Changes in Air Quality during the COVID-19 Lockdown in Singapore and Associations with Human Mobility Trends

Jiayu Li*, Federico Tartarini

Berkeley Education Alliance for Research in Singapore, 138602, Singapore

ABSTRACT

On the 7th of April, the Singaporean government enforced strict lockdown measures with the aim of reducing the transmission chain of the coronavirus disease 2019. This had a significant impact on the movement of people within the country. Our study aims to quantify the impact that these measures had on outdoor air pollution levels. We obtained air quality and weather data from April 2016 to May 2020, satellite data for 2019 and 2020 and mobility data for 2020 from Apple, Google, and the Singaporean Housing & Development Board. We determined that outdoor air pollution during the lockdown significantly decreased when compared with the same period in the previous four years even if we included corrections for long time trends in the analysis. The concentrations of the following pollutants PM₁₀, PM_{2.5}, NO₂, CO, and SO₂ decreased by 23, 29, 54, 6, and 52%, respectively, whilst that of O₃ increased by 18%. The Pollutant Standard Index decreased by 19%. The trends of PM_{2.5} and NO₂ were significantly correlated with mobility data. The NO₂ and SO₂ tropospheric concentrations and the total aerosol optical depth at 550 nm obtained from satellite data during the lockdown in 2020 were also lower than during the same period in 2019. Our results can be used to evaluate possible mitigation strategies for outdoor air quality in a longer term beyond this lockdown.

Keywords: Air pollutant; Anthropogenic pollution; Circuit breaker; SARS-CoV-2.

INTRODUCTION

On the 23rd January 2020, Ministry of Health of Singapore confirmed the first imported case of coronavirus disease 2019 (COVID-19) caused by the infection of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Ministry of Health, 2020a; Wong *et al.*, 2020). On the 7th of February 2020, the Singaporean government raised the Disease Outbreak Response System Condition (DORSCON) to Orange, slowly implementing measures to limit social gatherings and on the 23rd of March banned all short-term visitors from entering the country. However, due to the increasing rate of transmission of SARS-CoV-2 in the community, as shown in Fig. S1 in the Appendix, on the 7th of April 2020 Singapore implemented strict safe distancing measures (Ministry of Health, 2020b; Pung *et al.*, 2020). The Singaporean government named these measures “Circuit-Breaker”, however effectively were analogous to what other Countries referred as “lockdown” or “shutdown” measures. In this paper we, therefore, decided to use the term “lockdown”

to describe these measures. During the lockdown period schools were closed, all workers working in non-essential sectors were imposed to work from home, and shops were closed with the exclusion of those providing essential services to the community (Lim *et al.*, 2020; Ng, 2020). People were allowed to exit their home only for purchasing essential products or exercising, no social gatherings were allowed. These measures confined the population at home and reduced the vehicular traffic on the roads and emissions from industrial activities which in turn may had affected the concentration of anthropogenic pollutants in the outdoor air (Dutheil *et al.*, 2020; Filonchyk *et al.*, 2020; Le *et al.*, 2020; Muhammad *et al.*, 2020; Safarian *et al.*, 2020; Xu *et al.*, 2020). Lockdown measures in Singapore were implemented on the 7th of April 2020 and started to progressively ease on the 12th of May 2020 (Ministry of Health, 2020c). Hence, we labeled these 35 days from 7th April to 11th May 2020 as the lockdown period in this study.

Although the lockdown measures are designed to protect people from the disease, these measures have a severe impact on the economy and people’s daily lives. A silver lining under this scenario may come in the form of health benefits resulting from the reduction of air pollution (Lal *et al.*, 2020). The World Health Organization (WHO) defines outdoor air pollution as a major environmental risk to health, which negatively affects cardiovascular and respiratory health. The WHO classifies particulate matter with diameters less

* Corresponding author.
Tel.: 65-85251223
E-mail address: jiayu.li@berkeley.edu;
jiayuliaq@gmail.com

or equals to 10 micrometers (PM_{10}) and 2.5 micrometers ($PM_{2.5}$), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and ozone (O_3) as the major outdoor air pollutants (WHO, 2006). In Singapore the main sources of outdoor pollutants are industries and motor vehicles (National Environment Agency, 2020a). Sporadic elevated haze pollution from neighboring countries during the monsoon seasons (Velasco and Rastan, 2015) or caused by El Niño (Atwood *et al.*, 2013) also have an impact on outdoor air quality. In Europe a report (Myllyvirta, 2020) estimated that the lockdown measures have avoided 11,000 pollution-related deaths in April 2020. The avoided NO_2 and $PM_{2.5}$ related deaths in China due to the cleaner air were estimated as 8911 and 3214, respectively (Chen *et al.*, 2020a). The reduction of air pollutant has the potential to decrease the mortality rate of COVID-19 (Brandt *et al.*, 2020; Fattorini and Regoli, 2020; Ogen, 2020) and mitigate the spread of the virus (Jiang *et al.*, 2020; Pani *et al.*, 2020; Sciomer *et al.*, 2020; Yao *et al.*, 2020).

Our aim is to quantify the change in outdoor pollutants concentrations during the lockdown period in Singapore and to evaluate their associations with mobility trends. This would allow us to better understand how anthropogenic activities and various sources in Singapore affect the overall air quality.

METHODS

Air Quality Data

The National Environment Agency (NEA) in Singapore provides Application Programming Interfaces (APIs) for real-time weather readings and air quality data. The weather data APIs provide 1-minute intervals data of temperature, relative humidity, precipitations and wind conditions for a total of 64 weather stations across Singapore (National Environment Agency, 2020b).

Data on pollutants were obtained from five monitoring stations distributed strategically throughout Singapore (National Environment Agency, 2020c). The Singaporean government refers to these stations as Central ($1^\circ 21'N$ $103^\circ 49'E$), East ($1^\circ 21'N$ $103^\circ 56'E$), West ($1^\circ 21'N$ $103^\circ 42'E$), South ($1^\circ 18'N$, $103^\circ 49'E$), and North ($1^\circ 25'N$, $103^\circ 49'E$) according to their locations in Singapore, and the national level is calculated as the main value among these five stations. We obtained outdoor air quality data from April 2016 and May 2020 using Python. The NEA releases on an hourly basis data regarding pollutants mass concentrations for: 24-h mean PM_{10} and $PM_{2.5}$, 1-h mean NO_2 , 8-h mean CO, 24-h mean SO_2 , and 8-h mean O_3 and their relative sub-indices for each of the above-mentioned stations. In addition, it provides data on the 24-h Pollutant Standard Index (PSI). The NEA calculates the 24-h PSI value firstly by linearly mapping each individual sub-pollutant (i.e., 24-h PM_{10} , 24-h $PM_{2.5}$, 8-h CO, 24-h SO_2 , 1-h NO_2 , 8-h O_3) to a sub-index ranging from 0 to 500. Then the overall 24-h PSI value is assumed to be equal to the maximum value of any of the pollutants sub-indices (National Environment Agency, 2014). More information regarding the accuracy of the instrumentation used by NEA and the location of the

stations can be found on the NEA website (MSS, 2018, p. Annex 3; National Environment Agency, 2020d).

To better analyze the spatial temporal variations of NO_2 and SO_2 concentrations in Singapore during the lockdown period, we obtained data from the European Space Agency (ESA) Sentinel-5P TROPOMI satellite (European Space Agency, 2020). We also obtained the total aerosol optical depth (AOD) at 550 nm data from the Copernicus Atmosphere Monitoring Service (CAMS) (Benedetti *et al.*, 2009; Huijnen *et al.*, 2016; Morcrette *et al.*, 2009). Data were processed and plotted using the Earth Engine Data Catalog (Gorelick *et al.*, 2017). The spatial resolution of the Sentinel-5P TROPOMI satellite is 7 by 7 km^2 and the satellite scans the earth with a daily revisit frequency. However, for same specific days data were either not available or may have been filtered out due to the presence of clouds. Consequently, since we plotted the average data collected over a relative short period of time, from the 7th of April to the 11th of May, the mean concentration calculated for some areas may not be accurate due to missing data (Kramer, 2002).

Mobility Data

We use the datasets from both Apple and Google to analyze how changes in mobility affected the air quality. Both datasets show a relative trend of how people movements changed within Singapore each day due to the impact of the COVID-19 pandemic. Google's dataset is built from data collected from users who allowed Google to access their location information. Google's data are classified into the following macro categories: workplaces, residential, retail & recreation, grocery & pharmacy, transit stations, and parks (Google LLC, 2020). Google uses as baseline the median value for the corresponding day of the week during the period from the 3rd of Jan to the 6th of Feb 2020. The data reflects how the lockdown impacted each category. The data in Apple's dataset is based on the direction requested by the users in Apple Maps, and classified into three categories: driving, public transit, and walking (Apple Inc., 2020). From both datasets, we selected the mobility parameters which have the potential to impact air quality. The selected parameters are workplaces, residential, and transport station in Google's dataset and the data of driving and public transit in Apple's dataset.

In addition to the smartphone data we acquired data regarding the Housing and Development Board (HDB) carpark availability using the API provided by the Singaporean Government (HDB, 2020). Approximately 81% of the whole population in Singapore lives in HDB apartments (HDB, 2018; Li *et al.*, 2020), hence this data provides a meaningful estimation of how many Singaporean used their personal vehicle during the lockdown period. We gathered aggregate data on an hourly basis regarding the total number of residential occupied and free car spots across the whole country. We used this information to estimate at any point in time the percentage of people who commuted from and to their houses using a vehicle. From those data we could not infer how many cars were on the streets, since we only knew when the car left the residential parking and when it returned in the evening.

Data Analysis

To estimate the influence of the lockdown on the outdoor air pollutants concentrations, we firstly had to estimate the concentrations without COVID-19 measures. We call this the counterfactual concentrations. For each parameter at each location, we linearly regressed the data collected over the previous four years (2016, 2017, 2018, and 2019) during the period from the 7th April to the 11th of May to test whether there was a consistent change of pollutants concentrations over the years. We used two methods to estimate the counterfactual value for 2020. If the *p*-value of the linear regression is lower than 0.01 we used the value estimated by the linear regression; alternatively, we used the mean value of the last four years. The reduction was defined as the change from the counterfactual value to the measured one during the lockdown.

We have listed below the reasons why we chose to compare the outdoor concentrations to those measured in the same period of the last four years, instead of using the methodology proposed by (Kerimray *et al.*, 2020; Otmani *et al.*, 2020) who compared the lockdown data to a period of time in 2020 preceding the lockdown.

Firstly, we observed that the difference of meteorological parameters in the same period over different years is much smaller than the variation between two consecutive periods before and after the lockdown due to seasonal trends, as shown in Figs. S2–S5 in Appendix. The total rainfall in April is significantly higher than the rainfall in March, as shown in Fig. S4 in Appendix. Meteorological monthly or seasonal trends affect significantly some air pollutants in Singapore within each year. Hence, the difference between the lockdown period and the period of time preceding it could be inherently different and not related to the COVID-19 pandemic. On the contrary, the difference of the air pollutant between the same period in different years are much smaller.

Secondly, after the first confirmed cases in Singapore on 23 January, Singaporean government started to implement measures to contain the local transmission of the virus, such as raising the DORSCON level to orange (7 February) and an advisory about encouraging people work by telecommuting from home. These early measures may have impacted the air quality in Singapore even before the lockdown. Hence, air quality during a period before the lockdown is not suitable to serve as the baseline.

We used the Wilcoxon signed-rank test to compare the difference of the parameter during between different periods. We performed Spearman's rank correlation to access the

correlation between air quality and mobility. We analyzed the data in the R programming language. We processed and transformed the data with *data*, *table*, *lubridate*, and *magrittr* packages and visualized them with *ggplot2* and *patchwork* packages. We have published the data sets and source codes we used on a public GitHub repository (https://github.com/JiayuLIAQ/COVID-19_vs_air_quality_weather/), to allow other researchers to reproduce a similar analysis in other cities or countries.

RESULTS

The meteorological parameters in Singapore during the period between the 07th of April and the 11th of May from 2016 to 2020 are summarized in Table 1. During the lockdown period in 2020, temperature, relative humidity, rainfall, and wind direction were not significantly different from those recorded during the same period in previous years. Wind speed during the lockdown period was significantly higher than the previous years. However, while the difference was statistically significant, it only increased by 0.8 m s⁻¹. More detailed comparisons can be found in Figs. S2–S5 in the Appendix.

The Reduction of Air Pollutant Due to COVID-19 Lockdown

The national level of daily PSI and mass concentrations of PM₁₀, PM_{2.5}, NO₂, CO, SO₂, and O₃ measured from 07 April and 11 May for five consecutive years (2016–2020) are plotted using boxplots in Fig. 1. The filled boxes are the interquartile ranges (IQR) for the air quality values in each year. The horizontal line in the box is the median, and the rhombus dot is the arithmetic mean. Whiskers of the boxes start from the upper and lower limits of the box and end at the length of 1.5 times the IQR or at the maximum and minimum values whichever is reached first.

During the lockdown period, the PSI was always lower than 50, which is classified by the NEA as “Good” on a 5–point scale with the following categories “Good (PSI: 0–50)”, “Moderate (PSI: 51–100)”, “Unhealthy (PSI: 101–200)”, “Very Unhealthy (PSI: 201–300)” and “Hazardous (PSI: above 300)”. All air pollutant levels during the lockdown period were below the Singapore Targets by 2020 (National Environment Agency, 2011) which are listed in the Table S1 in Appendix. On the other hand, the PSI for the same period of last four years were higher than 50 (“Moderate”) for more than 65% of the time. All the air quality parameters in 2020

Table 1. Mean and standard deviation (SD, in parentheses) of the meteorological parameter from 7th of April to 11th of May in 2020, 2019, and 2016–2019 overall.

Parameters	2020	2019	2016–2019
Temperature (°C)	28.7 (0.9)	28.9 (0.9) ^{NS}	28.3 (0.9) ^{NS}
Relative humidity (%)	79.7 (5.5)	78.7 (4.5) ^{NS}	80.6 (4.4) ^{NS}
Daily rainfall (mm)	8.2 (10.8)	7.4 (12.1) ^{NS}	6.3 (9.2) ^{NS}
Wind direction (°)	145.2 (53.9)	167.0 (54.9) ^{NS}	162.4 (48.6) ^{NS}
Windspeed (m s ⁻¹)	4.7 (0.5)	3.9 (0.6) ^{***}	4.2 (0.9) ^{***}

*** and ^{NS} denote that the difference between the noted value and the corresponding value in 2020 are with high and no significance, respectively.

Fig. 1. National air quality parameters for the period starting on the 7th of April and ending on the 11th of May, from 2016 to 2020. NS, *, **, and *** denote the difference between two samples is at the level of no (Wilcoxon $p \geq 0.05$), low ($0.01 \leq p < 0.05$), medium ($0.001 \leq p < 0.01$), and high ($p < 0.001$) significances, respectively. The inverted triangle is the counterfactual concentration.

during the lockdown period were significantly lower than those in the previous years, with the exception of O_3 . Fig. 1 shows that some of the air quality variables (PSI, $PM_{2.5}$, CO, SO_2 , and O_3) improved over the years, others not (PM_{10} and NO_2). We used semi-transparent grey lines to depict those values with significantly decreased over the last 4 years (i.e., PSI, $PM_{2.5}$, CO, SO_2 , and O_3) in Fig. 1. For these parameters, predicted values in the year 2020 are used as the counterfactual concentration and marked as inverted triangles in Fig. 1. We then calculated the reduction by subtracting the average value measured this year from the counterfactual value. We showed these differences as blue arrows in Fig. 1, and summarized the results into Table 2.

During the lockdown period the national PSI decreased by 19% compared to the predicted value for 2020, which suggests that the lockdown due to the COVID-19 pandemic had a positive impact on the reduction of the overall PSI value. The reduction of 29% in the southern area of Singapore was the highest, and 17% in the west and north was the lowest. $PM_{2.5}$ dominated PSI in Singapore, which had the third-highest reduction of 29% nationally. The $PM_{2.5}$ level decreased by nearly a half in the southern area, which was the highest reduction among the five stations. NO_2 and SO_2 had the highest and second-highest reduction regarding percentage change rates, which decreased by 54% and 52% nationally in this year, respectively. The change in PM_{10} , CO, and O_3 concentrations were relatively low when compared to other pollutants. Also, their concentration variations were not consistent among the various locations.

Though PM_{10} and CO were decreasing this year nationally in general, we observed an increase in concentrations for some of the locations. In particular, we observed a nationwide increase of O_3 during the lockdown period, except for the western area. Similarly, increased O_3 concentrations were observed during the lockdown period in several cities around world (Chen *et al.*, 2020b; Collivignarelli *et al.*, 2020; Dantas *et al.*, 2020; Kerimray *et al.*, 2020), which may be explained by a significant reduction of NO_2 concentrations (Sicard *et al.*, 2020).

The different reduction rates among locations could be caused by the spatial distribution of the different pollution sources in Singapore. All the heavy industries, refineries and the harbor in Singapore are located in the south-west part of the island. Singapore is one of biggest harbor in the world. To better understand the spatial variations of outdoor pollutants in the outdoor air we obtained data from the ESA Copernicus Sentinel 5P satellite. Fig. 2 shows the mean value of the NO_2 and SO_2 tropospheric column over Singapore. Satellite images show similar trends to those observed by ground stations and the biggest reductions of NO_2 concentrations were observed in the south and west regions of the island. The biggest reductions of SO_2 concentrations were observed over the island of Pulau Bukom which is an oil and petrochemicals site with manufacturing facilities for fuels, lubricant base oils and specialty chemicals. These results would, therefore, suggest that the COVID-19 and related and concurrent oil crisis may have led to a reduction of petrochemical activities in Singapore. From Fig. 2, it can

Table 2. The change of air quality parameters during the COVID-19 pandemic at national level and at five different locations in Singapore.

Parameter	National			Central			East		
	Baseline	Lockdown	Δ %	Baseline	Lockdown	Δ %	Baseline	Lockdown	Δ %
PSI	51	41.3	−19	54.9 ***	43.7	−20	53.1 ***	42.6	−20
PM ₁₀ ($\mu\text{g m}^{-3}$)	29.8 ***	23	−23	28.1 ***	23.4	−17	32.5	25.5	−21
PM _{2.5} ($\mu\text{g m}^{-3}$)	14.4	10.1	−30	16.8 ***	11	−34	15.7 ***	10.4	−34
NO ₂ ($\mu\text{g m}^{-3}$)	33.1 ***	15.1	−54	27.7	14.4	−48	27.8 ***	14	−50
CO (mg m^{-3})	0.5	0.5	−6	0.4	0.4	−9	0.5 ***	0.6	35
SO ₂ ($\mu\text{g m}^{-3}$)	8.7	4.2	−52	6.1	3.6	−41	11.4 ***	2.9	−74
O ₃ ($\mu\text{g m}^{-3}$)	21.1	24.9	18	25.5 **	30	17	23.4 ^{NS}	23.7	1
Parameter	West			South			North		
	Baseline	Lockdown	Δ %	Baseline	Lockdown	Δ %	Baseline	Lockdown	Δ %
PSI	46.6	38.6	−17	57.3 ***	40.5	−29	50.7	42	−17
PM ₁₀ ($\mu\text{g m}^{-3}$)	22.6	22.9	1	34.1 ***	21.5	−37	19.2	21.5	12
PM _{2.5} ($\mu\text{g m}^{-3}$)	12.3	9.2	−25	18.3 ***	9.8	−46	13.9	10.2	−27
NO ₂ ($\mu\text{g m}^{-3}$)	22.9	15.2	−33	31.6 ***	18.9	−40	33.7 ***	14.1	−58
CO (mg m^{-3})	0.6 ***	0.5	−18	0.5 *	0.5	−13	0.6	0.4	−26
SO ₂ ($\mu\text{g m}^{-3}$)	15.4 ***	7.1	−54	10.1	5.3	−48	8.7 ***	2.2	−74
O ₃ ($\mu\text{g m}^{-3}$)	25.7 ***	15.9	−38	13.9	31.9	129	20.9	23	10

^{||} denotes that the predicted value in 2020, i.e., the counterfactual concentration, was used for the baseline. Otherwise, the mean value of same period of last four years was used for the baseline, and star signs are given according to p values (*: $0.01 \leq p < 0.05$, low significance; **: $0.001 \leq p < 0.01$, medium significance; ***: $p < 0.001$, high significance) after Wilcoxon signed-rank tests with the value in this year during the lockdown.

Fig. 2. Shows the mean tropospheric column concentrations of NO₂ (left side) and SO₂ (right side) from 7th of April and 11th of May 2019 (top side) and 2020 (bottom side). Data were obtained from the ESA Copernicus Sentinel 5P satellite.

also be observed that NO_2 concentrations decreased in the east side of Singapore. The reduction could be attributed to the reduced number of flights that landed and departed from Singapore's airport (located on the east side of the country) and possible due to the decrease in operation of the heavy industry in Malaysia located in Pasir Gudang (north east of Singapore).

Due to the low spatial resolution of AOD data, we could not analyze the spatial variations within Singapore, and we decided to report the data collected in the Southeast Asia region. Comparing to the same period in 2019, the total AOD at 550 nm in Singapore decreased significantly in 2020 during the lockdown. From Fig. 3, we observed that areas around Singapore also experienced a decrease of the AOD during this year. However, capitals of nearby countries such as Kuala Lumpur and Jakarta, showed an increase of the AOD level.

Correlations between Air Quality and Mobility

In order to better understand the relationship between outdoor air pollution and mobility data. We plotted in Fig. 4 the daily average levels of PSI, PM_{10} , $\text{PM}_{2.5}$, NO_2 , CO, SO_2 , and O_3 along with the selected mobility trends from HDB, Apple, and Google databases.

Fig. 4 shows an immediate change in community mobility on the 07th of April 2020 when the lockdown measures were implemented. Fewer people drove, took public transportation and went to work, while more people stayed at home. Mobility levels declined before and after the day the lockdown measures were implemented but in a much gentler way. This suggests that the measures were effective and widely adopted by the public. The daily averaged HDB car park availability decreased from 54% to 49%. Over the

same period, changes in outdoor pollutants concentrations were less pronounced than those observed in the mobility data. We can observe fluctuating downward trends for $\text{PM}_{2.5}$, and NO_2 levels during the lockdown period, while an increasing trend for SO_2 levels.

To better understand the impact that the reduction in mobility observed in Fig. 3 had on the number of people commuting to and from their home using a motorized vehicle, we plotted the HDB carpark availability in 2020 in Fig. 5. The figure shows that while in January during working days between 9 and 19 up to 70% of the parking spots were available, this percentage reduced to 55% during the lockdown period.

The correlations between air quality and mobility parameters were tested via Spearman's rank test and the results are listed in Table 3. $\text{PM}_{2.5}$ concentrations were significantly correlated with all the mobility trends and had the highest correlation coefficients with trends of people who visited transit stations comparing to other mobility data. The second-highest coefficient of $\text{PM}_{2.5}$ was the workplace from Google database, which implies that the shutdown of some industries could contribute to the reduction of $\text{PM}_{2.5}$. NO_2 only significantly correlated with the mobility trends of car park availability (HDB dataset), driving (Apple dataset), and transit station (Google dataset), but did not with the workplace and residential ones. Both workplaces and traffic are among the main sources of $\text{PM}_{2.5}$, but NO_2 are more traffic related. For SO_2 , we found positive correlations with the human mobility trend in residential places but negative correlations with the other mobility trends. For PM_{10} , CO, and O_3 , we did not find any significant correlation with mobility data, while O_3 concentrations showed a negative correlation with car park availability.

Fig. 3. Shows the mean total AOD at 550 nm from 7th of April and 11th of May 2019 (left side) and 2020 (right side). Data were obtained from the Copernicus Atmosphere Monitoring Service (CAMS).

Fig. 4. Daily trends of the air quality parameter and the mobility levels since the start of earlier measures on 20 Mar 2020. ^h, ^a, and ^g denote that sources of the dataset are from HDB, Apple, and Google, respectively.

Fig. 5. HDB carpark availability prior and during the lockdown period. We centered the color bar using the percentage of car spaces available on the 7th of April (first day of the lockdown period) at 11:00 the time of the day when generally the highest percentage of parking spots are available.

Table 3. Spearman's rank correlation coefficients (Spearman's ρ) between air quality and mobility parameters.

	Car park ^h	Driving ^a	Workplace ^g	Transit station ^g	Residential ^g
PM ₁₀ ($\mu\text{g m}^{-3}$)	−0.03 NS.	−0.05 NS.	−0.07 NS.	−0.05 NS.	0.09 NS.
PM _{2.5} ($\mu\text{g m}^{-3}$)	0.14 *	0.17 **	0.21 ***	0.28 ***	−0.19 ***
NO ₂ ($\mu\text{g m}^{-3}$)	0.33 ***	0.24 ***	0.03 NS.	0.18 **	−0.06 NS.
CO (mg m^{-3})	0.07 NS.	−0.01 NS.	−0.08 NS.	−0.07 NS.	0.06 NS.
SO ₂ ($\mu\text{g m}^{-3}$)	−0.12 *	−0.08 NS.	−0.21 ***	−0.19 ***	0.22 ***
O ₃ ($\mu\text{g m}^{-3}$)	−0.2 ***	−0.06 NS.	−0.02 NS.	0.04 NS.	0.02 NS.

^h, ^a, & ^g denote that the mobility data is from HDB, Apple and Google datasets, respectively. *, **, and *** denote correlations between two samples are significant at the levels of $0.01 \leq p < 0.05$, $0.001 \leq p < 0.01$, and $p < 0.001$; NS. denotes two samples are not significant correlated ($p \geq 0.05$).

It is important to note that in Singapore the great majority of the population uses public transportation to commute and to move around. In 2018, in Singapore there were 957,006 registered vehicles out of which 615,452 were cars (Land Transport Authority, 2018). Consequently, less than 11% of the people living in Singapore owned a car. During the lockdown period the daily bus and train ridership decreased by more than 71% and 75%, respectively. The Singaporean Transport Authority from the 15th of April announced a that few lines were closed, however, the great majority of the bus lines, and metro trains continued to operate (Land Transport Authority, 2020). Thus, while the number of people going to work and using public transportation decreased significantly the pollution released by public transportation sector did not decrease by the same percentage.

DISCUSSION

Health Benefits of the Reduction of Air Pollutant

Particulate matter negatively affects the health of people since it can penetrate inside the lungs and those particles with a diameter smaller than 2.5 microns can even enter the blood stream. This contributes to higher risks of developing cardiovascular, respiratory diseases and lung cancer. The World Health Organization (WHO) estimates that a reduction in the annual average concentration of particulate matter (PM_{2.5}) from 35 to 10 $\mu\text{g m}^{-3}$ (WHO, 2018), reductions similar to those observed during the lockdown period, correspond to a reduction in pollution related deaths by around 15%. Consequently, the reduction in outdoor pollutants during the COVID lockdown may have had a positive impact both in the short- and long-term health of Singaporeans. We observed PM₁₀ and PM_{2.5} 24-h mean concentrations lower than the WHO recommended level which are 50 $\mu\text{g m}^{-3}$ and 25 $\mu\text{g m}^{-3}$, respectively. Moreover, the measured PM concentrations fluctuated around the recommended annual mean annual mean concentrations which are 20 $\mu\text{g m}^{-3}$ for PM₁₀ and 10 $\mu\text{g m}^{-3}$ for PM_{2.5}.

Changes in Air Quality in Southeast Asia

In southeast Asia, NO₂ levels decreased by 27, 30, 22, 34, 34% in Kuala Lumpur, Singapore, Bangkok, Jakarta, Manila based on satellite images during 10 to 24 April in 2020 comparing to the average of the same period from 2015 to 2019 (Kasturi Devi Kanniah *et al.*, 2020). The neighboring nation of Malaysia reported a national-wide

drop of PM_{2.5} between 11.3 and 23.7% during 18 March to 14 April 2020 compared to 14 to 17 March 2020 (Abdullah *et al.*, 2020). Suhaimi *et al.* (2020) showed a reduction of PM_{2.5}, NO₂, CO, and SO₂ by 3 to 36%, 43 to 68%, 1 to 48%, and 2 to 48% according to different regions between 18 March and 21 April 2020 in Malaysia (Suhaimi *et al.*, 2020). Nadzir *et al.* (2020) reported that CO concentrations decreases ranging from 40.5 to 47.5%, but PM_{2.5} levels showed a both increase and decrease according to different regions in Malaysia during the period from 18 March to 08 April 2020 (Nadzir *et al.*, 2020). In general, the reported reductions of air pollutants during the lockdown were comparable with the results we obtained. Compared to those studies in Southeast Asia, the reductions of PM_{2.5}, NO₂, and SO₂ concentrations in Singapore were higher, while the reductions in CO were lower than in the neighboring regions, respectively.

Limitation

In Singapore outdoor pollutants concentrations vary as a function of those pollutants generated within the country and those from neighboring countries. In this study, we did not account the contribution of air pollutants from neighboring countries. The lockdown periods of Singapore and other neighboring countries were overlapped with each other, which may have had a mutual impact on the air quality of this region. Another limitation of this study was that while we gathered information on mobility from various sources, we did not have sufficient data to estimate the exact reduction of vehicular traffic on the roads. We also did not have data on how much some industrial activities (e.g., port, refineries, airport, power generation) decreased during the lockdown period. Consequently, while we observed that they play a significant role in generating harmful outdoor pollutants, we were not able to correlate a decrease in emission from industrial activities with a reduction in outdoor concentrations. Finally, while we observed a significant decrease in outdoor pollutants, it would be difficult to estimate the positive health effect on the population since the great majority of the population stayed indoor during the lockdown period and was exposed to the cleaner air only for a short period of time.

CONCLUSIONS

In this study, we used nationwide data of PSI, PM₁₀, PM_{2.5}, NO₂, CO, SO₂, and O₃ from 2016 to 2020 to determine how outdoor pollutants concentrations varies

during the lockdown period (from the 7th April to the 11th May) in Singapore. Detailed spatial distribution characteristics of NO₂ and SO₂ were analyzed using data from the European Space Agency Copernicus Sentinel 5P satellite. Mobility datasets from the Singaporean Housing Development Board, Apple, and Google were used to identify the influence factors of the improvement of air quality. The main findings are listed below:

1. Nationwide, the reductions in PSI, PM₁₀, PM_{2.5}, NO₂, CO, and SO₂ were 19, 23, 29, 54, 6, and 52%, respectively, while O₃ increased by 18%.
2. The levels of PSI, PM_{2.5}, NO₂, and SO₂ decreased during the lockdown in all the five areas of Singapore, while PM₁₀ in the north and CO in the east showed opposite trends. O₃ decreased only in the west but increased in the other four areas. The southern and western areas had the most substantial reduction of air pollution in Singapore, which is due to the local spatial distribution of heavy industries and the airport.
3. The levels of PM_{2.5} and NO₂ were significantly correlated with the reduction trend of human mobility data. The reduced visits to workplaces and transit stations had the highest two correlation coefficient with PM_{2.5}, and the reduction of traffic-related mobility data, such as, car park availability and driving, correlated with NO₂.
4. The satellite data showed that the slowdown in the aviation, refining, and port activities contributed to the reduction of NO₂, SO₂ and AOD concentrations.

ACKNOWLEDGMENTS

This research was funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore.

DISCLAIMER

The authors declare that they have no conflict of interest.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <https://aaqr.org/>

REFERENCES

- Abdullah, S., Mansor, A.A., Napi, N.N.L.M., Mansor, W.N.W., Ahmed, A.N., Ismail, M. and Ramly, Z.T.A. (2020). Air quality status during 2020 Malaysia Movement Control Order (MCO) due to 2019 novel coronavirus (2019-nCoV) pandemic. *Sci. Total Environ.* 729: 139022. <https://doi.org/10.1016/j.scitotenv.2020.139022>
- Apple Inc. (2020). *COVID-19 - Mobility trends reports*. <https://www.apple.com/covid19/mobility>
- Atwood, S.A., Reid, J.S., Kreidenweis, S.M., Yu, L.E., Salinas, S.V., Chew, B.N. and Balasubramanian, R. (2013). Analysis of source regions for smoke events in Singapore for the 2009 El Nino burning season. *Atmos. Environ.* 78: 219–230. <https://doi.org/10.1016/j.atmosenv.2013.04.047>
- Benedetti, A., Morcrette, J.J., Boucher, O., Dethof, A., Engelen, R.J., Fisher, M., Flentje, H., Huneeus, N., Jones, L., Kaiser, J.W., Kinne, S., Mangold, A., Razinger, M., Simmons, A.J. and Suttie, M. (2009). Aerosol analysis and forecast in the European Centre for medium-range weather forecasts integrated forecast system: 2. Data assimilation. *J. Geophys. Res.* 114: D13205. <https://doi.org/10.1029/2008JD011235>
- Brandt, E.B., Beck, A.F. and Mersha, T.B. (2020). Air pollution, racial disparities and COVID-19 mortality. *J. Allergy Clin. Immunol.* 146: 61–63. <https://doi.org/10.1016/j.jaci.2020.04.035>
- Chen, K., Wang, M., Huang, C., Kinney, P.L. and Anastas, P.T. (2020a). Air pollution reduction and mortality benefit during the COVID-19 outbreak in China. *Lancet Planetary Health* 4: e210–e212. [https://doi.org/10.1016/S2542-5196\(20\)30107-8](https://doi.org/10.1016/S2542-5196(20)30107-8)
- Chen, Q.X., Huang, C.L., Yuan, Y. and Tan, H.P. (2020b). Influence of COVID-19 event on air quality and their association in Mainland China. *Aerosol Air Qual. Res.* 20: 1541–1551. <https://doi.org/10.4209/aaqr.2020.05.0224>
- Collivignarelli, M.C., Abbà, A., Bertanza, G., Pedrazzani, R., Ricciardi, P. and Carnevale Miino, M. (2020). Lockdown for CoViD-2019 in Milan: What are the effects on air quality? *Sci. Total Environ.* 732: 139280. <https://doi.org/10.1016/j.scitotenv.2020.139280>
- Dantas, G., Siciliano, B., França, B.B., da Silva, C.M. and Arbilla, G. (2020). The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. *Sci. Total Environ.* 729: 139085. <https://doi.org/10.1016/j.scitotenv.2020.139085>
- Dutheil, F., Baker, J.S. and Navel, V. (2020). COVID-19 as a factor influencing air pollution? *Environ. Pollut.* 263: 114466. <https://doi.org/10.1016/j.envpol.2020.114466>
- European Space Agency (2020). Sentinel-5P TROPOMI user guide. Sentinel Online. <https://sentinel.esa.int/web/sentinel/user-guides/sentinel-5p-tropomi>
- Fattorini, D. and Regoli, F. (2020). Role of the chronic air pollution levels in the COVID-19 outbreak risk in Italy. *Environ. Pollut.* 264: 114732. <https://doi.org/10.1016/j.envpol.2020.114732>
- Filonchik, M., Hurynovich, V., Yan, H., Gusev, A. and Shpilevskaya, N. (2020). Impact assessment of COVID-19 on variations of SO₂, NO₂, CO and AOD over East China. *Aerosol Air Qual. Res.* 20: 1530–1540. <https://doi.org/10.4209/aaqr.2020.05.0226>
- Google LLC. (2020). COVID-19 community mobility report. COVID-19 Community Mobility Reports. <https://www.google.com/covid19/mobility>
- Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. and Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* 202: 18–27. <https://doi.org/10.1016/j.rse.2017.06.031>

- Housing and Development Board (HDB) (2018). Annual Reports - Housing & Development Board (HDB). <https://www.hdb.gov.sg/cs/infoweb/about-us/news-and-publications/annual-reports>
- Housing and Development Board (HDB) (2020). HDB Carpark Information. Data.gov.sg. <https://data.gov.sg/dataset/hdb-carpark-information>
- Huijnen, V., Eskes, H.J., Wagner, A., Schulz, M., Christophe, Y., Ramonet, M., Basart, S., Benedictow, A., Blechschmidt, A.M., Chabrillat, S., Clark, H., Cuevas, E., Flentje, H., Hansen, K.M., Im, U., Kapsomenakis, J., Langerock, B., Richter, A., Sudarchikova, N. and Thouret, V. (2016). Validation report of the CAMS near-real-time global atmospheric composition service: System evolution and performance statistics. Status up to 1 June 2016. [https://pure.au.dk/portal/en/persons/ulas-im\(e2356d82-8e7b-49c9-b660-76e719a4058e\)/publications/validation-report-of-the-cams-nearrealtime-global-atmospheric-composition-service-system-evolution-and-performance-statistics-status-up-to-1-june-2016\(d3511b2f-b56a-4fe5-9400-1e469b1de93f\).html](https://pure.au.dk/portal/en/persons/ulas-im(e2356d82-8e7b-49c9-b660-76e719a4058e)/publications/validation-report-of-the-cams-nearrealtime-global-atmospheric-composition-service-system-evolution-and-performance-statistics-status-up-to-1-june-2016(d3511b2f-b56a-4fe5-9400-1e469b1de93f).html)
- Jiang, Y., Wu, X.J. and Guan, Y.J. (2020). Effect of ambient air pollutants and meteorological variables on COVID-19 incidence. *Infect. Control Hosp. Epidemiol.* 1–5. <https://doi.org/10.1017/ice.2020.222>
- Kanniah, K.D., Zaman, N.A.F.K., Kaskaoutis, D.G. and M.T. (2020). COVID-19's impact on the atmospheric environment in the Southeast Asia region. *Sci. Total Environ.* 736: 139658. <https://doi.org/10.1016/j.scitotenv.2020.139658>
- Kerimray, A., Baimatova, N., Ibragimova, O.P., Bukenov, B., Kenessov, B., Plotitsyn, P. and Karaca, F. (2020). Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan. *Sci. Total Environ.* 730: 139179. <https://doi.org/10.1016/j.scitotenv.2020.139179>
- Kramer, H.J. (2002). *Observation of the Earth and its environment: Survey of missions and sensors*, Springer-Verlag, Berlin Heidelberg.
- Lal, P., Kumar, A., Kumar, S., Kumari, S., Saikia, P., Dayanandan, A., Adhikari, D. and Khan, M.L. (2020). The dark cloud with a silver lining: Assessing the impact of the SARS COVID-19 pandemic on the global environment. *Sci. Total Environ.* 732: 139297. <https://doi.org/10.1016/j.scitotenv.2020.139297>
- Land Transport Authority (2018). Annual Vehicle Statistics 2018.
- Land Transport Authority (2020). Changes to public bus and train operating hours and frequency. https://www.lta.gov.sg/content/ltgov/en/newsroom/2020/april/news-releases/Changes_to_public_bus_and_train_operating_hours.html
- Le, T., Wang, Y., Liu, L., Yang, J., Yung, Y.L., Li, G. and Seinfeld, J.H. (2020). Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. *Science* 2020: eabb7431 <https://doi.org/10.1126/science.abb7431>
- Li, J., Wan, M.P., Schiavon, S., Tham, K.W., Sultan, Z., Xiong, J., Fang, M. and Gall, E. (2020). Size-resolved dynamics of indoor and outdoor fluorescent biological aerosol particles in a bedroom: A one-month case study in Singapore. *Indoor Air* <https://doi.org/10.1111/ina.12678>
- Lim, L.W., Yip, L.W., Tay, H.W., Ang, X.L., Lee, L.K., Chin, C.F. and Yong, V. (2020). Sustainable practice of ophthalmology during COVID-19: challenges and solutions. *Graefes Arch. Clin. Exp. Ophthalmol.* 258: 1427–1436. <https://doi.org/10.1007/s00417-020-04682-z>
- Meteorological Service Singapore (MSS) (2018). *Annual climatological report 2018*. <http://www.weather.gov.sg/wp-content/uploads/2019/03/Annual-Climatological-Report-2018.pdf>
- Ministry of Health (2020a). Confirmed imported case of novel coronavirus infection in Singapore. <https://www.moh.gov.sg/news-highlights/details/confirmed-imported-case-of-novel-coronavirus-infection-in-singapore-multi-ministry-taskforce-ramps-up-precautionary-measures>
- Ministry of Health (2020b). circuit breaker to minimise further spread of COVID-19. <https://www.moh.gov.sg/news-highlights/details/circuit-breaker-to-minimise-further-spread-of-covid-19>
- Ministry of Health (2020c). Easing the tighter circuit breaker measures, preparing for gradual resumption of activity after 1 June. <https://www.moh.gov.sg/news-highlights/details/easing-the-tighter-circuit-breaker-measures-preparing-for-gradual-resumption-of-activity-after-1-june>
- Morcrette, J.J., Boucher, O., Jones, L., Salmond, D., Bechtold, P., Beljaars, A., Benedetti, A., Bonet, A., Kaiser, J.W., Razinger, M., Schulz, M., Serrar, S., Simmons, A.J., Sofiev, M., Suttie, M., Tompkins, A.M. and Untch, A. (2009). Aerosol analysis and forecast in the European Centre for medium-range weather forecasts integrated forecast system: Forward modeling. *J. Geophys. Res.* 114: D06206. <https://doi.org/10.1029/2008JD011235>
- Muhammad, S., Long, X. and Salman, M. (2020). COVID-19 pandemic and environmental pollution: A blessing in disguise? *Sci. Total Environ.* 728: 138820. <https://doi.org/10.1016/j.scitotenv.2020.138820>
- Myllyvirta, L. (2020). 11,000 air pollution-related deaths avoided in Europe as coal, oil consumption plummet. Centre for Research on Energy and Clean Air. <https://energyandcleanair.org/air-pollution-deaths-avoided-in-europe-as-coal-oil-plummet/>
- Nadzir, M.S.M., Ooi, M.C.G., Alhasa, K.M., Bakar, M.A.A., Mohtar, A.A.A., Nor, M.F.F.M., Latif, M.T., Hamid, H.H.A., Ali, S.H.M., Ariff, N.M., Anuar, J., Ahamad, F., Azhari, A., Hanif, N.M., Subhi, M.A., Othman, M. and Nor, M.Z.M. (2020). The impact of Movement Control Order (MCO) during pandemic COVID-19 on local air quality in an urban area of Klang Valley, Malaysia. *Aerosol Air Qual. Res.* 20: 1237–1248. <https://doi.org/10.4209/aaqr.2020.04.0163>
- National Environment Agency (2011). Executive summary report of the advisory committee on ambient air quality. <https://www.nea.gov.sg/docs/default-source/our-services/pollution-control/air-pollution/air-quality/executive-summary.pdf>
- National Environment Agency (2014). Computation of the

- Pollutant Standards Index (PSI). [https://www.haze.gov.sg/docs/default-source/faq/computation-of-the-pollutant-standards-index-\(psi\).pdf](https://www.haze.gov.sg/docs/default-source/faq/computation-of-the-pollutant-standards-index-(psi).pdf)
- National Environment Agency (2020a). Air quality in Singapore. <https://www.nea.gov.sg/our-services/pollution-control/air-pollution/air-quality>
- National Environment Agency (2020b). Realtime weather readings across Singapore. Data.gov.sg. <https://data.gov.sg/dataset/realtime-weather-readings>
- National Environment Agency (2020c). Pollutant standards index. (PSI) Data.gov.sg. <https://data.gov.sg/dataset/psi>
- National Environment Agency (2020d). The national environment agency. <https://www.nea.gov.sg/index>
- Ng, N.M. (2020). Things you need to know about Singapore's "circuit breaker" measures. Time Singap. <https://www.timeout.com/singapore/things-to-do/things-you-need-to-know-about-singapores-circuit-breaker-measures>
- Ogen, Y. (2020). Assessing nitrogen dioxide (NO₂) levels as a contributing factor to coronavirus (COVID-19) fatality. *Sci. Total Environ.* 726: 138605. <https://doi.org/10.1016/j.scitotenv.2020.138605>
- Otmani, A., Benchrif, A., Tahri, M., Bounakhla, M., Chakir, E.M., El Bouch, M. and Krombi, M. (2020). Impact of COVID-19 lockdown on PM₁₀, SO₂ and NO₂ concentrations in Salé City (Morocco). *Sci. Total Environ.* 735: 139541. <https://doi.org/10.1016/j.scitotenv.2020.139541>
- Pani, S.K., Lin, N.H. and RavindraBabu, S. (2020). Association of COVID-19 pandemic with meteorological parameters over Singapore. *Sci. Total Environ.* 740: 140112. <https://doi.org/10.1016/j.scitotenv.2020.140112>
- Pung, R., Chiew, C.J., Young, B.E., Chin, S., Chen, M.I.C., Clapham, H.E., Cook, A.R., Maurer-Stroh, S., Toh, M.P.H.S., Poh, C., Low, M., Lum, J., Koh, V.T.J., Mak, T.M., Cui, L., Lin, R.V.T.P., Heng, D., Leo, P.Y.S., Lye, D.C., ... Ang, L.W. (2020). Investigation of three clusters of COVID-19 in Singapore: Implications for surveillance and response measures. *Lancet* 395: 1039–1046. [https://doi.org/10.1016/S0140-6736\(20\)30528-6](https://doi.org/10.1016/S0140-6736(20)30528-6)
- Safarian, S., Unnthorsson, R. and Richter, C. (2020). Effect of coronavirus disease 2019 on CO₂ emission in the world. *Aerosol Air Qual. Res.* 20: 1197–1203. <https://doi.org/10.4209/aaqr.2020.04.0151>
- Sciomer, S., Moscucci, F., Magrì, D., Badagliacca, R., Piccirillo, G. and Agostoni, P. (2020). SARS-CoV-2 spread in Northern Italy: What about the pollution role? *Environ. Monit. Assess.* 192: 325. <https://doi.org/10.1007/s10661-020-08317-y>
- Sicard, P., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paoletti, E., Rodriguez, J.J.D. and Calatayud, V. (2020). Amplified ozone pollution in cities during the COVID-19 lockdown. *Sci. Total Environ.* 735: 139542. <https://doi.org/10.1016/j.scitotenv.2020.139542>
- Suhaimi, N.F., Jalaludin, J. and Latif, M.T. (2020). Demystifying a possible relationship between COVID-19, air quality and meteorological factors: Evidence from Kuala Lumpur, Malaysia. *Aerosol Air Qual. Res.* 20: 1520–1529. <https://doi.org/10.4209/aaqr.2020.05.0218>
- Velasco, E. and Rastan, S. (2015). Air quality in Singapore during the 2013 smoke-haze episode over the Strait of Malacca: Lessons learned. *Sustain. Cities Soc.* 17: 122–131. <https://doi.org/10.1016/j.scs.2015.04.006>
- Wong, J.E.L., Leo, Y.S. and Tan, C.C. (2020). COVID-19 in Singapore—current experience: Critical global issues that require attention and action. *JAMA* 323: 1243–1244. <https://doi.org/10.1001/jama.2020.2467>
- World Health Organization (WHO) (2006). *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global update 2005: Summary of risk assessment*. World Health Organization, Geneva.
- World Health Organization (WHO) (2018). Ambient (outdoor) air pollution. [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)
- Xu, K., Cui, K., Young, L.H., Hsieh, Y.K., Wang, Y.F., Zhang, J. and Wan, S. (2020). Impact of the COVID-19 event on air quality in central China. *Aerosol Air Qual. Res.* 20: 915–929. <https://doi.org/10.4209/aaqr.2020.04.0150>
- Yao, M., Zhang, L., Ma, J. and Zhou, L. (2020). On airborne transmission and control of SARS-Cov-2. *Sci. Total Environ.* 731: 139178. <https://doi.org/10.1016/j.scitotenv.2020.139178>

Received for review, June 11, 2020

Revised, July 2, 2020

Accepted, July 16, 2020