E-01	1.50E-01	2.88E-01	2.99E-01	2.33E-02	2.09E-02	1.02E-01	5.63E-02	2.42E-01	2.71E-01	4.34E-02	4.22E-02

pandemic in Malaysia on air pollution was investigated. Overall, the highest reduction in air pollutants was observed for NO_2 with an average percentage of 40%. Reductions of more than 50% NO_2 after the MCO was implemented were recorded at Kuala Lumpur (54%), Ipoh (58%), Seremban (50%), Kuantan (54%) and Kota Kinabalu (62%). $PM_{2.5}$ showed an increase in concentrations of between 0.10 and 2.90 $\mu g\ m^{-3}$ after the MCO at Kuala Lumpur, Alor Star, Ipoh, Seremban, Johor Bahru and Kota Bharu. On top of that, the concentrations of the six criteria air pollutants after the implementation of the MCO were significantly different to those before ($r < 0.05$) except for O_3. No non-carcinogenic risk exposure was recorded either before or during the MCO with HQ values of <1.0 in all cities. However, higher health risks from air pollutants were observed in Kuala Lumpur compared to other cities.

From the results obtained, this study provided evidence that the Malaysian Government's initiatives to reduce the transmission of the COVID-19 pandemic have a significant impact on the air pollutants concentration in Malaysia. Moreover, it can be said that reduced human outdoor activities, vehicle emissions and coal-fired power plant emissions play significant roles in achieving cleaner air. The results of this study can also help the respective government body to identify the concentration of air pollutants in each of the cities as a benchmark for and consideration of emission standards for air pollutants. Hence, Malaysia needs to design systematic policies based on pollution sources and characteristics in each city with the use of cleaner alternative and new vehicle technology, as most of the cites had air quality improvement with reduced vehicle numbers during the MCO period. In addition, each local authority can have its mitigation measures to reduce the air pollution concentration to be implemented on a small scale, which may eventually be expanded to a larger scale.

Further studies on the effects of meteorology on air pollutant concentrations are highly recommended in order to further evaluate the variation of air pollutants for the pre-MCO, MCO and post-MOC periods. There are uncertainties in identifying the source contribution of air pollutants in each city which are lack of chemical composition and other air pollution data, such as volatile organic compound (VOC), insufficient vehicle numbers data and the industries that operated during the MCO period. Despite the associated uncertainty, the results of this study have shown that the MCO is a mitigation strategy to reduce the transmission of COVID-19 but has also had an impact on air pollutant concentrations in city areas. Even though most of the air pollutants concentrations were reduced during the MCO period, O_3 still had showed not much different concentration that needs further investigation.

CRediT authorship contribution statement

Murnira Othman: Conceptualization, Formal analysis. **Mohd Talib Latif:** Writing - review & editing.

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

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