Investigation on the Impacts of COVID-19 Lockdown and Influence Factors on Air Quality in Greater Bangkok, Thailand

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Abstract

With the outbreak of the COVID-19 pandemic around the world, many countries announced lockdown measures, including Thailand. Several scientific studies have reported on improvements in air quality due to the impact of these COVID-19 lockdowns. This study aims to investigate the effects of the COVID-19 lockdown and its driving influence factors on air pollution in Greater Bangkok, Thailand using in-situ measurements. Overall PM2.5, PM10, O_3, and CO concentrations presented a significant decreasing trend during the COVID-19 outbreak year based on three periods: the before, lockdown and after periods, for PM2.5: 0.7%, 15.8% and 20.7%; PM10: 4.1%, 31.7% and 6.1%; O_3: 0.3%, 7.1% and 4.7%, respectively, compared to the same periods in 2019. CO concentrations, especially, were increased by 14.7%, but decreased by 8.0% and 23.6% during the before, lockdown and after periods, respectively. Meanwhile, SO_2 and NO_2 increased by 54.0%, 41.5% and 84.6%, and 20.1%, 3.2% and 26.6%, respectively, during the before, lockdown and after periods. PCA analysis indicated a significant combination effect of atmospheric mechanisms that were strongly linked to emission sources such as traffic and biomass burning. It has been demonstrated that the COVID-19 lockdown can pause some of these anthropogenic emissions, i.e. traffic, commercial and industrial activities, but not all, even low traffic emissions can't absolutely cause reductions in air pollution, since there are several primary emission sources that dominate the air quality over Greater Bangkok. Finally, these findings highlight the impact of the COVID-19 lockdown measures, not only on the air pollution levels, but also affects to air pollution characteristics, as well.

Introduction

The entire world has been battling with the Coronavirus since the first case was reported on 31 December 2019 in Wuhan, China. Ultimately, the Coronavirus was declared a pandemic by the World Health Organization (WHO) on 11 March 2020 [1] as COVID-19 spread. As of updated numbers, on 23 October 2020, there were 42,026,831 reported positive cases, and 1,143,225 deaths worldwide, including Thailand [2]. Soon after COVID-19 was discovered, lockdown measures and social distancing started being used as a global pandemic action plan to prevent COVID-19 from spreading. In Thailand, government authorities announced COVID-19 prevention and control actions including lockdown and curfew hours for the whole country from 26 March 2020 to 31 May 2020. This COVID-19 lockdown decreased human activities, especially in the traffic, industrial, and energy production sectors, which assumes a corresponding decrease in anthropogenic emissions of air pollutions. Generally, air quality is indicated by several pollutants such as surface ozone (O_3) levels, emissions of NO_x, CO, SO_2 and aerosol emissions (PM10 and PM2.5). Many research studies have reported on improvements in air quality due to the effects of COVID-19 lockdown measures [3-7]. For example, Xu, et al. [8] indicated that effects of the COVID-19 outbreak presented positive feedback in reductions of average concentrations of atmospheric PM2.5, PM10, SO_2, CO, and NO_2 in central China, by 30.1%, 40.5%, 33.4%, 27.9%, and 61.4%, respectively during February 2020 in Central China. Meanwhile, Southeast Asian cities such as Manila, Kuala Lumpur and Singapore also reported decreasing trends of NO_2 (27% - 30%) and of PM10, PM2.5, NO_2, SO_2, and CO concentrations, of 26–31%, 23–32%, 63–64%, 9–20%, and 25–31%, respectively [9]. In addition, Nadzir, et al. [3] found that in Malaysia, CO dropped by 48.7%, but PM2.5 and PM10 increased up to 60% and 9.7%, respectively, as their results indicated high AODs from Himawari-8, and NO_2 concentrations from Aura-OMI satellite sensors, associated with massive biomass burning in northern Thailand and Laos during the lockdown period (March 2020) which prevented the exploration of impacts due to lockdown on the air pollution in this region. Most of the research has been performed in the mega-city, Stratoulias and Nuthammachot [10] analysed concentrations of air pollutants over a medium-sized city (Songkhla Province) in Southern Thailand and found that concentrations of PM2.5, PM10, NO_2 and O_3 had decreased by 21.8%, 22.9%, 33.7% and 12.5% in the first 3 weeks of the lockdown compared to the respective pre-lockdown period. Kerimray, et al. [11] presented the effects of the COVID-19 lockdown with traffic-free conditions in Kazakhstan, with a PM2.5 reduction of 21%, and other gaseous pollutants down by 15% - 49%.

Recently, Bangkok has experienced winter pollution events with more frequency. Previous studies have mentioned that the common sources of PM2.5 emissions in Bangkok are from biomass burning, traffic and industrial activities with varying concentration caused by seasonal factors [12-14]. Moreover, Watcharavitoon, et al. [15] presented spatial and temporal variation trends of gaseous air pollutant concentrations for O_3, NO_x, CO, and SO_2 from 1996 to 2009 in Bangkok between residential and roadside areas. They reported seasonal trends of gaseous air pollutant concentrations which decrease from January to August and then increase from September to December. The gaseous air pollutant concentrations clearly presented higher concentration levels at the roadside areas than the residential areas.

Bangkok is a big city, if the people are largely restricted to their homes, with higher numbers of vehicles, there should have been greater reductions in vehicle emissions during the lockdown period, and the same should have been true for the industrial sector. However, the COVID-19 lockdown's impact on air quality in Bangkok is currently unknown. Therefore, this study aims to explore the effects and driving influence factors of the COVID-19 lockdown measures on air quality in Greater Bangkok, Thailand using in-situ measurements using Principal Component Analysis (PCA).

Materials and Methods

Study area

Greater Bangkok refers to Bangkok the capital along with the surrounding provinces, including Nakhon Pathom, Nonthaburi, Pathum Thani, Samut Prakan and Samut Sakhon. Greater Bangkok covers an area of 7,762 km^2 (100.20E to 100.9E, 13.0N to 14.0N) and is the center of economic development and an important industrial base for the surrounding provinces (Fig. 1). Some industries in Samutprakarn, Samutsakorn, and Pathumthani have already become the main emission sources of atmospheric pollution from industry.

Ground-based air pollution monitoring, traffic index and fire spots

Major air pollutants and aerosols, including carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), particulate matter with diameter lower than 10 µm (PM10) and 2.5 µm (PM2.5) concentration data were collected from the Pollution Control Department (PCD) of Thailand by observing 23 automatic monitoring sites [16]. The monitoring sites are almost all located in the Bangkok metropolitan area, as shown in Figure 1. Data was collected hourly from the period of 1 January 2019 to 20 July 2020 for both aerosols and gaseous pollutants. In addition, the traffic index refers as TI [17] for the same period, as the air pollutant dataset will be used to analyze the emission source from vehicles on the entire road network in Bangkok with a range of 0 to 10 (from Free-flow to Jam) to link air pollution with people movements. Moreover, in order to relate the emission source from biomass burning, active fire data (Fire) from satellite observations by the Visible Infrared Imaging Radiometer Suite (VIIRS), provided through NASA's Fire Information for Resource Management System [18] at same period as the air pollutants, will be used in this study.

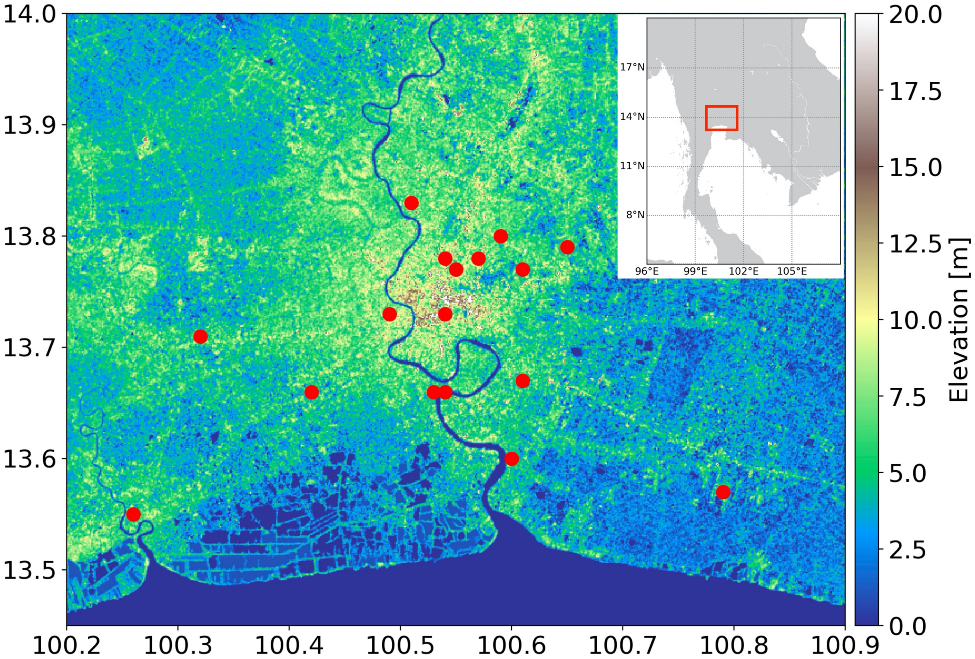

Figure 1: Study area and the 23 PM2.5 automatic monitoring stations in Grater Bangkok, Thailand.

Meteorological dataset

It's not only emission sources that influence air quality, meteorological factors also significantly impact the dilution and accumulation process of pollutants emitted from local sources [19]. Therefore, to access the variations of air pollutants, meteorological factors must be examined. In this study, the meteorological factors were achieved from the ECMWF's fifth-generation Reanalysis (ERA5), the European Centre for Medium-Range Weather Forecasts [20]. The meteorological dataset contains total precipitation (TP), 2-meter air temperature (T2M), planetary boundary layer height (BLH), relative humidity (RH), surface pressure (SP), and wind speed (WS), which have a horizontal resolution of 30 km × 30 km at hourly temporal resolutions. The meteorological data were picked up at the same hour of the day as the sampling time for the air pollutants.

Data analyses methods

Variations of air quality regarding the COVID-19 outbreak were investigated for three different periods, before-lockdown (from 1 January 2020 to 25 March 2020), lockdown (26 March 2020 to 31 May 2020) and after-lockdown (1 June 2020 – 20 June 2020). The evaluation of impacts of COVID-19 were compared with data in 2019 at the same period, which was used as a baseline. The changes in the air pollutant levels were evaluated by comparing those 3 different periods in year 2020 with 2019 at the same time (expressed in %) between the before, lockdown and after periods. In order to access the influences between meteorological factors, the air pollutants and other accompanying parameters gave different responses between the three periods associated with the COVID-19 lockdown. We performed data analysis using a Principal Component Analysis (PCA), which is a statistical multivariate analysis for data that features a large variable set. This method enables the researcher to identify correlations and patterns in a dataset by transforming them into a new smaller set of uncorrelated variables, namely principal components (PCs), that still contain most of the information in the large set [21]. Therefore, by applying a PCA method to air pollutant concentrations and meteorological variables, a dataset could be obtained with the most significant variables, which could indicate the source of the pollutants and largely explain the variations in the air pollution [22]. In this study, the meteorological variables of T2M, SP, TP, RH, WS and BLH; the major air pollutants: PM10, PM2.5, NO_2, SO_2, CO and O_3 concentrations; and the anthropogenic activities, TI and Fire, were taken up for analysis. The PCs created by PCA were rotated using an orthogonal rotation method (varimax) to compute the explained variance matrix, the number PCs were selected according to an eigenvalue greater than or equal to 1. These PCs are a linear combination of the explanatory variables; therefore, Pearson correlation tests were used to determine the correlation between the PCs and the original variables as a loading factor. The significant variables were identified when the correlation value was greater than or equal to 0.3.

Results and Discussion

The influence of COVID-19 lockdown on variations of air quality over Greater Bangkok

Figure 2 presents a time series of the rolling 24-hour average of daily PM2.5 concentration variations on a daily scale for 23 measurement stations for the periods from 1 March to 31 July of 2019 and 2020 in Greater Bangkok, Thailand. The grey colour represents the lockdown period from 26 March 2020 to 31 May 2020. The concentrations of PM2.5, PM10, NO_2, O_3, SO_2, and CO were compared between the 3 different periods: before (1 January–25 March 2020), lockdown (26 March–31 May 2020) and after (1 June–31 July 2020). There were similarly significant seasonal variations in the PM2.5, PM10, NO_2, O_3 and CO concentrations, where the highest mean concentrations occurred in January during the before lockdown period for Greater Bangkok, then decreasing concentrations during and after the lockdown period. While SO_2 concentrations show highly fluctuating time series throughout the year, especially in 2020, there were higher concentration levels and more fluctuation by degree than those in 2019. As illustrated in Fig. 3, changes in the mean concentration values of six major pollutants during the COVID-19 outbreak reveal that there were no different decreases in PM2.5 (0.7%), PM10 (4.1%) and O_3 (0.3%) concentrations during the before-lockdown period with the previous year. But there were 54.0%, 20.1% and 14.7%, increases in SO_2, NO_2 and CO concentrations during the before-lockdown period. Whereas there were reductions in PM2.5, PM10, CO and O_3 concentrations by 15.8%, 31.7%, 8.0% and 7.1% during the lockdown period, and by 6.11%, 20.7%, 23.6% and 4.72% during the after-lockdown period, when compared to the previous year. Stratoulias and Nuthammachot [10] similarly reported a decreased range in PM2.5 and PM10 concentrations during the lockdown period. On the other hand, NO_2 and SO_2 concentrations increased in this study during the lockdown (3.2% and 41.5%) and the after-lockdown periods (26.6% and 84.6%) in 2019 and 2020, respectively. In contrary, Kanniah, et al. [9] and Stratoulias and Nuthammachot [10] found that there were decreased concentrations of NO_2 according to the Aura satellite in Malaysia and Southern Thailand. Generally, the average concentration of PM2.5, PM10, NO_2, O_3 and CO have a decreasing trend from March to August [15], even in the previous years before the COVID-19 outbreak, as shown in Fig 2, excepting SO_2. Seasonal variations (summer and rainy seasons) denoted by rising temperatures and more frequent rains caused decreasing air pollutant concentrations, excluding some periods when the air pollutant concentrations showed several peaks association with open biomass burning and traffic index peaks, due to added anthropogenic pollutants during harvest season [23] and road traffic congestion in Bangkok [24].

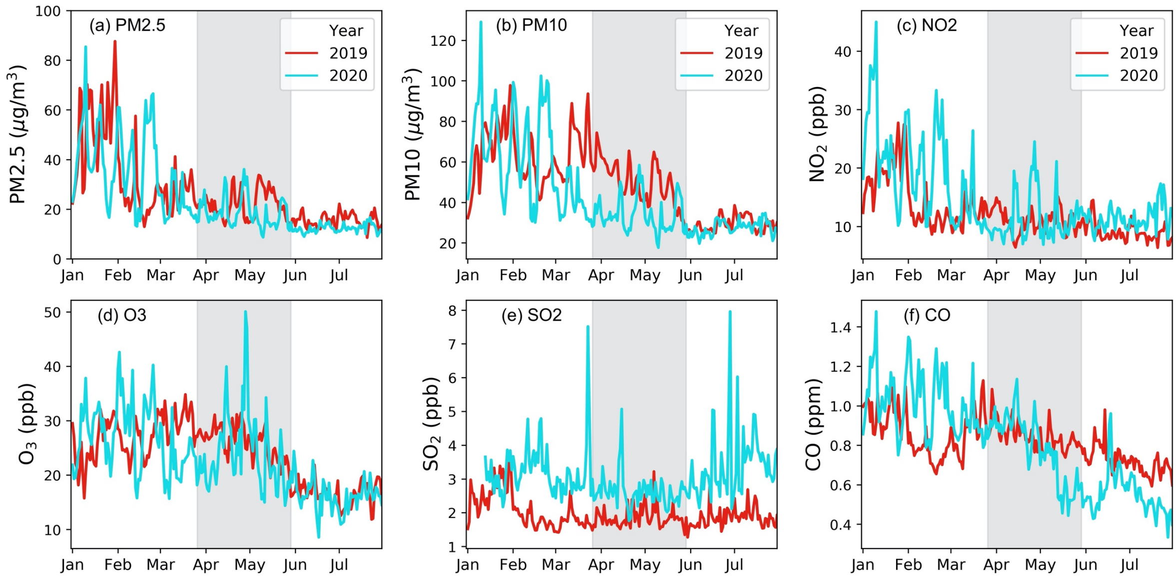

Figure 2: Rolling 24-hour average of hourly air pollutant concentration variations of major air pollutants over 23 ground-based stations in Greater Bangkok for year 2019 and 2020. Grey color highlights the lockdown period from 26 March 2020 to 31 May 2020.

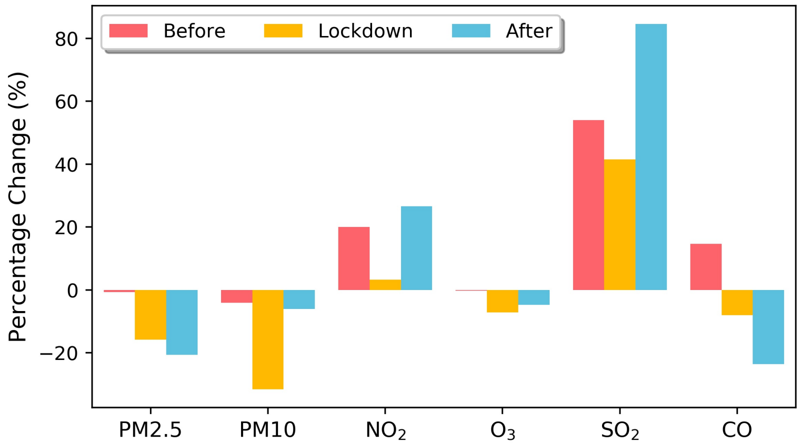

Figure 3: Impact of the COVID-19 lockdown on mean concentrations of air pollution: PM10, PM2.5, O_3, NO_2 and SO_2 and CO at 23 ground-based measurements during the before, lockdown and after lockdown periods in Bangkok, Thailand.

In principle, air pollutant concentrations in the atmosphere fluctuate by complex factors such as emission sources (TI and Fire), meteorological factors (BLH, T2M, TP, WS and RH) and so on [25]. Anthropogenic sources and meteorological condition changes during the COVID-19 outbreak period were examined by comparing them with previous years, as shown in Table 1. During the before-lockdown period, TI, Fire, WS and RH all increased by 4%, 26%, 22% and 14%, respectively, whereas there were decreases in BLH, TP and T2M by 42%, 99% and 5%, respectively. The increasing TI and Fire conditions in 2020 may cause higher NO_2, SO_2, and CO concentrations than in 2019 at the same time. During the first weeks of lockdown beginning in 2020, there was a sharp decrease in the TI due to limited transportation in greater Bangkok; after that, the concentrations increased gradually until the end of June (Fig. 4a). A similar trend is observed for NO_2 (Fig. 2c). As well, Fire (counts per day) within a 240 km. radius of Bangkok city (Fig. 4b) shows a high number in the first week of the lockdown period. News reports indicate there were great wildfires in northern Thailand, which produced tons of aerosols and pollutants [26]. The hourly meteorological data of Greater Bangkok during the study period in 2019 was compared to 2020, with results shown in Table 1. As indicated in Fig. 4 c-h, there is no obvious change during the COVID-19 outbreak in terms of SP, T2M, WS, BLH and TP from January to March 2020 compared with previous years. Whereas SP and RH during the lockdown period are somehow higher than previous years, T2M and BLH are lower than in previous years. As shown during the after-lockdown period, RH was higher, while BLH, TP, WS and T2M were lower than in previous years.

Table 1: Statistical description of meteorological factors; mean and standard deviation (S.D.) values in 2019 and 2020 over Greater Bangkok.

	Before 2019		Before 2020	
	Mean	S.D.	Mean	S.D.
TI	3.66	1.79	3.79	0.40
Fire (counts/day)	389.77	338.04	492.06	303.68
SP (mbar)	1011.86	2.25	1012.11	1.90
BLH (m)	511.71	428.72	295.21	160.70
TP (mm)	0.03	0.18	0.00	0.01

WS (m/s)	13.75	11.52	16.81	11.30
RH (%)	72.72	16.44	82.84	10.14
T2M (ºC)	28.22	2.92	26.93	1.07
	Lockdown 2019		Lockdown 2020	
	Mean	S.D.	Mean	S.D.
TI	3.93	1.93	3.10	0.38
Fire (counts/day)	80.68	81.87	164.55	326.44
SP (mbar)	1007.66	2.33	1009.69	1.73
BLH (m)	615.80	371.17	393.45	130.12
TP (mm)	0.11	0.36	0.04	0.21
WS (m/s)	14.77	11.33	18.64	11.30
RH (%)	72.30	13.75	83.48	3.70
T2M (ºC)	30.81	2.50	28.99	1.02
	After 2019		After 2020	
	Mean	S.D.	Mean	S.D.
TI	4.29	1.94	3.82	0.63
Fire (counts/day)	8.72	8.65	7.84	7.60
SP (mbar)	1006.72	1.54	1007.13	2.73
BLH (m)	584.75	350.74	301.21	125.16
TP (mm)	0.22	0.58	0.10	0.21
WS (m/s)	12.74	10.70	8.66	5.67
RH (%)	76.81	11.25	85.30	5.29
T2M (ºC)	29.95	2.16	27.94	0.89

It is evident that the lockdown corresponding to COVID-19 has had an effect on average pollutant concentrations because of human activity restrictions since the lockdown measure began on 26 March 2020 in Greater Bangkok. Moreover, higher WS in 2020 could help to dilute the pollutant concentrations in the air [27]. In contrast, Kerimray et al. (2020) reported no significant change in average PM2.5 concentrations during the COVID-19 lockdown when compared with previous years in Almaty, Kazakhstan. It is possible that they had a shorter period of lockdown (19 March 2020 – 14 April 2020) than in Bangkok, thus, the impact of COVID-19 can't be well taken compared to Almaty. In addition, it is during the seasonal transition from summer to rainy seasons in Almaty, and PM2.5 concentrations may be highly influenced by meteorological factors. As well as the after-lockdown period, there were decreases in both the source and meteorological variables, excepting RH, which increased compared with the previous year. In additional, many studies report that O_3 concentrations had increasing trends [28-30], while in this study we found decreasing O_3 concentrations over Greater Bangkok. NO_2 is an oxidation product from Nitrogen oxides (NOx) and O_3, which is emitted from combustion sources such as vehicle exhausts, industries, power plants and residential heating [14]. Thus, this decrease in O_3 could be due to greater increases in NO_2 concentrations.

Furthermore, different degrees of reduction in the pollutant concentrations point out that the decreasing pollution levels in three different periods cannot be explained by the limited emissions only, but depend on meteorological condition too. To obtain influence factors driving the air quality improvement between expected emission sources, meteorological variables and these six pollutants during the COVID-19 outbreak, this study used PCA to investigate more details, as shown in the following sections.

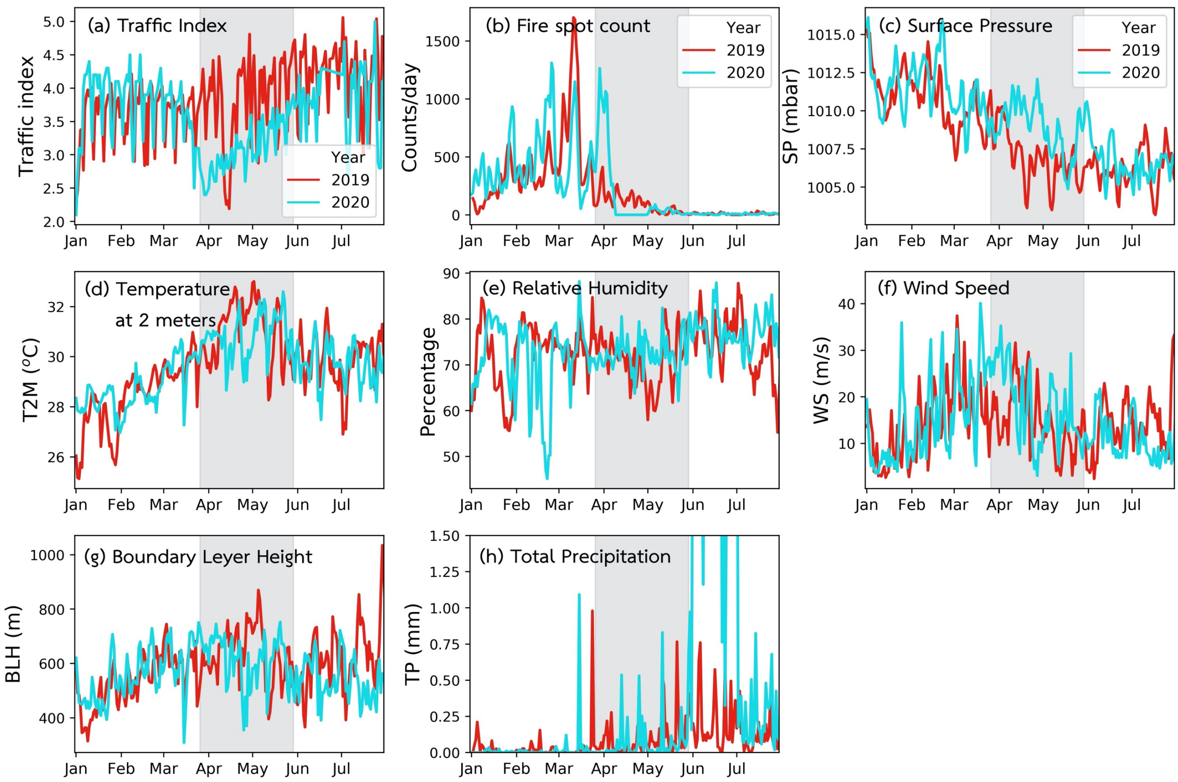

Figure 4: Temporal variations of the Traffic index (a), Fire spot count (b), surface pressure (c), air temperature at 2 meters (d), relative humidity (e), wind speed (f), boundary layer height (g) and total precipitation (h), respectively. Grey color highlights the lockdown period from 26 March 2020 to 31 May 2020.

Influence factors driving the improvements in air quality

In order to clarify what the main influence is between expected emission sources, meteorological parameters and the six pollutants during the COVID-19 outbreak will be explored in this section. To obtain a better understanding and interpretation of the data, the principal components (PC) were subjected to a Varimax rotation matrix. Only components with an eigenvalue greater than 1 are determined as principal components (grey color), as shown in Table 2. There are five major PCs in each subset period, comprising PC1, PC2, PC3, PC4 and PC5. The percentage of total variance represents how much proportion of that PC largely explains the variation in air quality. In each period at the same year, the percentage of total variance was slightly different. However, it had some significant differences between the before-lockdown and the lockdown periods. To obtain the factor loading, the Varimax rotation with Kaiser Normalization (Fig. 5) was computed, a loading factor higher than 0.3 contained from the output will become a principle component (PC). The results of PCA are summarized in Fig. 5, presenting the significant PC contributions. A loading factor of more than 0.70 is considered as strong, a range of 0.50 – 0.69 is considered moderate, and a range of 0.31 - 0.49 is considered weak.

Table 2: Total Variance explaining the principal components of air pollutants and meteorological elements in 2019 and 2020 over Greater Bangkok.

2019	Before			Lockdown			After		
Component	Eigent	Variance (%)	Cumulative (%)	Eigent	Variance (%)	Cumulative (%)	Eigent	Variance (%)	Cumulative (%)
1	**3.84**	27.40	27.40	**3.50**	25.00	25.00	**3.58**	25.60	25.60
2	**2.55**	18.20	45.60	**2.32**	16.60	41.60	**2.21**	15.80	41.40
3	**1.22**	8.70	54.40	**1.34**	9.50	51.10	**1.44**	10.30	51.60
4	**1.08**	7.70	62.10	**1.28**	9.10	60.30	**1.34**	9.50	61.20
5	**1.02**	7.30	69.30	**1.14**	8.10	68.40	**1.16**	8.30	69.40
6	0.83	5.90	75.30	0.98	7.00	75.40	0.87	6.20	75.70
7	0.82	5.80	81.10	0.77	5.50	80.80	0.84	6.00	81.70
8	0.66	4.70	85.80	0.64	4.60	85.40	0.57	4.10	85.70
9	0.61	4.40	90.10	0.58	4.20	89.60	0.53	3.80	89.50
10	0.45	3.20	93.40	0.46	3.30	92.80	0.45	3.20	92.70
2020	**Before**			**Lockdown**			**After**		
Component	**Eigent**	**Varience (%)**	**Cumulative (%)**	**Eigent**	**Varience (%)**	**Cumulative (%)**	**Eigent**	**Varience (%)**	**Cumulative (%)**
1	**5.15**	36.70	36.70	**3.58**	25.50	25.50	**3.25**	23.00	23.00
2	**1.67**	11.90	48.60	**2.20**	15.70	41.20	**2.43**	17.20	40.20
3	**1.22**	8.70	57.30	**1.84**	13.10	54.20	**1.68**	11.90	52.10
4	**1.09**	7.80	65.10	**1.61**	11.50	65.70	**1.62**	11.50	63.60
5	**0.96**	6.80	71.90	**0.99**	7.00	72.80	**1.15**	8.10	71.70
6	0.89	6.40	78.30	0.85	6.10	78.80	0.87	6.10	77.90
7	0.86	6.10	84.40	0.74	5.30	84.10	0.80	5.70	83.60
8	0.60	4.30	88.70	0.57	4.10	88.20	0.61	4.30	87.90
9	0.48	3.50	92.20	0.47	3.30	91.50	0.52	3.70	91.60
10	0.43	3.10	95.30	0.41	2.90	94.40	0.42	3.00	94.50

During the before-lockdown period, which denotes the winter season in Thailand, the PC1 and the PC2 could explain the variance by 27.4% and 18.2% for 2019, and 36.7% and 11.9% for 2020, respectively. The results reveal some similarities between those two years, there were significant mechanisms associated with the air quality. PM10, NO_2 and CO are dominant pollutant parameters that associate with the particular atmospheric mechanism of low T2M, BLH and WS, and high SP and RH. Hence, these atmospheric mechanisms reduced the ability of the pollutants to disperse from their sources [31]. These pollutants relate to unknown emissions as major and traffic-originated emissions were minor sources in 2019, while in 2020 the major and minor pollutants related to biomass burning and unknown emission sources, respectively. These results supporting a comparison of concentrations for PM2.5, PM10 and O_3 in Section 3.1 between those two years are not significantly different. As mentioned before, the common sources of air pollution in Greater Bangkok are from biomass burning, traffic and industrial activities with varying concentrations due to seasonal factors [12-14]. Due to some limitations, emission-related data for the industrial sector was not available for this study. Thus, the unknown emission source might be from industrial or other sources. Moreover, the PC2 in 2019 shows moderate positive contributions of O_3 and T2M, which indicates a strong oxidative air condition producing the formation of secondary particles, which could result in a positive loading factor of PM2.5 and O_3. As well, in 2020 the PC2 exhibits moderate positive contributions of T2M but negative contributions of O_3, this is mainly affected by photochemical reaction. The reaction system can produce NO_2 (positive contribution) due to the reaction of NO with O_3 [32]. Additionally, a comparison of the PC1 also explains the increase of NO_2 and CO regarding higher positive contribution magnitude in 2020 than those in 2019. As well, the PC5 had a higher contribution magnitude for SO_2 in 2020 than in 2019, resulting in increased SO_2 (Section 3.1).

During the lockdown period, which denotes the summer season in Thailand, there were significantly different major pollutant parameters contributing to the PC1 (explained: 25.0% and 25.5%) and PC2 (explained: 16.6% and 15.7%) for 2019 and 2020, respectively. In 2019, O_3 contributed as a major pollutant (PC1) corresponding to photochemical reaction ($NO_2 + O_2 \rightarrow NO + O_3$), as seen in the strong contribution of T2M with the significant emission source of TI. This explains the correlations with temperature and, partly, with O_3 concentrations that are commonly higher in summer [15]. For PM2.5, PM10, NO_2, SO_2, and CO, these are minor pollutants (PC2) which relate to unknown emission sources, with the exception of SO_2 and CO, which are associated with biomass burning (the PC4). And vice versa in 2020, the increases in PM2.5, PM10, NO_2 and CO concentrations originated from unknow emission sources (PC1), accompanied with strong contributions from decreases in BLH, T2M and WS. Meanwhile, the moderately negative O_3 was related to chemical reaction ($NO + O_3 \rightarrow NO_2 + O_2$), becoming a minor mechanism (PC2) corresponding to the NO added from traffic (TI) and biomass burning (Fire) emissions. These results indicate some important evidence which explains the reduction of air pollutant concentrations in Section 3.1. With COVID-19 lockdown measures, people were largely restricted to their homes, and greater Bangkok with its higher numbers of vehicles should have had greater reductions in traffic emissions during the lockdown period. The decreases in PM2.5, PM10 and CO concentration in 2020 strongly contributed to the increased fire (PC1) and the decreased TI (PC2), suggesting that the changes in traffic emissions were more responsible for the improvements air quality during the lockdown period, especially fine particles, than biomass burning. On the contrary, the increases in NO_2 concentrations in 2020 (PC2) are significantly related to biomass burning. According to during the lockdown period (March 2020), there were massive forest fires in northern Thailand, which reduced the impact of the lockdown on air pollution in that region. A report found an increase in some pollutants during the lockdown period regarding forest fires in Malaysia [3, 10]. In addition, the increased SO_2 concentrations were associated with unknown emission sources, which were probably emitted from the industrial sector.

During the after-lockdown period, which denotes the rainy season in Thailand, the PC1 and the PC2 could explain the variance by 25.6% and 15.8% for 2019, and 23.0% and 17.2% for 2020, respectively. In 2019, there were similar contributions of air pollutants with the lockdown period in 2020, as seen with the increases in O_3 concentrations by the production of photochemical reactions being the major mechanism (PC1), and the increased PM2.5, PM10, NO_2, SO_2, and CO concentrations, which were minor mechanism (PC2). In 2020, PM2.5, PM10, NO_2, SO_2, and CO were major pollutants that originated from unknown resources, with the exception of the PC3, where SO_2 concentrations were weakly associated with biomass burning. It can be denoted that there are decreases in BLH, WS and T2M, which are accumulative atmospheric conditions. Interestingly, there were significant decreases in both TI and Fire, while all pollutants except O_3 concentrations had increasing trends. However, as the results in Section 3.1 exclaim, concentrations of PM2.5, PM10 and CO were still decreased to a lower degree during the after-lockdown period. Therefore, the results demonstrate that the improvement of air quality in Greater Bangkok after the easing of lockdown were a combined effect of other emission sources (industrial, household, etc.) and the atmospheric mechanism.

All PCs during the lockdown of 2020 are important evidence that indicates influence factors driving the improvement of air quality were affected by the COVID-19 lockdown in Greater Bangkok. Atmospheric mechanisms play an important role in diluting or accumulating pollutant concentrations, while the emission sources influence the concentrations and type of major pollutants. Therefore, the COVID-19 lockdown measures influenced not only the air pollution levels, but also affected to the air pollution characteristics.

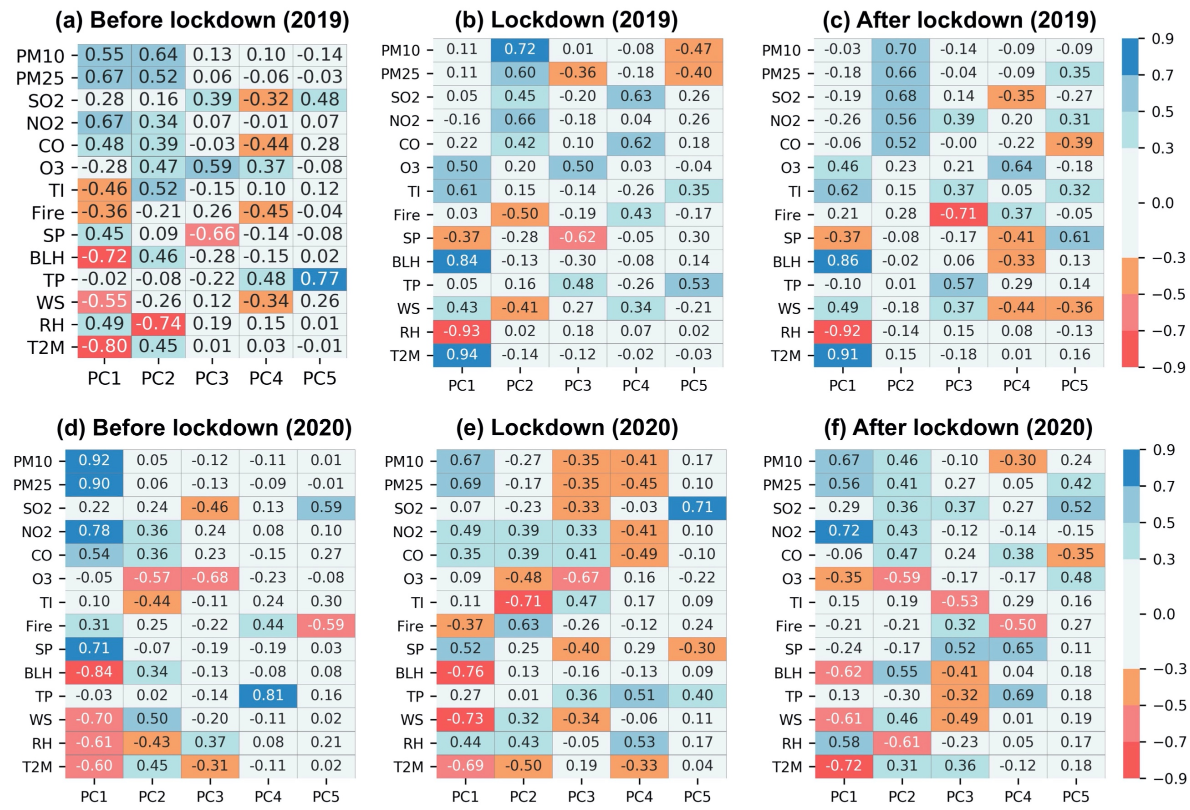

Figure 5: Loading factors of 14 companies in 5 principal components and their estimated comprehensive eigenvalues.

Conclusions

This study was carried out to expose the affects and influence factors of air quality due to the COVID-19 lockdown in Greater Bangkok, Thailand. Low traffic conditions and reduced human activities due to lockdown measures led to improved air quality in Bangkok. Overall PM2.5, PM10, O_3, and CO concentrations presented a significant decreasing trend during the COVID-19 outbreak year based on three periods: the before-lockdown, lockdown and after-lockdown periods, by the following amounts: PM2.5 by 0.7%, 15.8% and 20.7%; PM10 by 4.1%, 31.7% and 6.1%; O_3 by 0.3%, 7.1% and 4.7%, respectively. CO increased by 14.7% and decreased by 8.0% and 23.6%, respectively, compared to the same periods in 2019, while SO_2 and NO_2 increased by 54.0%, 41.5% and 84.6%, and 20.1%, 3.2% and 26.6% during the before-lockdown, lockdown and after-lockdown periods, respectively. PCA analysis was used to explore influence factors driving the improvements in air quality. The results indicated significant combination effects from atmospheric mechanisms that were strongly linked to emission sources such as traffic and biomass burning. The atmospheric mechanisms played an important role in diluting or accumulating the pollutant concentrations, while the emission sources influenced the concentrations and types of major pollutants. However, it was demonstrated that the COVID-19 lockdown measures had a significant positive impact on the improvement of air quality due to decreased traffic emissions. With regard to the lockdown measures, they are not restricted by natural disasters such as forest fires in northern Thailand, the pollution from these sources can transport to Greater Bangkok, resulting in decreasing magnitudes of each pollutant being lower than other countries. Furthermore, the results show that after the lockdown was relieved, all pollutants except O_3 tended to increase, even though Greater Bangkok's people still kept to decreased mobility and social activity. This implies that the COVID-19 lockdown was able to pause some anthropogenic emissions i.e. traffic, commercial and industrial activities, but not all, even low traffic emissions could not absolutely cause a reduction in air pollution, since several primary emission sources dominate the air quality over Greater Bangkok. In addition, social distancing guideline recommend that people stay at home, which causes consumption of higher electricity, resulting in electric power plant increasing their production capacity and emitting more air pollution. Finally, the results demonstrate that the COVID-19 lockdown measures influenced not only the air pollution levels, but also affected air pollution characteristics.

Data Availability

All the data used in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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