Effects of Coronavirus Induced City Lockdown on $PM_{2.5}$ and Gaseous Pollutant Concentrations in Bangkok

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Abstract

Partial lockdown measures took effect in Thailand from March 22, 2020 to prevent the spread of the coronavirus. People widely believed that the air quality in Bangkok would improve during the lockdown. This study aims to understand the effects of the traffic on Bangkok $PM_{2.5}$ and gas concentrations, by comparing the air quality before and during the lockdown. Some pollutant concentrations in pre-lockdown period were higher, but the differences were not significant, except for O_3. When results in the full lockdown month, April 2020, were compared to the same period in 2019, the average $PM_{2.5}$ concentrations at the road sites decreased by 11.1%. On the other hand, it increased by 16.7% at the business area sites. No clear relation of the $PM_{2.5}$ change to the reduction of traffic and diesel fuel consumption was observed. The reduction of NO_2 was clear, caused by the significant drop in traffic and fuel consumption: in turn, it contributed to an increase of O_3. The increment of $PM_{2.5}$ levels during the lockdown was an external effect, even though significant change of local sources occurred. The values of OC/EC ratios in fine particles and the backward trajectory simulation confirmed that the peaks of $PM_{2.5}$ levels were affected by both transboundary and local aerosol transport from open biomass burning. Hence, it is clear that road traffic, as well as industries or other human activities, were not the most influential factors on high $PM_{2.5}$ levels in Bangkok in normal conditions. Possible solutions to reduce sources of Bangkok air pollutants include introduction of small-scale machinery for sugarcane harvesting to reduce biomass burning, adoption of higher standards to control diesel engine emission, and mutual agreement and action among ASEAN members in transboundary haze reduction.

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INTRODUCTION

A coronavirus outbreak occurred in late 2019 and caused a COVID-19 pandemic in early 2020. Many countries have used different approaches to handle the pandemic. One of the most used measures was lockdowns of cities, regions or countries in an attempt to control the virus. Details of the measures varied from country to country. It has been interesting to many aerosol scientists or environmental researchers to know how the lockdown and activity constraints, including road traffic, affected air pollution (Jain and Sharma, 2020; Mahato *et al.*, 2020; Xu *et al.*, 2020; Nakada and Urban, 2020; Tobías *et al.*, 2020). Thailand adopted a series of partial lockdown measures since March 22, 2020. In the first phase, from March 22-May 2, 2020, the measure was most strict. All business, including industries, transportation, shopping, tourism and hotels, along with many entertainment and recreation venues, were shutdown and limited access to certain areas was announced. A state of emergency was announced on March 26, 2020, and a curfew, involving prohibition of all activities, outside residences from 10 pm - 4 am, was enforced from April 3 until May 16, 2020; curfew hours were reduced to 11 pm - 4 am from May 17 to 31 and further reduced to 11 pm – 3 am from June 1 to June 14, before it was lifted. All incoming international flights were banned from April 4, 2020 (and remain constricted, even in November, 2020), except for state and military aircraft and emergency and technical landings. It was clear that road traffic in Bangkok city, as well as many cities, was significantly reduced during these periods. Industrial processes and manufacturing activities were halted. The period from March 22 - April 31 was then selected

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as representing the strictest 'lock down' period in the present study, where air pollution, due to road traffic would be minimum.

Researchers studied the impact of the COVID-19 pandemic on air quality in many countries, e.g. China, India, Brazil, and Spain. Jain and Sharma (2020) studied the overall effect of lockdown measures on air quality in five Indian megacities - Delhi, Mumbai, Chennai, Kolkata, and Bangalore. Results showed that all pollutants, i.e. $PM_{2.5}$ PM_{10}, NO_2 and CO significantly declined in all the megacities, especially in Delhi, except for O_3. The concentration of $PM_{2.5}$, PM_{10}, NO_2 and CO declined by 41%, 52%, 51% and 28%, respectively, during the 2020 lockdown period in comparison to the period in 2020 before the lockdown. This was similar to the decrease in air pollution in Delhi, India reported by Mahato et al. (2020). Xu et al. (2020) reported the impact of COVID-19 control on air pollution levels, including $PM_{2.5}$, PM_{10}, CO and NO_2, in three cities of central China during the lockdown period: it resulted in reduction in concentrations of $PM_{2.5}$ (3-45%), PM_{10} (30-48%), NO_2 (30-61%) and CO (7-23%), during January to March 2020, compared to January to March 2017–2019. Nakada and Urban (2020) reported reduced concentrations of NO (by 77%), NO_2 (by 54%) and CO (by 65%) in São Paulo, Brazil, during the partial lockdown, compared to the same period from 2015 to 2019. In contrast, a 30% increase of O_3 concentrations was observed. Tobías et al. (2020) presented the similar reduction in air pollutant trends during the lockdown period in Barcelona, Spain. The significant reduction in NO_2, BC and

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PM_{10} were 51%, 45% and 231% at traffic air quality monitoring stations. The results from several investigations clearly indicated the similar trends in air pollutant reduction, except for O_3.

Bangkok, the capital of Thailand, and a megacity has faced serious air pollution problems, particularly fine particles or $PM_{2.5}$, for a long time. It has been widely believed that traffic is the most influential factor on Bangkok air quality, especially $PM_{2.5}$ concentration, though some studies indicated that biomass burning was the major cause of atmospheric aerosols, during the dry period, including haze episodes in January of recent years (Oanh, 2017; Dejchanchaiwong et al., 2020). It is interesting to understand the effect of the traffic on Bangkok $PM_{2.5}$ concentration by comparing air quality, during the lockdown period, to the same period of the preceding year, a normal situation, as well as nearly a month prior to the city lockdown. In the present study, $PM_{2.5}$ and gaseous pollutant concentrations data from the Thailand Pollution Control Department (PCD) stations in key areas in Bangkok in four periods are reported. Backward trajectories were used to identify possible external biomass burning sources of $PM_{2.5}$.

METHODS

Real time data and sampling stations

Ambient $PM_{2.5}$ (24-hr average), NO_2 (1-hr average), O_3 (8-hr average) and CO (8-hr average) concentrations were obtained from five stations operated by the Thailand Pollution Control Department (PCD). They were located in busy areas of Bangkok, including business

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districts: Phaya Thai District (13.780965°N, 100.538566°E), Bang Na District (13.667852°N, 100.605512°E), Bang Kruai District (13.810672°N, 100.506430°E), and roadsides: Kanjanapisek Road, Bang Khun Thian District (13.644727°N, 100.408773°E) and Din Deang Road, Din Deang District (13.764134°N, 100.548752°E) – see Fig. 1. All sites used the Tapered Element Oscillating Microbalance (TEOM) or beta ray attenuation methods for $PM_{2.5}$ measurements, non-dispersive infrared detection (NDIR) or gas filter correlation method for CO measurements, chemiluminescence method for NO_2 measurements and UV absorption method for O_3 measurement, approved by the U.S. Environmental Protection Agency (US-EPA). The first three stations were 'business area sites' in busy areas, where traffic is highly congested from normal to slow speed vehicles. In particular, the Phaya Thai District is the center of the business area, where the traffic congestion is one of the worst in Bangkok. The Bang Na District is also a busy area, in the east side of Bangkok, with traffic problems mostly from local roads and the expressway. The Bang Kruai District represents the highly congested area in West Bangkok. Two 'road site' stations were beside major roads: the Kanjanapisek Road Station monitored highway traffic south of Bangkok, while the Din Deang Road Station monitored an expressway roadside in the center.

Sampling periods, traffic data and fuel consumption

Both the $PM_{2.5}$ and gas concentrations were measured during March-April 2020, when the COVID-19 pandemic heavily affected Thailand. From March 1-21, 2020, the way of life was

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normal: this period represented a normal period of 2020, labelled ‘pre-lockdown’ here. During Mar 22-April 30, 2020, labelled the ‘lockdown’ period, most activities were frozen. Many business sectors were shut down. People were urged to stay home and work at home under the ‘Stay home, stop disease for the nation’ campaign. The $PM_{2.5}$ and gas concentrations, during both periods, were measured, so we could compare levels, pre- and during the lockdown. Continuous average pollutants concentrations at each site during April 1-30, 2019 formed a reference ‘2019 normal’ period, and April 1-30, 2020 was a ‘2020 lockdown’ period – as listed in Table 1. Because vehicles in Bangkok play an important role in air quality, vehicle numbers and diesel and gasoline fuel consumption on air quality in Bangkok were analyzed to find any correlation with air pollutant contributions. The number of passenger vehicles traveling to and from Bangkok were provided by Ministry of Transport Operation Center (Ministry of Transport Operation Center, 2020), while the diesel and gasoline fuel consumption data was provided by Department of Energy Business, Ministry of Energy (Department of Energy Business, 2020).

Chemical analysis

Carbon components in the atmospheric particles are a good indicator for the sources of aerosol (Phairuang et al., 2019; Dejchanchaiwong et al., 2020). They were analyzed for several particle size ranges. A PM0.1 sampler or nanosampler, capable of segregating particle size to 100 nm, was used to collect samples (Furuuchi et al., 2010). Particles were separated into six size

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ranges: <0.1 µm ($PM_{<0.1}$), 0.1-0.5 µm ($PM_{0.1-0.5}$), 0.5-1.0 µm ($PM_{0.5-1}$), 1.0-2.5 µm ($PM_{1-2.5}$), 2.5-10 µm ($PM_{2.5-10}$) and >10 µm ($PM_{>10}$). A 55-mm quartz fiber filter (Pallflex, 2500QAT- UP) was used for particle collection in each stage. The stage, with an inertial filter (IF), used a stainless steel filter pack (SUS304, fiber diameter = 9.8 µm) to collect $PM_{0.1-0.5}$. A sample was collected at the King Mongkut's University of Technology North Bangkok (KMUTNB: 13°51'06. 4" N, 100°34'22.9"E) site which is 8 km away from Bang Kruai PCD station during March 3-4, 2019. A sample at the same site, during March 16-18, 2020, a few days before lockdown, was collected to study time variation of the sources of carbon. Organic carbon (OC) and elemental carbon (EC) components in PM were investigated to identify major sources. The carbonaceous components in PM on the quartz fiber filters were analyzed using a Carbon Aerosol Analyzer (Sunset Laboratory, Model 5), following the Interagency Monitoring of Protected Visual Environments Thermal/Optical Reflectance (IMPROVE-TOR) protocol (Dejchanchaiwong et al., 2020). Organic carbon fractions were taken in a non-oxidizing helium (He) at temperatures 120, 250, 450 and 550°C for OC1, OC2, OC3 and OC4, respectively, while EC fractions were taken in 2% O_2/98% He at temperatures 550, 700, 800 °C for EC1, EC2, and EC3, respectively. The samples were punched to 15 mm^2, using a rectangular cutter. The number of spots on each punched sample was set at 1, 2, 4 and 8 for samples in the $PM_{>10}$, $PM_{2.5-10}$, $PM_{1-2.5}$ and $PM_{0.5-1}$ stages, respectively. The analyzer was calibrated with a blank filter and standard sucrose solutions, following the same

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procedure to confirm the analysis reliability based on the total carbon (TC). The detection limits for EC and OC analysis were below 0.1 μg cm^{-2}. However, the IMPROVE-TOR protocol could not be applied to particles collected on an inertial filter, as described by Dejchanchaiwong et al. (2020)

Air mass trajectories

48-hour backward trajectories (48-hr BT) of air and aerosol particles from external sources focused on biomass burning outside of Bangkok were simulated using the Hybrid Single-Particle Langrangian Integrated Trajectory Model version 4 (HYSPLIT4) (Air Resources Laboratory, 2020). Wind direction at 1,000 m altitude (AGL) was selected as the height of the mixing layer. The start time for backward trajectories was 00UTC (07:00 am Bangkok time). The sampling site was chosen to represent the receptor in Bangkok (13.84°N, 100.56°E). Hotspots from open biomass burning were obtained from the NASA VIIRS 375 m active fire data (Earthdata, 2020).

RESULTS AND DISCUSSION

Effect of lockdown on $PM_{2.5}$ mass concentration in Bangkok

Because $PM_{2.5}$ is the most important air pollutant affecting Bangkok recently (Oanh et al., 2000; Thongsanit et al., 2003; Chuersuwan et al., 2008; Oanh et al., 2011; Pongpiachan et al., 2014; Oanh, 2017; Phairuang et al., 2019; Dejchanchaiwong et al., 2020), it was investigated first. The

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24-hr average $PM_{2.5}$ mass concentration at five sites in Bangkok were observed in pre-lockdown)March 1-21, 2020(and during the lockdown (March 22 - April 30, 2020) periods to compare the air pollution during both periods, when road activities were significantly different. Daily $PM_{2.5}$ concentrations in both periods are shown in Fig. 2. In pre-lockdown, the daily roadside $PM_{2.5}$ concentrations ranged from 22.5-47.5 µg m^{-3}, with a mean of 32.0±6.6 µg m^{-3} and at business sites, it ranged from 12.2-34.1 µg m^{-3} with a mean 20.9±6.3 µg m^{-3}, i.e. roadside levels were about 34.5% higher than business areas. Most vehicles on the highways were diesel powered and the major PM emitter, compared to gasoline or gasohol passenger vehicles in business areas. During the lockdown, the daily $PM_{2.5}$ concentrations at the same road sites ranged from 19.4-44.4 µg m^{-3}, mean 28.0±6.4 µg m^{-3}, and ranged from 11.1-33.6 µg m^{-3}, mean 18.6±6.1 µg m^{-3} in the business areas. $PM_{2.5}$ concentrations decreased by 12.5% on the roads and 11.0% in business areas, during lockdown compared to immediately before lockdown in 2020. $PM_{2.5}$ concentrations in pre-lockdown reached 47.5 µg m^{-3} at road sites on March 16, 2020 while, at business area sites, the peak was 34.1 µg m^{-3} on March 9, 2020. During lockdown, the highest $PM_{2.5}$ concentrations were 44.4 µg m^{-3} (roads) and 33.6 µg m^{-3} (business areas) on April 27, 2020. The 24-hr average $PM_{2.5}$ concentrations at both sites did not exceed *Thai national ambient air quality standards (*50 µg m^{-3} for $PM_{2.5}$(. However, they exceeded the WHO standard (25 µg m^{-3}, 24-hr average) in some periods.

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Apparent effects of road activities on the daily $PM_{2.5}$ concentrations were compared in the same period of the previous year (2019) and the 2020 lockdown periods to clearly understand the effects. The most strict lockdown in 2020 covered the full month of April. The concentrations at both the road and business area sites are shown in Fig. 3. At road sites, average $PM_{2.5}$ concentrations during April 2020 were 28.1±7.1 μg m^{-3}, ~11.1% decrease from April 2019 (31.6±6.6 μg m^{-3}). The *p*-values of 0.1 indicated this was not a significant difference. In contrast, at business sites, a 16.7% increase in daily $PM_{2.5}$ concentrations was observed in April 2020 (mean 18.9±6.6 μg m^{-3}) *vs* April 2019 (mean 16.2±5.2 μg m^{-3}), but the difference was also not significant (*p*-value = 0.13). Hence, the April 2020 pandemic lockdown had insignificant effect on $PM_{2.5}$ concentrations. The small observed reductions could be attributed to normal random variations.

Effect of lockdown on gaseous pollutants

Variations in the levels of NO_2, O_3, and CO concentrations at road and business area sites in Bangkok between pre- and during 2020 lockdown are shown in Fig. 4. The levels of three air pollutants, i.e., NO_2, O_3 and CO, were decreased, except for O_3 at business area sites. It is important to note that O_3 concentrations at many stations increased during the 2020 lockdown period. In pre-lockdown periods, the average NO_2, O_3, and CO concentrations at the road sites were 19.1±7.1 ppb, 22±11.7 ppb, and 1.2±0.3 ppm, and at the business area sites were 9.8±3.4 ppb, 20.5±7.4 ppb, and 0.3±0.2 ppm, respectively. During the lockdown, average NO_2, O_3, and CO concentrations at the road site were 17.6±8.4 ppb, 17.6±6.8 ppb, and 1.1±0.2 ppm, while at the business area sites, they were 8.5±2.1 ppb, 25.4±8.9 ppb, and 0.3±0.1 ppm, respectively. 7.9%, 20.0%, and 8.3%, decreases in of NO_2, O_3 and CO concentrations at road sites during lockdown period were observed, compared to the pre-lockdown period in the year 2020. Similarly, NO_2 concentrations at business area sites decreased by 13.3%. In contrast, a 23.9% increase in O_3 concentration and no change in CO concentrations were observed in business areas. NO_2, and CO in pre-lockdown period were slightly higher, but the difference was not considered significant. Also, average gaseous pollutant concentrations did not exceed Thailand's national ambient air quality standards (NO_2 = 170 ppb based on 1-hours average, O_3 = 70 ppb and CO = 9 ppm based on 8-hour average).

Concentrations of three gases between 2019 normal period (April 1-30, 2019) and 2020 lockdown period (April 1-30, 2020) are compared in Fig. 5 and Table 2. In the 2019 normal period, levels at the road sites were NO_2 (24.7±9.6 ppb), O_3 (9.2±4.3 ppb) and CO (1.2±0.2 ppm), and at the business area sites were 11.3±6.9 ppb, 17.9±5.5 ppb, and 0.7±0.1 ppm, respectively. In the 2020 lockdown period, the average NO_2, O_3 and CO concentrations at the road sites were 18.9±10.5 ppb, 15.6±5.0 ppb, and 1.1±0.3 ppm, and, at the business area sites, they were 9.3±7.2 ppb, 26.0±9.8 ppb, and 0.3±0.1 ppm, respectively. NO_2 concentrations during 2020 lockdown period were significantly lower than the same period in 2019, 23.5% less near roads and 17.7% less in business

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areas. CO concentrations reduced by 8.3% (roads) and 57.1% (business areas). Road side CO did not change significantly, but dropped considerably in business areas. In contrast, O_3 concentrations significantly increased by 69.6% (road sites) and 45.3% (business area sites). Similar reductions in NO_2 and CO and an increase in O_3 concentrations was reported in Indian megacities (Jain and Sharma, 2020) and central China (Xu et al., 2020). The higher level of O_3 during lockdown could be the result of the more suitable sunlight conditions for photochemical reactions and reductions of NO_2 (Jain and Sharma, 2020). O_3 production is controlled by either volatile organic compounds (VOCs) or nitrogen oxides (NO_x). The O_3 formation from these two precursors depends on the hydroxide (OH) radical and NO_x. In general, O_3 production in business areas is limited by VOCs (US EPA, 2020). During the 2020 lockdown, 42.1% of passenger vehicles (see in section 3.3) and other combustion activities were reduced. This resulted in reduced NO_x emissions in a VOC limited condition. As a result, when NO_x decreased, more OH radical was available to react with the VOCs, leading to increased O_3 formation (National Research Council, 1991; Tobías et al., 2020; Jain and Sharma, 2020; Xu et al., 2020).

Effects of vehicle numbers and diesel fuel consumption on $PM_{2.5}$ concentration

Trends of $PM_{2.5}$ concentration *versus* numbers of vehicles in Bangkok are shown in Fig. 6. The average number of vehicles in Bangkok ranged from 2.1-2.8M cars (mean 2.4M±0.2M cars)

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for the pre-lockdown periods. It reduced to 0.89-2.1M cars (mean 1.5M±0.3M cars) during the lockdown, a significant reduction of 38%. However, the average $PM_{2.5}$ concentrations during the lockdown only declined by 12.5% (road sites) and 11.0% (business sites). Correlations between $PM_{2.5}$ concentrations and numbers of vehicles are not clear, with large deviations, as shown in Fig. 7. Linear fits showed a slight increase of $PM_{2.5}$ concentration with numbers of vehicles, but the correlations were weak - $R^2 = 0.1145$ for roads $R^2 = 0.031$ for business areas. Most highways vehicles are diesel engines in contrast to gasoline or gasohol engines in passenger cars in the business areas. We concluded that there was no clear correlation between $PM_{2.5}$ concentrations and the number of vehicles in Bangkok.

Variations observed in $PM_{2.5}$ and gas concentrations at road and business area sites in Bangkok during the 2019 normal and 2020 lockdown periods, along with number of vehicles and diesel and gasoline fuel consumption in Bangkok, are also shown in Table 2. The number of vehicles and gasoline fuel consumption during the 2020 lockdown decreased significantly – vehicle numbers by 42.1% and gasoline by 26.8%. Petroleum sourced diesel consumption reduced by 28.6%. Total diesel (including biodiesel) fuel consumption, on the other hand, remained nearly unchanged. The biodiesels, B10 and B20, contain 10% and 20%, respectively, of methyl ester in petroleum sourced diesel. They were a much larger portion in 2020 than 2019. Many studies indicated that the use of biodiesel helped reduce the $PM_{2.5}$ concentration. B10 and B20 fuels led to

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a significant decrease of 5-15% and 10-15% in $PM_{2.5}$, compared to the diesel (Morris and Jia, 2003; Pino-Cortés et al., 2015; Hutter et al., 2015; Riberio et al., 2016; Dias et al., 2019). Thailand intends to enhance biodiesel use for transport energy, where about 40% increase of biodiesel consumption was observed in 2020 in Bangkok (Department of Energy Business, 2020). However, the increase of B10 and B20 diesel consumption had only a slight influence on the ambient $PM_{2.5}$ reduction during the lockdown. This implied that the observed $PM_{2.5}$ was mainly from other sources. Gasoline consumption changed with the number of vehicles, indicating that major portion of vehicles in Bangkok were gasoline engine passenger cars and diesel vehicles were mostly for transportation of goods, that were only slightly affected by the lockdown. The decline of NO_2 and CO, during the lockdown, was then attributed to the large decrease in the gasoline vehicle use. In contrast, O_3 concentrations increased at business sites.

The decrease in $PM_{2.5}$ levels during the lockdown may also be attributed to the reduction in NO_2 levels, which played an important role in the formation of secondary aerosols. In addition to transportation, industries, construction and many other activities were shut down during the lockdown and this led to a reduction in pollutant levels. There is an indication that, due to the city lockdown, a slightly significant reduction in $PM_{2.5}$ levels occurred only at road sites in Bangkok. A countertrend of $PM_{2.5}$ concentrations was observed with a 16.7% increase at business sites during

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the lockdown period. It is important to highlight that both $PM_{2.5}$ and O_3 increased during the lockdown.

Impact of external biomass burning on $PM_{2.5}$ in Bangkok

Effects of biomass burning on Bangkok $PM_{2.5}$ concentrations were studied by a 48-hr backward trajectory (BT) simulation during the 2019 normal and 2020 lockdown periods, as shown in Fig.8. There were open biomass burning areas in central of Thailand as well as Myanmar, Laos and Cambodia. BT simulations on April 1, 2019 showed south wind flowing from the Gulf of Thailand to Bangkok resulting in drops of $PM_{2.5}$ levels, as shown in Fig. 8(a). Conversely, west wind flowed towards Bangkok from west part of Thailand and some parts of Myanmar, where partial hotspots from open biomass burning occurred with peaks, on April 21, 2019, as shown in Fig. 8(b). On April 26, 2019, wind flowed to Bangkok from every direction, where hotspots from open biomass burning were observed, as shown in Fig. 8(c). During the 2020 lockdown period, backward trajectories on April 14, 2020 showed west-bound air mass movement, passing through some hotspots in Cambodia, to Bangkok, as shown in Fig. 8(d). Moreover, simulations for April 27 (Fig 8(e)) and April 29, 2020 (Fig. 8(f)) showed northeast wind to Bangkok, passing through open burning in northeast Thailand, Laos, Vietnam and some parts of Cambodia. Although a small number of hotspots were found in Cambodia during this period, it was sufficient for the PM to transport and affect Bangkok air quality.

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Hence, the 48-hrs backward trajectories showed aerosol transported from open biomass burning areas in Thailand, and some parts of Myanmar, Cambodia, Laos and Vietnam affecting the Bangkok air quality. This agrees with previous studies of potential sources of PM in Bangkok (Oanh, 2000; Chuersuwan et al., 2008; Pongpiachan et al., 2014; Oanh et al., 2017; Phairuang et al., 2019 Dejchanchaiwong et al., 2020). Chuersuwan et al. (2008) reported the major sources of PM in Bangkok during years 2002-2003 were vehicle emission and biomass burning. Contribution of biomass burning was approximately 6-41% for $PM_{2.5}$ and 28-36% for PM_{10}. Oanh (2017) also confirmed that $PM_{2.5}$ in Bangkok in the dry period had a 35.5% contribution from biomass burning. Dejchanchaiwong et al. (2020) stated that petroleum combustion was the major source of PM during the 2017 non-haze period, whereas the sources were mixed petroleum and biomass combustion during the 2018-2019 haze period, where the contribution of biomass burning was pronounced. Our present study clearly showed that sources of $PM_{2.5}$ were mixed - between traffic and biomass burning. Effects from traffic were not significant as reduction of traffic and diesel consumption did not lower the $PM_{2.5}$ concentration in Bangkok. The increment of $PM_{2.5}$ level during the lockdown could be an external effect as a significant decrease of local sources occurred, from the 2019 normal period to the 2020 lockdown period.

Source Identification

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The organic carbon (OC) and elemental carbon (EC) concentrations, along with OC/EC ratios for each particle size during March 3-4, 2019 and March 16-18, 2020 in Bangkok are shown in Fig. 9. Both periods represented normal situations, when traffic activities were comparable. Average concentrations of $PM_{2.5}$ at Bang Kruai PCD station near the KMUTNB sampling point were 21.8±3.4 and 24.1±7.7 µg m^{-3} in March 2019 and 2020, respectively. BT simulations over Bangkok, on March 4, 2019 and March 16, 2020, are shown in Fig. 10. Air mass movements to Bangkok on March 4, 2019 were from the Gulf of Thailand, and from the southwest and west, where some hotspots were observed (Fig. 10a). Moreover, simulations for March 16, 2020, showed air mass movements, by the east wind from Cambodia and Vietnam, where high concentrations of hotspots from biomass burning were observed. This caused aerosol transport to Bangkok, as shown in Fig. 10(b). Both periods were affected by biomass burning from external sources, especially on March 16, 2020.

OC/EC ratios are commonly used as an index for identifying sources of PM. OC/EC ratios ranging from 0.06 to 0.8 indicate diesel exhaust (Dallman et al., 2014; Na et al., 2004) while values from 3.8 to13.2 indicate biomass burning (Zhang et al., 2007). In the present study, significant carbonaceous components were focused on the nuclei and accumulation mode particles. In $PM_{<0.1}$, the OC and EC concentrations, during March 16-18, 2020, were 2.6 µg m^{-3} and 0.7 µg m^{-3}, i.e. slightly increased - by 4.6% and 12.5%, compared to March 3-4, 2019 (OC at 2.5 µg m^{-3} and EC

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at 0.6 μg m^{-3}). The OC/EC ratios were 4.0 (March 2019) and 3.7 (March 2020), indicating mixed sources from petroleum and biomass combustions, during both periods. During March 2020, the OC/EC ratios were 5.1 ($PM_{0.5-1}$) and 9.9 ($PM_{1-2.5}$). They were significantly higher than March 2019 with 2.9 ($PM_{0.5-1}$) and 5.1 ($PM_{1-2.5}$). This was also consistent with previous reports and it confirmed that the dominant size of PM from biomass burning was in $PM_{0.5-1.0}$)Hata et al., 2014). This agrees with the $PM_{2.5}$ concentrations and back trajectory results presented earlier. The ratios for $PM_{0.1-0.5}$ were not obtained due to limitation in the analysis. Increased ratios in accumulation mode particles clearly suggest the significant influence of biomass burning emission (Phairuang et al., 2019; Dejchanchaiwong et al., 2020).

Challenges and solutions

We showed that background air pollution, due to Bangkok local traffic, exists, but effects of biomass burning of agricultural residues in the country, as well as aerosol transport from neighboring countries, cannot be underestimated. The solution to the problem involves long term commitment from many parties.

To reduce the $PM_{2.5}$ concentration generated by diesel vehicles, the government needs to impose the Euro-5 or Euro-6 standards to control engine emissions. Diesel particulate filters (DPFs) must be introduced. The problem of air pollution from biomass burning is, however, more complicated. Farmers burn crops and agricultural residues, both for harvesting and residue removal.

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More than 60% of sugarcane, in central, northeast and lower north parts of Thailand, is burned annually to harvest it before sending it for sugar production. Most of sugarcane producers are smallholders and they cannot afford large harvesting machinery, because of the cost and lack of economy of scale. The solution may be an adoption of small-scale machinery. Government may need to support interest-free loans to farmers or farmer groups to purchase such machines. This approach can also be applied to other farmers growing rice and maize, in which the residues are burned for replanting following cropping. The solution to transport of aerosol from neighboring countries requires diplomatic approaches. The ASEAN haze free agreement needs to be put into real action, before the problem expands further.

CONCLUSIONS

$PM_{2.5}$ and gaseous pollutants (NO_2, O_3 and CO) concentrations obtained from different Bangkok PCD monitoring stations in key areas before and during the lockdown resulting from the COVID-19 pandemic during March-April 2020 at a representative selection road and business area sites were investigated. Data from a similar period in 2019 was added to represent a normal situation. Decreases of $PM_{2.5}$ as a result of the lockdown were not significant, despite significant reduction of traffic and diesel consumption. Backward trajectory simulation and OC/EC ratios showed that open biomass burning impacted $PM_{2.5}$ levels in Bangkok. The decline of NO_2 was, however, pronounced, due to the significant drop in gasoline vehicle use. This then contributed to

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an increase of O_3, as more OH radicals were available to react with VOCs to form O_3. CO concentration did not drop at the road sites, compared to business area sites, because highway road traffic was much less affected by the lockdown. Our results highlighted that a significant increase in $PM_{2.5}$ levels in Bangkok during the 2020 lockdown periods was caused by external effects. The backward trajectory simulations confirmed that both transboundary and local aerosol transport from open biomass burning, in Thailand and some parts of Myanmar, Cambodia, Laos and Vietnam, affected the Bangkok city air quality, when the wind direction favored long distance transport.

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Table 1. Air pollutants monitoring during 2019 normal and 2020 lockdown periods details.

Periods studied			
Label used	From	To	Comments
2019 norma1	April 1, 2019	April 30, 2019	Reference period - represents 'normal' April conditions
pre-lockdown	March 1, 2020	March 21, 2020	Normal conditions, closest to lockdown period
lockdown	March 22, 2020	April 30, 2020	The strictest lockdown measures, during COVID-19 pandemic
2020 lockdown	April 1, 2020	April 30, 2020	A 'lockdown' April period

Table 2. Change in $PM_{2.5}$ and gaseous pollutant concentrations at road and business area sites, as well as number of vehicles and fuel consumption in Bangkok during April 2019 normal and April 2020 lockdown periods.

Factors		2019 normal	2020 lockdown	% change
Number of vehicles (million cars)		75.4	43.7	-42.1%??
Diesel fuel consumption (ML)		0.42	0.30	-28.6%
B10 consumption (ML)		-	0.09	NA
B20 consumption (ML)		0.01	0.03	+273.6%
Total diesel (ML)		0.43	0.42	-1.68%
Gasoline fuel consumption (ML)		0.25	0.18	-26.8%
Pollutants				
NO_2 (ppb)	Road site	24.7±9.6	18.9±10.5	-23.5%
	Business area	11.3±6.9	9.3±7.2	-17.7%
O_3 (ppb)	Road site	9.2±4.3	15.6±5.0	+69.6%
	Business area	17.9±5.5	26±9.8	+45.3%
CO (ppm)	Road site	1.2±0.2	1.1±0.3	-8.3%
	Business area	0.7±0.1	0.3±0.1	-57.1%
$PM_{2.5}$ ($\mu g\ m^{-3}$)	Road site	31.6±6.6	28.1±7.1	-11.1%
	Business area	16.2±5.2	18.9±6.6	+16.7%

Note: ML = mega litres = 10^6 L

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Figure Captions

Fig. 1. Locations of PCD monitoring stations in Bangkok.

Fig. 2. $PM_{2.5}$ concentration between pre lockdown (March 1-21, 2020) and during lockdown (March 22 - April 30, 2020) periods at road and business area sites in Bangkok.

Fig. 3. Daily $PM_{2.5}$ concentration in April: 2019 (blue circles) and 2020 (COVID-19 pandemic period – orange circles) at (a) road and (b) business area sites in Bangkok.

Fig.4. Gaseous air pollutants in pre- (black bars) and during the 2020 lockdown period (gray bars) at road sites and business area sites in Bangkok.

Fig. 5. Bangkok gaseous air pollutant concentrations for April: 2019 (normal 2019, blue bars) *vs* 2020 (lockdown 2020, orange bars) at road sites and business area sites.

Fig. 6. Daily vehicle counts *vs* $PM_{2.5}$ mass during 2020 normal and lockdown periods at (a) road sites and (b) business sites.

Fig. 7. Correlations between vehicle counts and $PM_{2.5}$ concentration in Bangkok during 2020 pandemic at (a) road sites and (b) business sites.

Fig. 8. Backward trajectory simulation and hotspot overlay for 2019 normal and 2020 lockdown periods: (a) April 1, 2019 low, (b) April 21, 2019 peak, (c) April 26, 2019 peak (d) April 14, 2020 peak, (e) April 27, 2020 peak and (f) April 29, 2020 peak.

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Fig. 9. Size distribution of OC and EC concentrations along with OC/EC ratios during 2019 normal and 2020 lockdown periods.

Fig. 10. Backward trajectory simulation and hotspot overlay on (a) March 4, 2019 and (b) March 16, 2020.

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Fig. 1.

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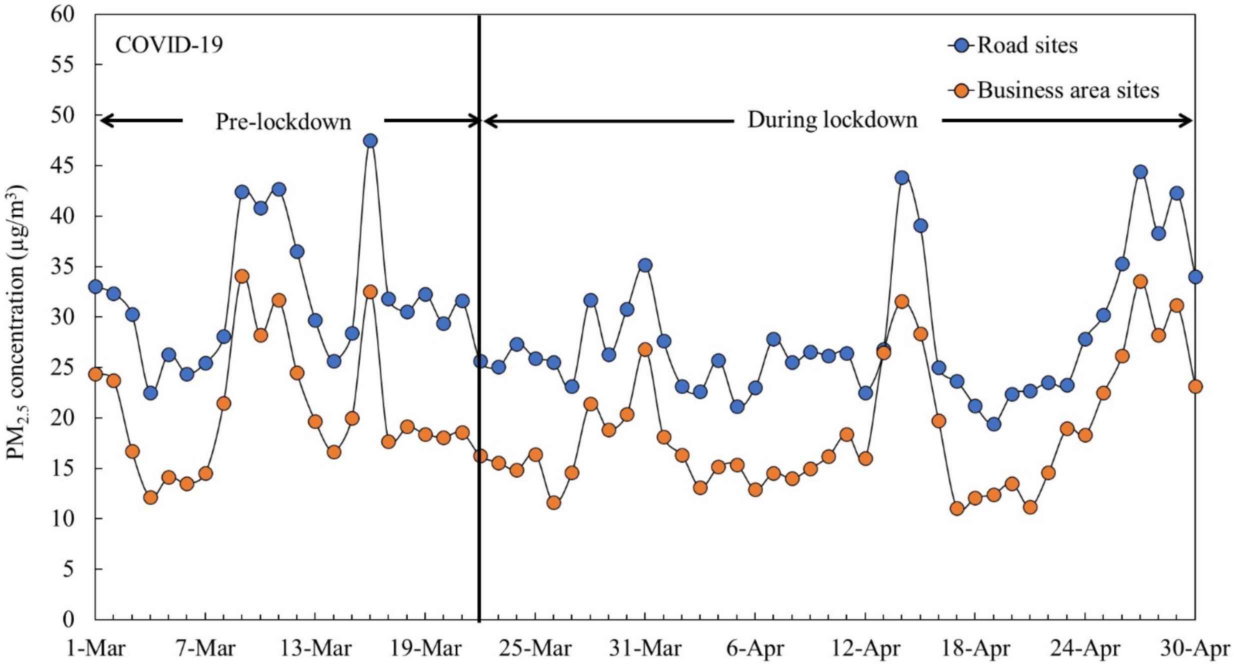

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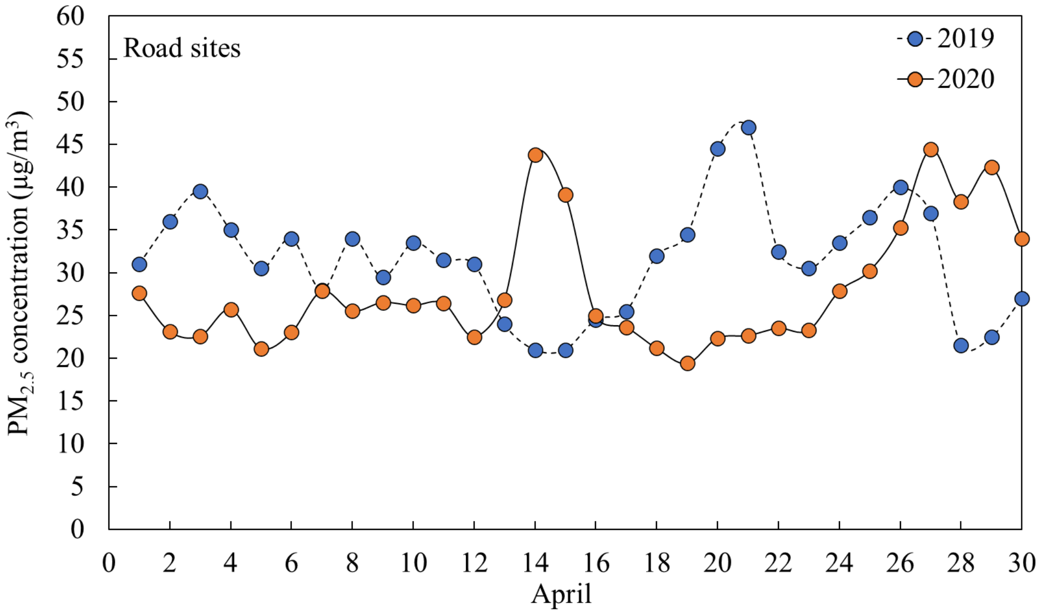
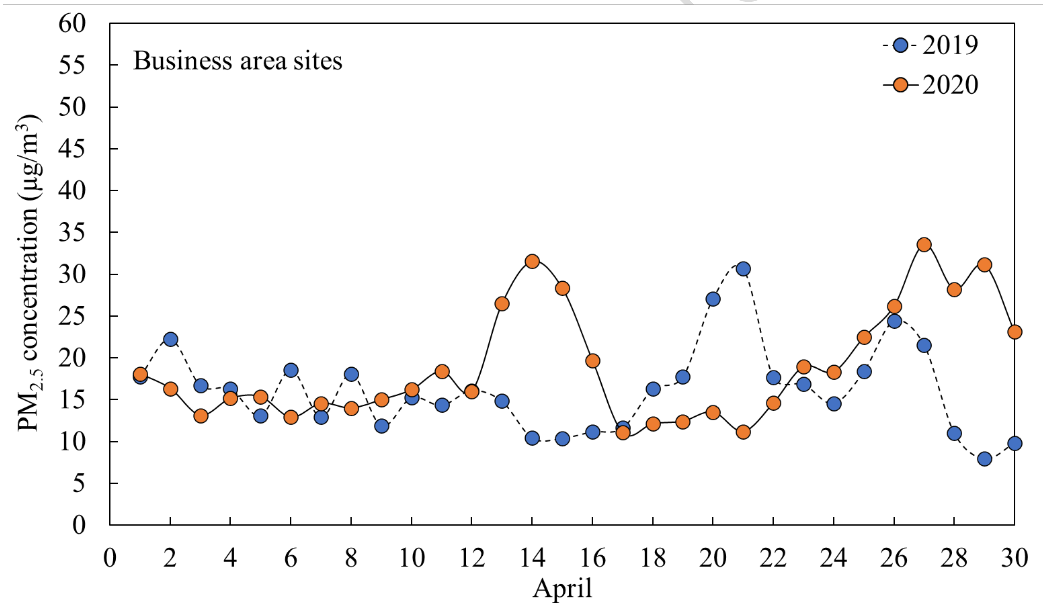
Fig. 2.

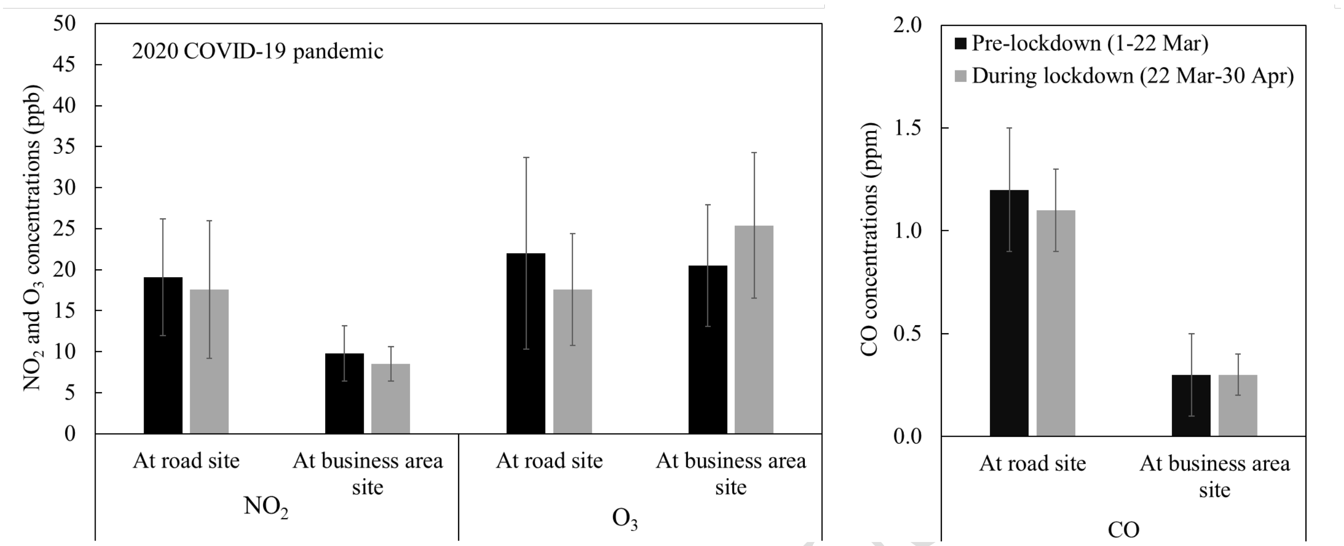


(a) Road sites



(b) Business areas

Fig. 3.



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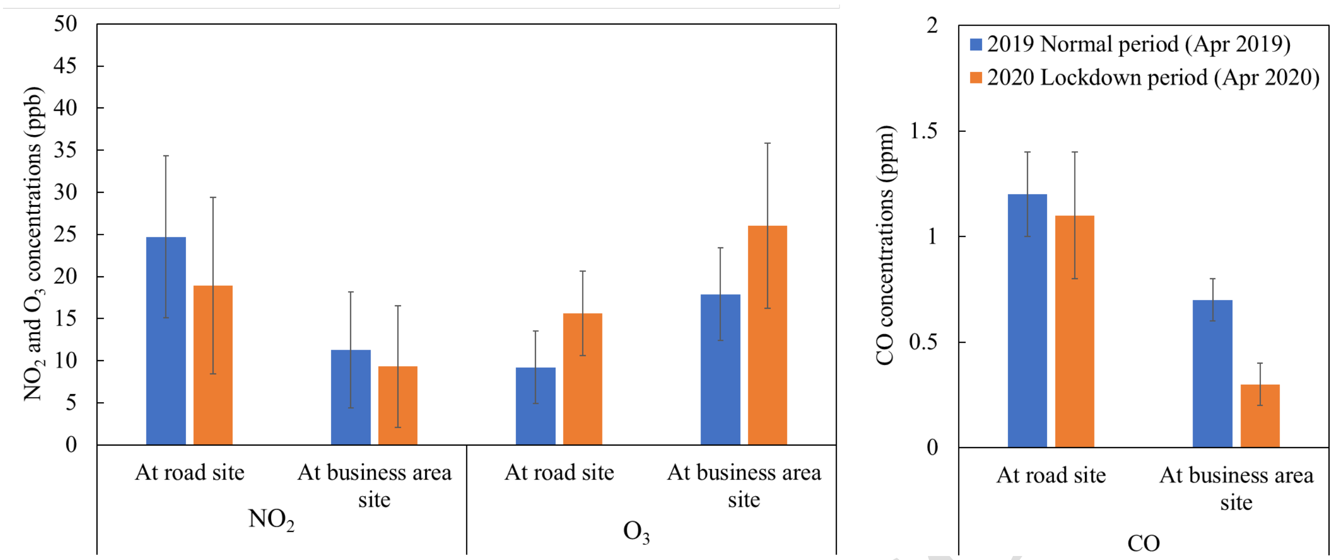

Fig. 5.

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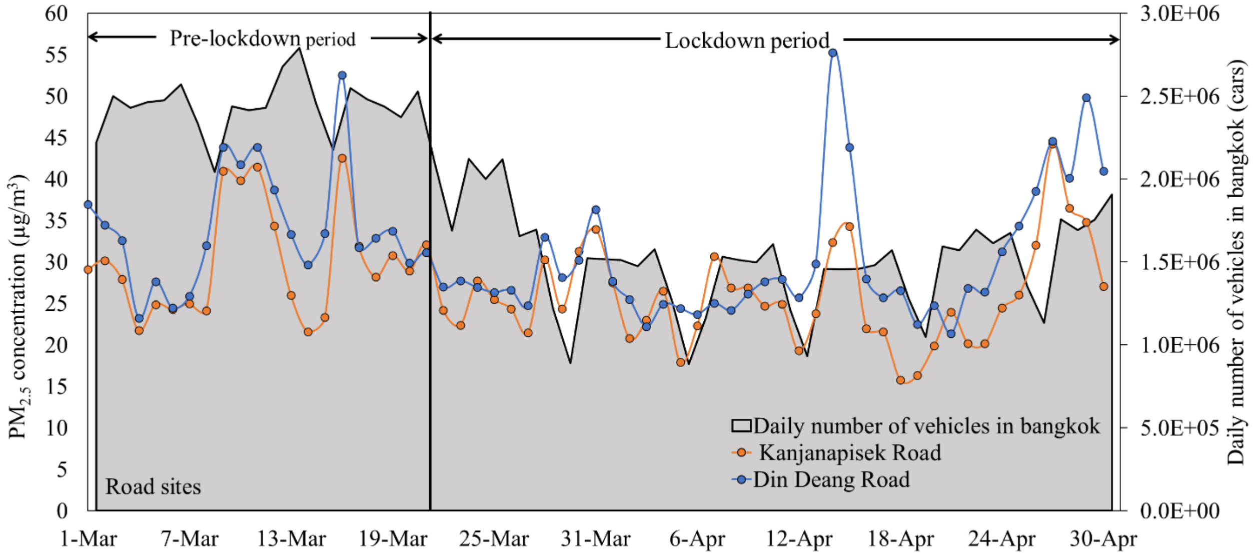
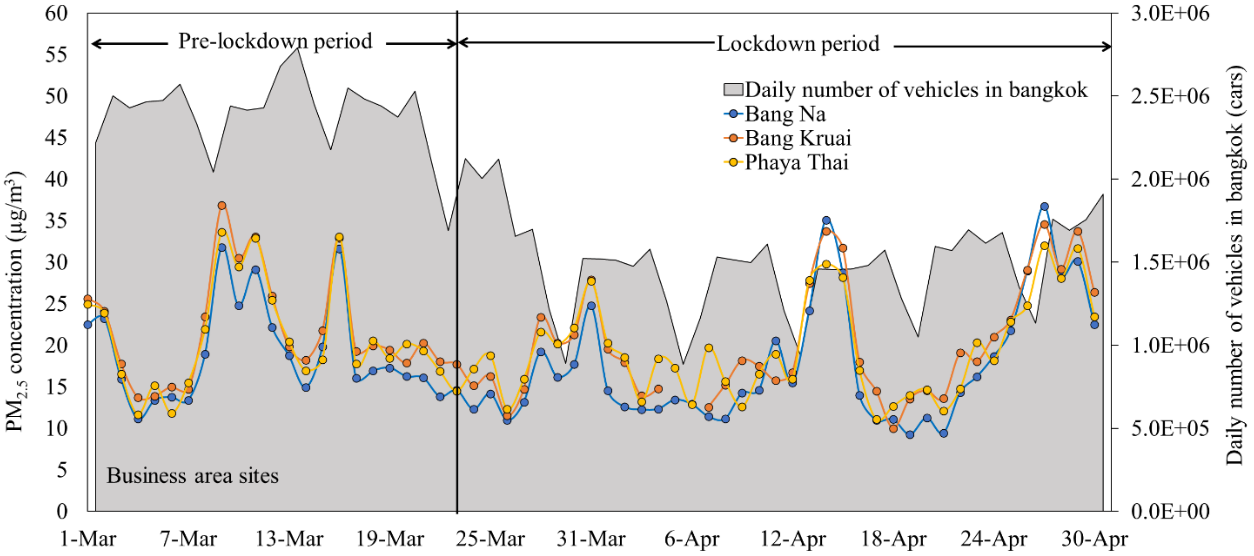
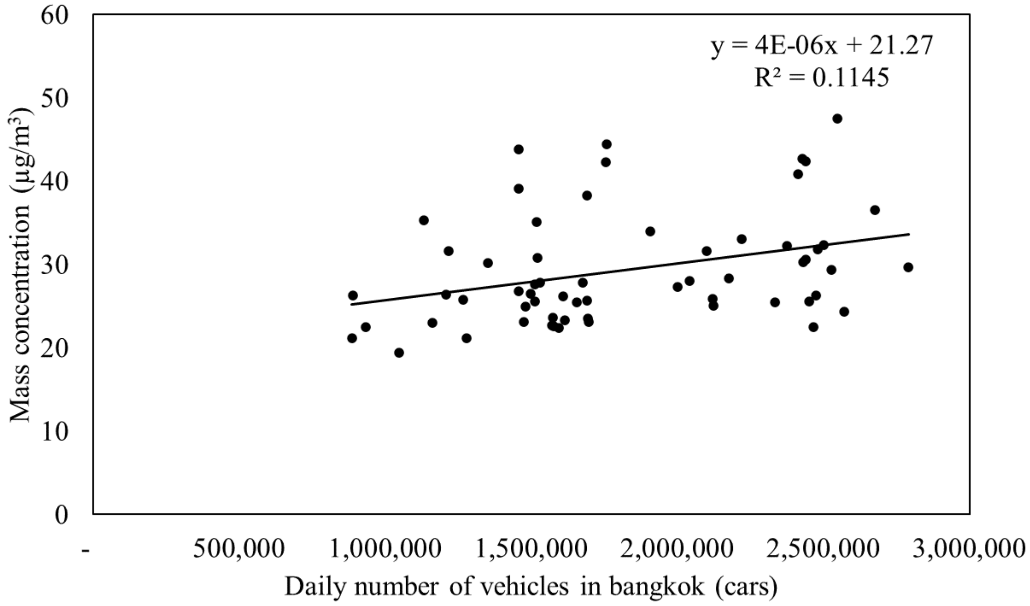


(a) Road sites



(b) Business sites

Fig. 6.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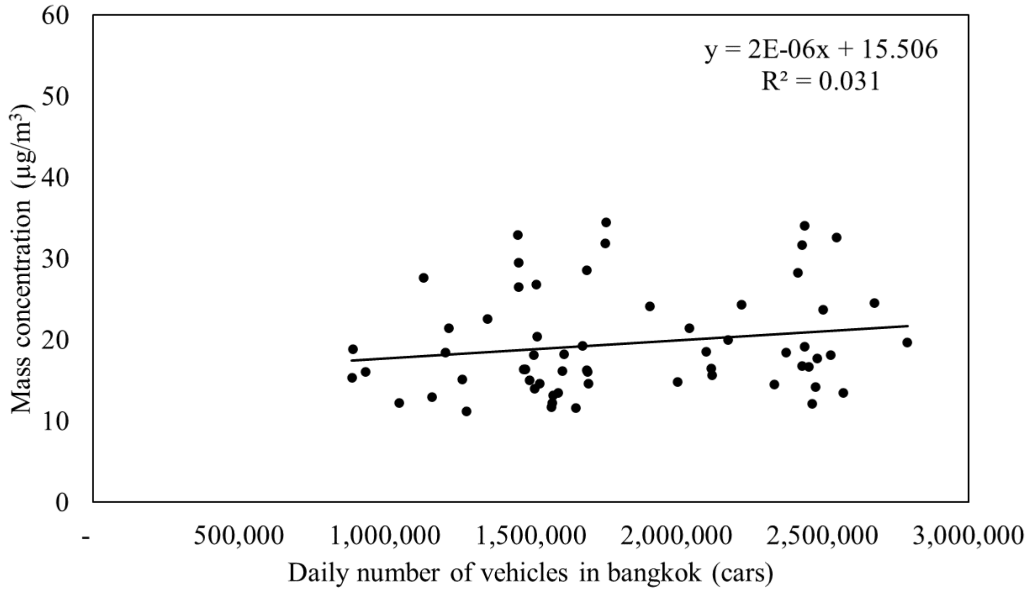
R² = 0.1145
Mass concentration (µg/m³)
0
10
20
30
40
50
60
-
500,000
1,000,000
1,500,000
2,000,000
2,500,000
3,000,000
Daily number of vehicles in bangkok (cars)

(a)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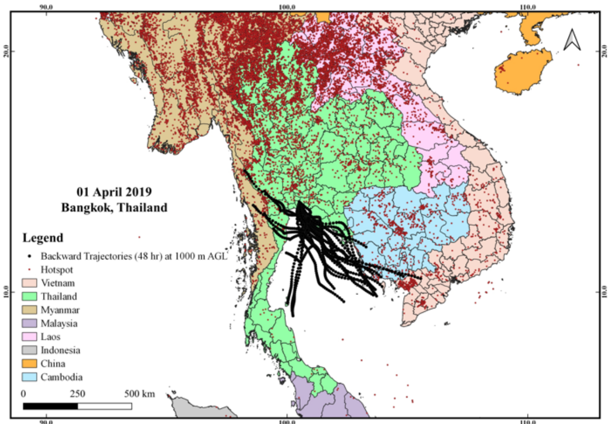
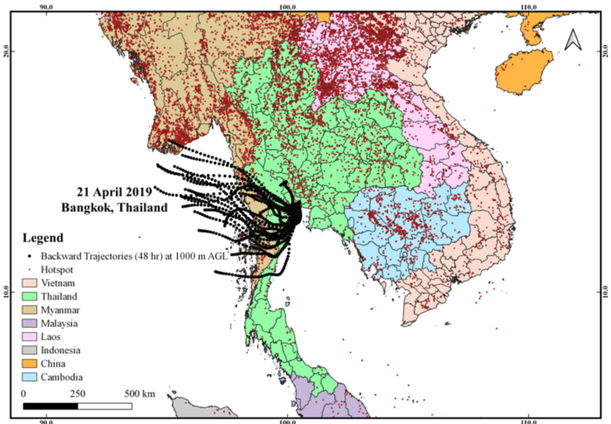
R² = 0.031
Mass concentration (µg/m³)
0
10
20
30
40
50
60
-
500,000
1,000,000
1,500,000
2,000,000
2,500,000
3,000,000
Daily number of vehicles in bangkok (cars)

(b)

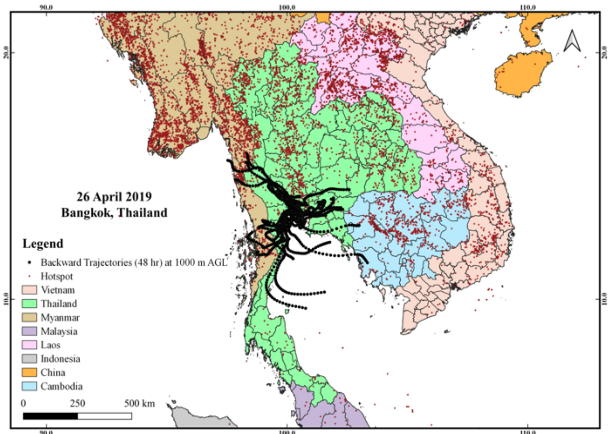
Fig. 7.



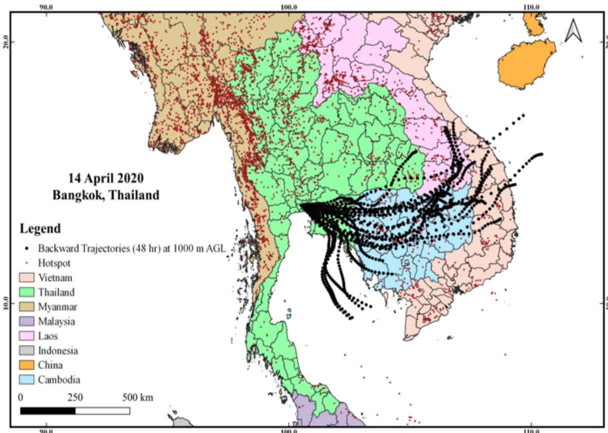
(a) April 1, 2019 low



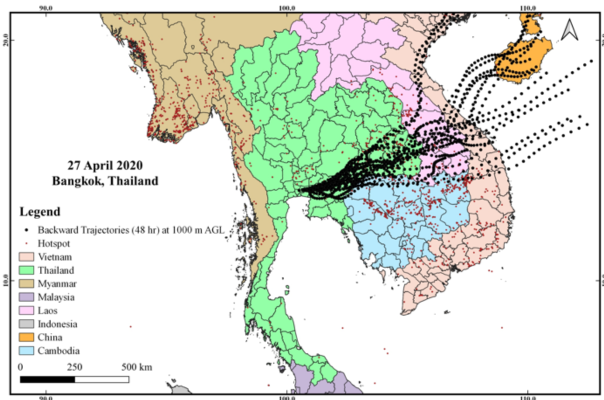
(b) April 21, 2019 peak



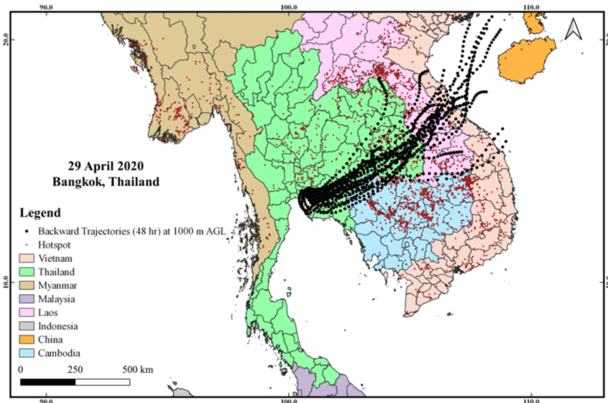
(c) April 26, 2019 peak



(d) April 14, 2020 peak



(e) April 27, 2020 peak



(f) April 29, 2020 peak

Fig. 8

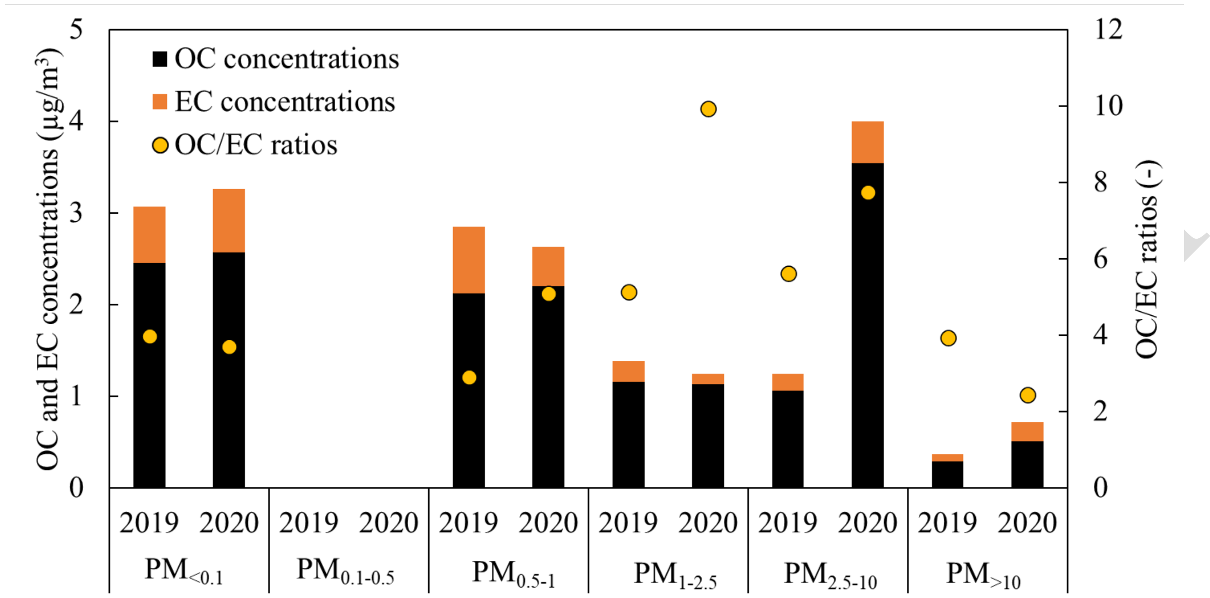
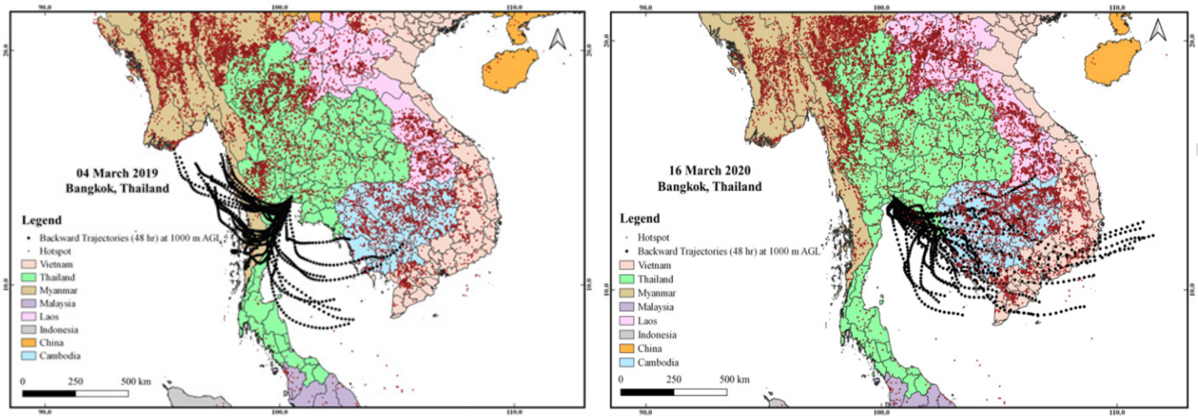

OC concentrations
EC concentrations
OC/EC ratios
OC and EC concentrations (μg/m³)
OC/EC ratios (-)
0
1
2
3
4
5
0
2
4
6
8
10
12
2019 2020
2019 2020
2019 2020
2019 2020
2019 2020
2019 2020
PM<0.1
PM0.1-0.5
PM0.5-1
PM1-2.5
PM2.5-10
PM>10

Fig. 9.



(a) March 4, 2019 (b) March 16, 2020

Fig. 10.

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