Air Quality Improvement during COVID-19 Lockdown in Bangkok Metropolitan, Thailand: Effect of the Long-range Transport of Air Pollutants

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ABSTRACT

Lockdown measures have been adopted in many countries worldwide due to the onset of the COVID-19 pandemic, including in Thailand. Air quality improvements with regard to restrictions of daily movement among Bangkok people have been reported. This study explores the impact of the COVID-19 outbreak and long-range pollution on air quality in Bangkok Metropolitan, Thailand by using ground-based and satellite measurements such as MODIS and TROPOMI data. Moreover, the results project some possible future trends of air quality in Bangkok Metropolitan. The 24-hr average concentrations of PM_{2.5}, O₃, NO₂, CO and SO₂ were compared between the periods of Normal, Lockdown and New Normal. PM_{2.5} concentrations increased by 20.56% during the Normal period and decreased by -15.79% and -23.34% during the Lockdown and New Normal periods, respectively, compared to the same periods in 2017–2019. There were also significant decreasing trends in O₃: -7.13% and 4.72%; and CO: -8.01% and 23.59% during the Lockdown and New Normal periods, respectively, while NO₂ and SO₂ concentrations showed increasing trends during the three periods. The MODIS and TROPOMI data analyses indicate the COVID-19 outbreak has had significant positive impact on surface pollution, but no impact on upper atmospheric pollution due to added pollution from long-range transport. The results also demonstrate that surface air pollution had a combination effect from biomass burning, traffic, industrial and household sources during the Lockdown period, except for SO₂ concentrations, which were attributed to long-range transport pollution loading. In some cases, a negative impact of the COVID-19 lockdown on air pollution can be observed due to certain activities increasing within Bangkok Metropolitan. Additionally, the results also show that changing the lifestyle into a “new normal” for people in Bangkok after the Lockdown period has had a positive effect on air pollution.

Keywords: COVID-19, Pollution, Long-range air pollution, PM_{2.5}, Bangkok, Thailand

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1 INTRODUCTION

The world has been struggling with COVID-19 since the first case has been reported on December 31, 2019 in Wuhan, China. After that, COVID-19 was declared a pandemic by the World Health Organization (WHO) on March 11, 2020 (WHO, 2020). As of February 13, 2021, there were 108,730,653 reported cases of infection and 2,394,127 deaths in all countries around the world, including Thailand (ECDC, 2020). Lockdown measures and social distancing are being used as a pandemic action plan to prevent spreading of COVID-19. Thai government imposed a curfew from March 26, 2020 to May 31, 2020 as the COVID-19 prevention plan for the whole country. These actions immediately affected daily life of human, particularly a switch to remote working systems (including working from home, takeout only restaurants, and online shopping and delivery) and a

transition in schools to online learning. The COVID-19 lockdown reduced economic activity, especially in the transportation, industrial, and energy production sectors, which in turn implies a decrease in anthropogenic emissions of greenhouse gases and other air pollutants such as O_3 , NO_x , CO, SO_2 and aerosols. Improvements in air quality due to the effects of the COVID-19 outbreak have been reported in some news media sources and research studies (Bao and Zhang, 2020; Dantas *et al.*, 2020; Jain and Sharma, 2020; Li *et al.*, 2020; Otmani *et al.*, 2020; Sicard *et al.*, 2020; Zambrano-Monserrate *et al.*, 2020). For example, Xu *et al.* (2020) presented the reductions of average concentrations of atmospheric $PM_{2.5}$ (−30.1%), PM_{10} (−40.5%), SO_2 (−33.4%), CO (−27.9%) and NO_2 (−61.4%) during the COVID-19 outbreak in central China during February 2020. Whereas, there are decreasing trends of NO_2 (27%–30%) as well as PM_{10} (26%–31%), $PM_{2.5}$ (23%–32%), NO_2 (63%–64%), SO_2 , (9%–20%) and CO (25%–31%) concentrations in Southeast Asian cities such as Manila, Kuala Lumpur, and Singapore (Kanniah *et al.*, 2020).

In addition, Nadzir *et al.* (2020) discovered reduction of CO (48.7%) in Malaysia, while $PM_{2.5}$ and PM_{10} increased up to 60% and 9.7%, respectively. Their results revealed that forest and vegetation fires in northern Thailand and Laos during the Lockdown period (March 2020) prevented the effects of the lockdown on air pollution in this region. On the other hand, Kerimray *et al.* (2020) reported the impact of the COVID-19 lockdown due to free flow traffic conditions in Kazakhstan which caused decrease in $PM_{2.5}$ by 21%, and other gaseous pollutants by 15%–49%.

Recently, air pollution events have occurred frequently in Bangkok during the winter. Previous researches have reported that the major sources of $PM_{2.5}$ in Bangkok are originated from traffic, biomass burning, and industrial activities, with concentration variations caused by seasonal effects (Uttamang *et al.*, 2018; Narita *et al.*, 2019; Chirasophon and Pochanart, 2020). Moreover, spatial and temporal variations of gaseous air pollutant concentrations (O_3 , NO_x , CO, and SO_2) from 1996 to 2009 showed seasonal variations of gaseous pollutant concentrations which tend to decrease from January to August and then increase from September to December (Watcharaviton *et al.*, 2013). The gaseous pollutant concentrations obviously exhibited lower concentration levels at residential areas than in roadside areas. Thailand has been one of the most successful nations at recovering from COVID-19 by imposing a strict and long period of Lockdown. Thus, it was one of the first countries to remark on a reduction of pollutant emissions. As reported by Stratoulis and Nuthammachot (2020) and Kaewrat and Janta (2021), major pollutants showed a significant reduction of 20%–50% over metropolitan cities in Thailand during the Lockdown period. Additionally, Wetchayont (2021) revealed that air pollution levels decreased by 1%–30%, except for NO_2 and SO_2 , and their characteristics also changed over Bangkok metropolitan, corresponding to COVID-19 lockdown measures and the influence of meteorological factors. Since there are multiple primary emission sources in Bangkok that dominate the air quality, an absolute reduction in air pollution can't occur only through lockdown measures. However, these research studies noted the important factor that the reduced levels of air pollutants in Thailand were not as pronounced as those recorded in other countries due to open burning activity.

Nevertheless, the effect of biomass burning on air quality improvements during the COVID-19 lockdown in Bangkok metropolitan was not clearly investigated. Furthermore, the COVID-19 outbreak also created a new lifestyle, called the “New Normal”, for people around the world after the lockdown. Bangkok people are now preparing to transition towards this “New Normal” lifestyle, which will probably have an impact to the air quality as well. Therefore, this study aims to investigate the impact of the COVID-19 outbreak on long-range pollution and air quality in Bangkok, Thailand and project the future trend using ground-based and satellite measurements.

2 STUDY AREA AND DATA

2.1 Study Area

Bangkok Metropolitan is an urbanized and agglomerated area with the highest population in Thailand. It is also an economic center and an important industrial park for the surrounding provinces, covering over 1,568.7 km² (100.20°E–100.9°E, 13.0°N–14.0°N), and could be expected to receive a large impact from the COVID-19 lockdown. Thus, the present study focuses on understanding the effects of COVID-19 on air quality status in Bangkok. Fig. 1 shows the locations of observation sites for surface measurements (dots) and average surface $PM_{2.5}$ readings from

Fig. 1. Study area and locations of 17 ground-based measurements (dots). The colored bar presents the level of mean $PM_{2.5}$ concentration from January 1, 2020 to June 20, 2020.

2019 to 2020 (colors). We used data from 17 monitoring sites located in four different environments: residential (10T and 18T), roadside (3T, 50T, 52T, 53T and 54T), commercial (5T, 8T, 11T, 17T, 59T) and suburban sites (13T, 14T, 19T, 20T and 27T), as shown in Fig. 1. The observation sites are operated by the Pollution Control Department (PCD) of Thailand.

2.2 Data

Particulate matter (PM) with an aerodynamic diameter less than $2.5\ \mu m$ ($PM_{2.5}$) and trace gases, including CO , O_3 , NO_2 , SO_2 , and $PM_{2.5}$, were observed at each site, where hourly data of each are made public. We used $PM_{2.5}$ data covering the period of January 1, 2017 to June 20, 2020, and trace gas data covering the period of January 1, 2019 to June 20, 2020. Due to some limitations, the trace gas data were available only for 2019 to 2020. Additionally, in order to relate air pollution with people's movements, a traffic index (Longdo, 2020), which represents road traffic congestion levels for the same periods as the $PM_{2.5}$ dataset, was used to analyze the free-flow travel times of all vehicles on the entire road network in Bangkok, with a range of 0 to 10 (from Free-flow to Jam).

Furthermore, we used satellite observation data as re-analysis data. We used aerosol optical thickness (AOT) observed by MODerate Resolution Imaging Spectroradiometer (MODIS) aboard Terra and Aqua satellites, which have overpass times at 10:30 and 13:30 local time (LT), respectively. In this study, Collection 6 aerosol product (Corrected_Optical_Depth_Land) with 3 km spatial resolution (Remer *et al.*, 2013; Levy *et al.*, 2015) was used for the period of January 1, 2017 to June 20, 2020. The column densities (molecules per cm^2) of sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and carbon monoxide (CO) were observed using a Tropospheric Monitoring Instrument (TROPOMI) onboard the Sentinel-5 satellite (Veefkind *et al.*, 2012). The overpass time of TROPOMI is $\sim 13:40$ LT. The TROPOMI products have spatial resolutions of 3.5×7.0 km and 3.5×5.5 km for observations before and after August 6, 2019. We further used Modern-Era Retrospective analysis for Research and Applications, Version 2 MERRA-2 (Gelaro *et al.*, 2017) data. From MERRA-2 products, AOTs of total and sea salt aerosols, vertical and horizontal components of wind direction at 850hpa, and vertical profiles of the CO mixing ratio were used. The spatial resolution of MERRA-2 was 0.5° (Latitude) $\times$ 0.625° (Longitude).

3 METHODOLOGY

The effect of COVID-19 on air quality was investigated for three different periods, Normal (before the lockdown: from January 1, 2020 to March 25, 2020), Lockdown (during lockdown:

March 26, 2020 to May 31, 2020) and New Normal (after lockdown: June 1, 2020–June 20, 2020) for both aerosols and gaseous pollutants. In order to find and evaluate the changes within each time series, and to quantify the lockdown impacts on air pollutant quality, the changes in 24-hr mean concentrations (expressed in %) were calculated as $(y_i - x_i)/x_i \times 100\%$, where x and y represent values for 2020 and reference year(s) before 2020, and i represents the study period (e.g., Lockdown). We further computed the mean difference among the Normal, Lockdown and New Normal periods. Data corresponding to reference years are termed as baseline in this study. Moreover, the $PM_{2.5}$ concentrations were compared to the traffic index details on the same day of the year to find any variations of $PM_{2.5}$ concentrations from people's movements.

For satellite data analyses, we selected the satellite pixels falling with a 50 km radius of the center of Bangkok (13.76N, 100.51E). Those data were then averaged for each day to generate the temporal variation. As satellite data are available only for clear sky days, the missing information was extracted by interpolating data using a cubic spline method, which were then used to derive a running mean of 10 days. The relative change in air pollution concentrations during different periods of 2020 were studied using the same approach as for the surface observations mentioned above. Though MERRA-2 data used in this study are available for each hour, we used only those data that coincided with satellite observation times. Specifically, we extracted the MERRA-2 data coinciding with MODIS observation times, which were then analyzed using the same procedure mentioned above. We further used fire counts observed with the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor aboard the Joint NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi NPP). Though the spatial resolution of native data is 375 m, they were analyzed for a spatial grid of $0.1^\circ \times 0.1^\circ$.

4 RESULTS AND DISCUSSION

4.1 Surface Observations

4.1.1 Aerosols and trace gases

Fig. 2 shows a time series of the 24-hour average (solid line) of hourly (a) $PM_{2.5}$ concentration variations (open circles) on the day of year (DOY) for 17 measurement stations, and (b) the traffic indices, for the periods from March 1 to June 20, of 2017–2019, and 2020 in Bangkok, Thailand.

Fig. 2. Time series of 24-hour average hourly (a) $PM_{2.5}$ concentration variations for 17 stations, and (b) traffic index, for the periods from January 1, to June 20 of the baseline (years 2017–2019), and 2020 in Bangkok, Thailand. Blue color highlights the Lockdown period from March 26, 2020 to May 31, 2020 and red color presents three major case studies during the Lockdown period.

The blue color represents the Lockdown period from March 26, 2020 to May 31, 2020. In principle, $PM_{2.5}$ concentrations in the atmosphere are varied by multiple factors, such as emission sources, meteorological factors and so on (Carslaw and Beevers, 2012; Shi *et al.*, 2019). As mentioned before, road traffic and industrial sectors are considered to be significant sources of air pollution in Bangkok (Watcharavitoon *et al.*, 2013), and the number of vehicles on the road have been increasing every year, which implies that $PM_{2.5}$ concentrations are also increasing. Generally, the average $PM_{2.5}$ concentration has a declining trend from March to September (Chirasophon and Pochanart, 2020), even in previous years before the COVID-19 outbreak. Due to seasonal variations (summer characterized by rising temperatures, and the rainy season with a high frequency of precipitation), decreasing $PM_{2.5}$ concentrations in the atmosphere occurred, excluding some periods when $PM_{2.5}$ concentration peaks showed significant association with open biomass burning and traffic index peaks due to added anthropogenic pollutants during harvesting season (Khamkaew *et al.*, 2016) and rush hour in Bangkok (Kim Oanh *et al.*, 2013). Additionally, the $PM_{2.5}$ concentration time series shows two individual peaks during the Lockdown period. They are discussed at the end of this section.

Similarly, Fig. 3 shows the average daily concentrations of (a) O_3 , (b) NO_2 , (c) SO_2 and (d) CO in a time-series plot. Generally, concentrations of O_3 in Bangkok have a decreasing trend during the period from April to August, corresponding to seasonal variations from meteorological dispersion (Watcharavitoon *et al.*, 2013). As seen in Fig. 3(a), O_3 concentrations in 2019 gradually increased from January to April and then changed to decrease from the beginning of May. In 2020, on the other hand, O_3 concentrations had larger swings than in 2019, with an upward and downward pattern during the Normal and Lockdown periods, and had a decreasing trend during the New Normal period. Especially during the Lockdown period, O_3 concentrations showed a consistent trend with $PM_{2.5}$ concentrations. Note that the temporal trends of NO_2 and CO, and to some extent SO_2 , were consistent with that of $PM_{2.5}$, as shown in Fig. 2, suggesting that they could have common emission sources, showing higher values in the dry winter season than in the summer season. Those high values in the winter season could be due to the influence of biomass burning activities and/or low boundary layer heights in winter. We will discuss in Section 4.2.1 how CO, NO_2 and SO_2 could be high during opening burning events. NO_2 concentrations also presented with several peaks during the Lockdown period relating to the O_3 peaks (Fig. 3(b)). NO_2 is generated from vehicles, power plants, and combustion activities. A changing trend in O_3 concentrations is associated with photochemical reactions between primary gases such as CO, SO_2 , NO_2 and VOCs, which transform to generate O_3 and secondary aerosols (Uttamang *et al.*, 2018; Rogers *et al.*, 2020). Fig. 3(c) shows constant SO_2 concentrations with several spikes and higher levels of concentration in 2020 than in 2019. The peak during the Lockdown period is consistent with a peak in $PM_{2.5}$ concentrations. Major sources of SO_2 include fuel burning from industries and power plants, as well as ships, vehicles and heavy equipment (Watcharavitoon *et al.*, 2013). Fig. 3(d) also shows a larger variation of CO concentrations in 2020 than in 2019 during the Normal period, followed by concentrations sharply decreasing to lower levels in early May 2020. CO is emitted through fossil fuel burning from vehicles, biomass burning and heavy machinery. CO concentrations generally show a decreasing trend from April to August, corresponding to seasonal agricultural residue burning (Watcharavitoon *et al.*, 2013). These decreasing trends during the Lockdown period (from the middle of May 2020) reveal a significant impact of the lockdown measures on surface CO concentrations due to reduced numbers of agricultural residue burning around the Bangkok area. Additionally, agricultural burning season ends at the beginning of May and the air pollution suddenly decreases.

As seen in Fig. 2(a), $PM_{2.5}$ concentrations exhibited two major peaks, at April 11–14, 2020 (DOY 102–105) and April 28–30, 2020 (DOY 119–121), referred to as Case Nos. 1 & 2, respectively. For Case No. 1, the traffic index shows a sharp decline in previous years before the COVID-19 outbreak, a similar trend can be observed in $PM_{2.5}$ concentrations. Due to the national holiday (Songkran), millions of Thai people normally travel from Bangkok city to their hometowns to celebrate the holiday. According to a report in 2019 from the Department of Land Transport (DLT, 2019), this causes low traffic volumes and $PM_{2.5}$ concentrations in Bangkok (Kaewrat and Janta, 2021; Wetchayont, 2021). Meanwhile, during the COVID-19 lockdown in 2020, transportation between provinces was restricted and the Songkran holidays were postponed to another month by the government, resulting in maintained traffic volumes and working hours in Bangkok, which

Fig. 3. Daily time series of air pollutants: (a) O_3 , (b) NO_2 , (c) CO and (d) SO_2 , at 17 ground-based measurements during Normal, Lockdown (light blue color) and New Normal periods in Bangkok, Thailand.

caused higher $PM_{2.5}$ concentrations, as seen in Case No. 1 during the lockdown period. In addition, surface NO_2 , SO_2 and CO spikes are evidence of local source emissions (such as traffic, residential and industrial sources) in Case No.1.

For Case No. 2, it presents with corresponding trends between $PM_{2.5}$ concentrations and the traffic index in both the baseline and the 2020 data. As it is the end of month, many people working at offices get paid their monthly salary and go out to buy food, resulting in a slightly elevated traffic index. The higher numbers of vehicles should have had greater increases in vehicle emissions during the Lockdown period, and the same should have been true for the industry sectors. Elevated NO_2 concentrations at ground level provide evidence of vehicle and industrial emissions, and surface CO concentrations also display a peak, which is probably a combined effect from local sources (traffic and industrial). Moreover, Fig. 7 presents with decreased southeastern wind speeds, which mainly contributed to the elevated pollutant concentrations in Case No. 2, even though there were slight local emissions. Along with such local emissions, long-range transported biomass burning and low atmospheric dispersion conditions could have also contributed to generate such peaks, as has been reported in similar studies (Kaewrat and Janta, 2021; Wetchayont, 2021).

Table 1. Average air pollution concentrations: PM_{2.5} in the Normal, Lockdown and New Normal periods between baseline (2017–2019) and the COVID-19 outbreak (January 1 and May 20, 2020).

PM _{2.5} (μg m ⁻³)	Baseline (2017–2019)		COVID-19 Outbreak (2020)		% Change
	Mean	S.D.	Mean	S.D.	
Normal	29.54	1.39	35.61	1.96	20.56
Lockdown	21.79	1.03	18.35	2.18	–15.79
New normal	15.84	1.32	12.30	1.10	–23.34

For overall averages of the 17 observation sites, Table 1 shows the relative change in PM_{2.5} concentrations in different periods of 2020 with respect to those in 2019. It was found that there were –15.79% and –23.34% decreases in PM_{2.5} concentrations during the Lockdown and the New Normal periods in the COVID-19 outbreak year, compared to the averaged baseline values in the same periods of 2017–2019, as shown in Table 1. There are some reports that PM_{2.5} concentrations decreased by 23%–32% in Malaysia (Kanniah *et al.*, 2020), 29% in China (Li and Tartarini, 2020), and 1%–21% in Bangkok (Wetchayont, 2021) respectively, which are in similar ranges as with this study. In contrast, Kerimray *et al.* (2020) reported no significant change in average PM_{2.5} concentrations during the COVID-19 outbreak from previous years in Almaty, Kazakhstan. PM_{2.5} concentrations during the Lockdown period in Almaty might have been highly influenced by meteorological factors. In addition, Almaty had a shorter period of lockdown (March 19, 2020–April 14, 2020) than in Bangkok, thus, the impact of COVID-19 cannot be well exhibited in Almaty.

Table 2 shows a statistical summary of the gaseous pollutants in each period compared with the average concentrations in 2019 as a baseline. In the Normal period, concentrations of NO₂, SO₂ and CO were higher than the baseline, by 20.06%, 54.03% and 14.65%, while O₃ concentrations indicated to no significant change from the baseline (–0.28%, Table 2). NO₂ concentrations increased for all three periods, and concentrations of SO₂ increased in all three periods: The Normal, Lockdown and New Normal periods, ranging from 41% up to 85%. In addition, the results indicate that traffic emissions did not influence SO₂ concentrations, and that it was possibly contributed to by the non-traffic and non-industrial sectors (Wetchayont, 2021). Similarly, positive impacts of the COVID-19 outbreak on air pollutants were seen in studies from India, Morocco and China (Jain and Sharma, 2020; Otmani *et al.*, 2020; Xu *et al.*, 2020).

In summary, this section reveals that the COVID-19 outbreak had positive impacts on concentrations of PM_{2.5}, O₃ and CO during the Lockdown period, which was investigated using surface measurements. Moreover, continuing concentration reductions of these pollutants in

Table 2. Average air pollution concentrations: CO, NO₂, O₃, SO₂ during the period between January 1, 2019 and May 20, 2020.

Pollutant	2019	2020	% Change
CO (ppm)			
Normal	0.87	1.00	14.65
Lockdown	0.85	0.78	–8.01
New normal	0.72	0.55	–23.59
NO ₂ (ppb)			
Normal	14.91	17.90	20.06
Lockdown	11.00	11.36	3.20
New normal	9.01	11.41	26.62
O ₃ (ppb)			
Normal	27.17	27.09	–0.28
Lockdown	25.84	23.99	–7.13
New normal	16.71	15.93	–4.72
SO ₂ (ppb)			
Normal	2.10	3.23	54.03
Lockdown	1.85	2.62	41.53
New normal	1.86	3.44	84.57

the New Normal period indicate that Bangkok people have created a new lifestyle, which probably also affects air pollution in Bangkok.

4.1.2 COVID-19 impacts on different pollution sectors

The comparison between PM_{2.5} concentrations and the traffic index were not quite straight forward because the sites of PM_{2.5} measurements were not the same as the traffic index. Fig. 4 presents the analysis results for sites of different pollution source sectors. This 4-sector analysis shows that all the sectors had decreasing trends of PM_{2.5} concentration during the Lockdown and the New Normal periods, except for the residential sites, which had an increasing trend during the Lockdown (13.56%) and the New Normal periods (37.87%), respectively. These higher emissions might be related to household combustion corresponding to lockdown measures which restricted the daily activity of Bangkok people. It forced most people to stay at home while some people still went to work at their office. During the Lockdown period significant positive impacts from the Covid-19 outbreak were found at the residential (Fig. 4(a)), the commercial (Fig. 4(c)) and suburban (Fig. 4(d)) sites, as shown by the decreasing NO₂ concentrations. Meanwhile, concentrations of O₃ increased, corresponding to photochemical reactions (NO_x = NO₂ + NO) (Sicard *et al.*, 2020), while increased concentrations of NO₂ were observed at roadside areas, with the lowest magnitude happening in the Lockdown period. This suggests that the Covid-19 lockdown reduced emissions from transportation, industrial and social activities, causing a decrease in concentrations of pollutants at the roadside and suburban sites (Wang *et al.*, 2020). Concentrations of SO₂ have rapidly increased at the residential, roadside and suburban sites during the New Normal period due to reoperation of Small and Medium Enterprises and industrial sites which are located in residential and suburban areas.

4.2 Satellite Observations

4.2.1 Aerosols and trace gases

Fig. 5 shows a time series of aerosols and trace gases as observed from space. If observations from both Terra and Aqua MODIS are available, they are averaged; otherwise, available data from

Fig. 4. Impact of the COVID-19 outbreak on concentrations of particle matter and gaseous pollutants between the baseline (2017–2019) and the COVID-19 outbreak (2020) in Bangkok, Thailand during Normal, Lockdown and New Normal periods for different sectors: (a) Residential, (b) Roadside, (c) Commercial, and (d) Suburban.

Fig. 5. Time series for aerosol optical thickness (AOD) from MODIS (Terra + Aqua) and trace gases (CO, NO₂, SO₂) from Tropomi for 2019 and 2020 (open circles). The solid lines show the 10-day running mean of each by interpolating missing data using the cubic spline method.

a single satellite sensor is used to represent a daily value. The open circles in Fig. 5(a) show daily MODIS AOT values, and a solid line shows the 10-day running mean values. Figs. 5(a), 5(b), 6(c) and 5(d) show time series of the satellites observed as instantaneous (open circles) and 10-day running mean (solid line) values for NO₂, SO₂ and CO, respectively. In each, the shaded area shows the Lockdown period in 2020. Despite the lockdown, notable reductions in columnar pollution concentrations were noted neither for mass loadings of aerosol, nor for trace gases. Table 3 shows the relative change of each in different periods of 2020 with respect to those of 2019. Interestingly, AODs of 2020 were even higher than those of 2019 during the Lockdown period. A similar result can be seen for SO₂ and CO, though NO₂ is noted to get lower during the Lockdown period in 2020 with respect to that in 2019. One can also note the decrease of NO₂, even during the Normal and New Normal periods. Those data suggest relatively less influence from the lockdown in columnar pollution concentrations over Bangkok, though lockdown was noted to reduce pollution concentrations, except for NO₂, at the surface. At the same time, those data suggest that local emissions are not the only source of atmospheric burden over Bangkok. In the section below, we discuss the plausible reasons for such enhanced columnar pollution concentrations during the Lockdown period.

Table 3. Average air pollution concentrations observed by satellite: AOD, CO, NO₂, and SO₂ during the period between January 1, 2019 and May 20, 2020.

Pollutant	2019	2020	% Change
AOD			
Normal	0.73	0.84	15.03
Lockdown	0.67	0.85	25.94
New normal	0.57	0.51	-9.68
CO (molecules cm ⁻²)			
Normal	3.01×10^{18}	3.20×10^{18}	6.40
Lockdown	2.36×10^{18}	2.71×10^{18}	15.06
New normal	1.70×10^{18}	1.68×10^{18}	-0.84
NO ₂ (molecules cm ⁻²)			
Normal	5.01×10^{15}	4.17×10^{15}	-16.75
Lockdown	3.40×10^{15}	3.16×10^{15}	-6.94
New normal	2.86×10^{15}	2.80×10^{15}	-2.14
SO ₂ (molecules cm ⁻²)			
Normal	1.82×10^{16}	2.20×10^{16}	20.63
Lockdown	2.02×10^{16}	2.07×10^{16}	2.23
New normal	1.72×10^{16}	2.22×10^{16}	28.87

4.2.2 Plausible reasons of enhanced columnar air pollution during lockdown

As Southeast Asia, including Thailand, has agriculture-based economies, a large amount of agricultural residue is generated from harvesting and is generally burnt in the field. This type of agricultural burning is primarily done more during the dry season from November to May, than in the wet season from June to October (Phairuang *et al.*, 2020). Additionally, forest fires also occur in significant numbers during the dry season (Chaiyo *et al.*, 2013). The land use map of Thailand published by the Land Development Department (LDD) shows that northern Thailand is generally covered by dense forest in the upper north and paddy fields in the lower north; the central and northeastern parts of Thailand are covered by crop fields of rice, sugarcane etc.; the southern part is covered by crop fields of para-rubber, oil palm etc. Figs. 6(a) and 6(b) show the total number of fire counts for the full year of 2019 until end of May of 2020. They were observed by VIIRS sensor. It is evident from Fig. 6 that open burnings occur over nearly the whole of Thailand during the dry season. Thus, Bangkok can easily be affected by air pollutants of such open burnings, unless the wind comes from the Gulf region of the South.

Fig. 7 shows wind speed and directions for 2019 and 2020 at the altitude of 850hpa. Fig. 7(b) shows that the predominant winds are from the eastern parts of Bangkok during January, then generally shift towards the south and then the southeast until the end of the dry season. Such air masses are driven by the northeast monsoon, and they can easily transport air pollutants from open burning activities occurring in the north to eastern parts of Bangkok and its vicinity. One very important observation to be noted in Fig. 7 is that winds were weak and slightly pushed towards the Gulf of Thailand in 2020, more so than in 2019. This especially happened during the Lockdown period of 2020. As a result, air masses from continental regions traveled relatively short distances with less interaction with fresh air masses from the Gulf region before arriving Bangkok in 2020, as opposed to 2019, with its long distances and more interaction between those air masses. This fact is further justified in Fig. 8, which shows a relatively low sea salt fraction in the total AOT in 2020, compared with 2019. Thus, Bangkok received more influence from open burning activities in 2020 than in 2019. To get an idea of the relative abundance of such open burning and the generated pollution that results in the free troposphere of Bangkok, we analyzed vertical profiles of the CO mixing ratio in both 2019 and 2020. They are shown in Figs. 9(a) and 9(b). The difference in the CO mixing ratio between 2020 and 2019 is shown in Fig. 9(c). Fig. 9 suggests a considerable abundance of CO at high altitudes in both in 2019 and 2020. Such CO levels at high altitudes suggest that air pollutants emitted from burning activities are transported to Bangkok from far distances. At the same time, Fig. 9 shows high concentrations of CO near the surface, which could be due to the combined effects of long-range transported pollutants as well

Fig. 6. Total number of fire counts from January to May for (a) 2019 and (b) 2020 for pixel resolution of $0.1^\circ \times 0.1^\circ$. Data were observed by VIIRS.

Fig. 7. Wind speed (a) and direction (b) at 850hpa during 2019 and 2020, corresponding to MODIS observation times shown in Fig. 6. Similar to Fig. 6, the open circles and solid lines show instantaneous and 10-day running mean values. Data are from MERRA-2.

Fig. 8. Sea salt AOD fractions during 2019 and 2020 corresponding to MODIS observation times shown in Fig. 6. The open circles and solid lines show instantaneous and 10-day running mean values. Data are from MERRA-2.

as emissions from local sources, such as household activities, transportation, etc. Fig. 9(c) clearly shows enhanced CO levels at higher altitudes in 2020, more than in 2019, suggesting the higher influence of long-range transported air masses in 2020 than in 2019. This result is consistent with Figs. 6 and 7. Thus the increased columnar pollutants in 2020, including during the Lockdown period,

Fig. 9. Time series of daily mean vertical profiles of CO mixing ratios for (a) 2019, (b) 2020, and (c) the difference between 2020 and 2019.

can be suggested to be due to the effect of air pollutants transported to Bangkok from continental regions. Open burning activities can generate not only CO, but also NO₂ and SO₂, depending on the abundance of nitrogen and sulfur content in the burned materials (e.g., Hegg *et al.*, 1987; Itahashi *et al.*, 2018). It can be postulated as the devolatilization of previously deposited nitrogen and Sulphur in forest/crops (Hegg *et al.*, 1987) and/or the burning of organic matter in soil that contains significant amounts of Nitrogen, Phosphorous, or Sulfur (Stevenson, 1994). Further, Figs. 10(a) and 10(b) show CO/NO₂ and SO₂/NO₂ ratios for 2019 and 2020, which are derived from the data presented in Fig. 5. It is notable that, in Fig. 9, both the CO/NO₂ and SO₂/NO₂ ratios are higher in 2020 than in 2019. Note that CO is the product of incomplete combustion, and SO₂ is produced from the burning of sulfur-containing materials/fuels. Similarly, NO₂ is high for efficient combustion and vice versa. Thus, CO/NO₂ and SO₂/NO₂ ratios for open burning are generally higher than those corresponding to emissions from urban areas. This result again provides additional evidence to suggest the enhanced influence from biomass burning in 2020 compared to 2019, which increased columnar air pollution in 2020 above that in 2019.

4.3 Comparison of Surface Measurements and Satellite Retrievals

Surface measurements have high accuracy but they are a single data point. To study large surface areas, satellite observations can help to counter this limitation. The variation of surface concentrations of CO, SO₂ and NO₂ during the Before, the Lockdown and the New Normal periods between 2019 and 2020 were compared with the corresponding TROPOMI columns averaged

Fig. 10. Time series of (a) CO/NO₂ and (b) SO₂/NO₂ ratios derived from Fig. 5 (surface level).

over the same temporal term. The results are displayed in Fig. 3 and Table 2, showing surface stations lying in Bangkok during the lockdown of 2020 with increasing SO₂ and NO₂ concentrations, in respect to the satellite retrievals. Moreover, surface observations reveal a higher percentage of change in both of the surface SO₂, and NO₂ concentrations than those columns which were obtained from the satellite. As seen in Table 2 and Table 3, the surface NO₂ concentrations have no significant difference in magnitude of change in the Lockdown period, and the NO₂ columns show no significant changes compared to those in the Lockdown and New Normal periods in 2019. It was revealed that the COVID-19 lockdown did not have an impact on NO₂ in both the surface and the columns, whereas there were significant changes in the surface SO₂ concentrations, but not in the columns. This suggests that the pollutant concentrations are mainly loading from local sources depending on the changes in activities within each different source sector, which is evidently represented in Fig. 4. On the other hand, surface CO concentrations during the lockdown of 2020 had decreased values, but the columns showed increased values. As seen in Table 2, comparing the surface CO concentrations in the three different periods indicates that the surface CO concentrations tended to slightly decrease in Bangkok during the Lockdown period. Interestingly, while COVID-19 lockdown measures restricted anthropogenic emissions, CO from the surface and the columns increased, and there was a particularly higher magnitude of change in the columns. This implies that there probably was CO loading from long-range transport. Figs. 10 and 11 display CO/NO₂ and SO₂/NO₂ ratios from the surface and the columns, respectively. It illustrates similar trends in both the surface and the columns, but the magnitudes of those ratios are different, with the columns being tenfold higher for CO/NO₂ and SO₂/NO₂ ratios than at the surface. This is evidence that, at upper air levels, pollutant concentrations are highly affected from loading by long-range transport from far distances, and which gets less impact from the COVID-19 lockdown. On the contrary, pollutant concentrations at the surface level are primarily sensitive to local emission sources because the COVID-19 lockdown changes the human activities that could impact the surface air pollution level. Additionally, the long-range transport pollutants also affected the surface air pollution levels when the atmospheric conditions permitted such.

5 CONCLUSIONS

Impact of the COVID-19 outbreak on air pollution over Bangkok was investigated in this study. Low traffic conditions and reduced human activities due to lockdown measures led to improved air quality in Bangkok. Overall surface PM_{2.5} concentrations presented a significant decreasing

Fig. 11. Time series of CO/NO₂ (a) and SO₂/NO₂ (b) ratios derived from Fig. 6 (upper level).

trend during the COVID-19 outbreak year (2020) based on two periods: The Lockdown and New Normal periods, by -15.79% and -23.34% , respectively, compared to the same periods in baseline years (2017–2019). While the concentrations of O₃ decreased by $\sim 4\%$ – 7% , and CO by $\sim 8\%$ – 23% , during the Lockdown and New Normal periods, respectively, NO₂ concentrations increased by $\sim 3\%$ – 26% , and SO₂ by $\sim 41\%$ – 84% , in all three periods. Satellite data from MODIS AOD and TROPOMI column data were used to explore air pollution in the upper atmosphere. The results indicate that the surface concentrations of NO₂ and SO₂ had not decreased during the Lockdown period because of added pollutants from the long-range transport of these pollutants from the north and eastern regions of Thailand. The results indicated significant inter-annual variability that is strongly linked to biomass-burning activity. In addition, it was revealed that the COVID-19 outbreak had a significant positive impact on air pollutions at the ground level, but no impact at upper levels. Since the lockdown measures did not restrict agricultural burning activity and natural disasters such as forest fires, the pollution from these sources could be transported to other regions. Therefore, the impacts of the COVID-19 outbreak on surface pollutant concentrations vary depending on the source sectors and the loading of long-range pollutants. Furthermore, the results imply that Bangkok people are expected to adopt a new normal lifestyle (e.g., working from home, online learning, online shopping), which displays decreasing mobility and economic activity. However, there still remain some challenging points, with more detailed analysis and the role of meteorology over longer periods still being required.

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