Impact of COVID-19 pandemic lockdown on air pollution in 20 major cities around the world

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Abstract

In order to fight against the spread of COVID-19, the most hard-hit countries in the spring of 2020 implemented different lockdown strategies. To assess the impact of the COVID-19 pandemic lockdown on air quality worldwide, we use Air Quality Index (AQI) data to estimate the AQI change in 20 major cities on six continents. Our results show significant declines of AQI in NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} in most cities, mainly due to the reduction of transportation, industry and commercial activities during lockdown. This work shows the reduction of primary pollutants, especially NO_2, is mainly due to lockdown policies. However, preexisting local environmental policy regulations also contributed to declining NO_2, SO_2 and $PM_{2.5}$ emissions, especially in Asian countries. In addition, higher rainfall during the lockdown period could cause decline of PM2.5, especially in Johannesburg. By contrast, the changes of AQI in ground-level O_3were not significant in most of cities, as meteorological variability and ratio of VOC/NO_x are key factors in ground-level O_3 formation.

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Key Points:

- We analyzed the change in Air Quality Index for major air pollutants during the COVID-19 lockdown periods in 20 major cities worldwide.
- NO_2, SO_2, CO and PM significantly declined in most cities, but ground-level O_3 increased in most cities.
- Recent policies to reduce air pollution contributed to declining AQI prior to the COVID-19 lockdowns in some cities.

Plain Language Summary

At the beginning of 2020, the COVID-19 pandemic lockdown caused restriction of human mobility and reduction of industrial activities in most countries worldwide. The strictness of lockdown policies varied in different countries. In order to estimate the impact of COVID-19 lockdown on air quality around the world, we use AQI data from aqicn.org to estimate the air quality change in 20 major cities on six continents. We find that AQI in NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} declined significantly in most cities, because of the reduction of their emissions and gaseous precursers during lockdown. This reduction of primary pollutants, especially NO_2, was mainly caused by strictness of lockdown policies, but preexisting local environmental policy regulations and meteorological variability is also be responsible. Contrary to other pollutants, the changes of AQI in ground-level O_3 were not significant in most cities, as in ground-level O_3 formation depends on different factors.

Abstract

In order to fight against the spread of COVID-19, the most hard-hit countries in the spring of 2020 implemented different lockdown strategies. To assess the impact of the COVID-19 pandemic lockdown on air quality worldwide, we use Air Quality Index (AQI) data to estimate the AQI change in 20 major cities on six continents. Our results show significant declines of AQI in NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} in most cities, mainly due to the reduction of transportation, industry and commercial activities during lockdown. This work shows the reduction of primary pollutants, especially NO_2, is mainly due to lockdown policies. However, preexisting local environmental policy regulations also contributed to declining NO_2, SO_2 and $PM_{2.5}$ emissions, especially in Asian countries. In addition, higher rainfall during the lockdown period could cause decline of PM2.5, especially in Johannesburg. By contrast, the changes of AQI in ground-level O_3 were not significant in most of cities, as meteorological variability and ratio of VOC/NO_x are key factors in ground-level O_3 formation.

1 Introduction

The majority of the world's major cities suffer from serious air pollution issues, leading to more than two million deaths globally through damage to the lungs and the respiratory system (Shah et al., 2013). The International Agency for Research on Cancer (IARC) has classified air pollution as Carcinogenic to Humans (Group 1), as studies show exposure to outdoor air pollution causes lung cancer (IRAC, 2013). The common pollutants of concern are nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), ground-level ozone (O_3), and particulate matter ($PM_{2.5}$ and PM_{10}). NO_2, SO_2, PM, and O_3 all cause respiratory diseases that reduce lung function, particularly in vulnerable populations with pulmonary disease or asthma (Halonen et al., 2009; WHO, 1995; Johns & Linn, 2011). CO and $PM_{2.5}$ cause cardiovascular impairment, and prolonged or acute exposure to CO can lead to death (Raub et al., 2000). Because of these severe health issues associated with air pollution, these six criteria pollutants are measured in many countries. If the concentration of these air pollutants is high enough to impact human heath, this can lead to governmental action plans and policies to control pollutant discharge and improve the air quality.

While air pollution is released from a wide variety of natural and anthropogenic activities (Poschl, 2005), primary pollutants are directly emitted into air. NO_2, SO_2 and CO are mainly from anthropogenic activities globally (Huang et al., 2017; Chin et al. 2000; Zhong et al., 2016).

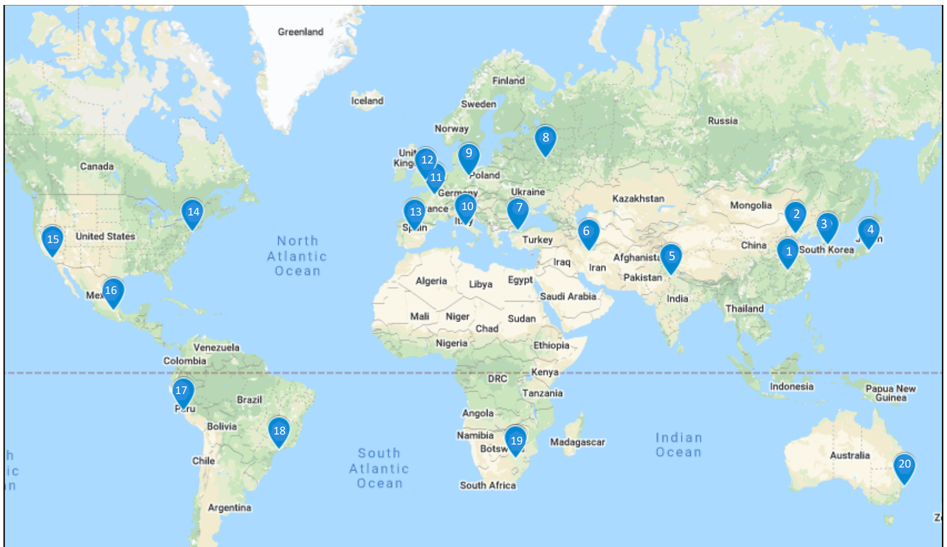
Among anthropogenic sources, transportation and combustion in power plants are the primary and secondary sources of NO_2 (US EPA, 2020; Airparif, 2016; GLA, 2017) and CO (US EPA, 2020; Gurjar & Nagpure, 2015). However, the main source of SO_2 is generally combustion of coal in power plants and the manufacturing industries (US EPA, 2020; EMEP/CEIP, 2019). Ground-level O_3 is a secondary pollutant formed in the air by a series of photochemical reactions, the key factors are sunlight, NO_x and a variety of volatile organic compounds (VOCs). Primary particulate matter is directly released into the atmosphere by natural and anthropogenic activities, while secondary particles are formed in the atmosphere from other precursor pollutants, such as SO_2, NO_2, NH_3 and VOCs. In urban areas, anthropogenic sources of PM_{10} (aerodynamic diameter ≤ 10μm) and $PM_{2.5}$ (aerodynamic diameter ≤ 2.5μm) dominate, and the major sources are residential combustion, large-scale combustion (i.e., power plants), industrial processes, agriculture and transportation (road and non-road) (Klimont et al., 2017).

In December 2019, cases of pneumonia of "unknown etiology" were first identified in Wuhan, China (Lu et al., 2020). On February 11, 2020, the World Health Organization (WHO) announced an official name "COVID-19" (coronavirus disease 2019) for this epidemic disease. After the first outbreak in Wuhan, several community outbreaks occurred in February in countries outside of China, such as South Korea, Italy, Germany and Spain. In early 2020, the epicenter moved from Asia to Europe, and then to the Americas by March. In order to mitigate the infection rate of COVID-19, many countries applied different lockdown strategies. Lockdown measures included partial or full closure of international borders, schools, non-essential business and citizen mobility restriction (Pepe et al., 2020). The reduction of transportation, commercial and industrial activities due to these lockdown strategies has the potential to reduce the emissions of primary pollutants and change the formation rate of secondary pollutants, due to the change of precursor emissions.

Recent studies suggested that lockdown measures contributed to improvements in air quality. For example, the concentration of NO_2 decreased between January and April 2020 in many Chinese cities, in Western Europe, and in the United States relative to the same period in 2019 (Bauwens et al. 2020) and $PM_{2.5}$ levels decreased in China in February compared to the same period of 2017, 2018 and 2019 (Zambrano-Monserrate et al., 2020). In contrast, the concentration of ground-level ozone increased compared to the same period of 2019 in Sao Paulo, Brazil (Nakada and Urban, 2020). However, these studies focused on analysis of only a few pollutants or focused on limited locations. Thus, in order to provide a more comprehensive analysis of the impact of lockdowns on critical air pollutants, and to assess the impact of different lockdown strategies on air pollution, we examined air quality in 20 major cities worldwide.

2 Materials and Methods

2.1 City selection



1 Wuhan	2 Beijing	3 Seoul	4 Tokyo	5 Delhi	6 Tehran	7 Istanbul	8 Moscow	9 Berlin	10 Rome
11 Paris	12 Madrid	13 London	14 NYC	15 LA	16 Mexico City	17 Lima	18 Sao Paulo	19 Johannesburg	20 Sydney

Figure 1. Twenty major cities impacted by COVID-19 that applied lockdown or social distancing policies around the world.

We selected 20 major cities (Figure 1) representing all continents except Antarctica, including seventeen cities in the most hard-hit countries: Wuhan, Beijing (China), Delhi (India), Tehran (Iran), Istanbul (Turkey) in Asia; Rome (Italy), Madrid (Spain), Paris (France), London (UK), Berlin (Germany) and Moscow (Russia) in Europe; Johannesburg (South Africa) in Africa and Los Angeles, New York City (USA), Mexico city (Mexico), Sao Paulo (Brazil) and Lima (Peru) in North and South America. We also examined three major cities in countries less hard-hit by COVID-19 to provide a more comprehensive examination: Seoul (South Korea), Tokyo (Japan) in Asia; Sydney (Australia) in Oceania.

2.2 Air quality data

After the outbreak of COVID-19, the World's Air Pollution, Real-time Air Quality Index (WAQI project) started to provide a new dedicated, dataset specific for COVID-19 related research, covering approximately 380 major cities throughout the world (aqicn.org/data-platform/COVID19/). The World Air Quality project is a non-profit started in 2007 to provide air quality information for more than 100 countries, covering more than 30,000 stations (local governmental/professional monitoring network) in 1,000 major cities. The data for each major city is based on the median of several stations. The data set provides min, max, median and standard deviation for each of the air pollutant species when available. In this dataset, all air pollutant species are converted to an Air Quality Index (AQI) with the U.S. Environmental Protection Agency (EPA) standard calculation.

The AQI is a dimensionless index that quantitatively describes air quality conditions based on standards of each pollutant, which provides a comprehensive evaluation on the combined effects of the six criteria pollutants (NO_2, SO_2, CO, ground-level O_3, $PM_{2.5}$ and PM_{10}). The AQI is classified into six grades calculated from the concentrations of various pollutants, i.e., AQI: 0–50 (Good), 51–100 (Moderate), 101–150 (Unhealthy for Sensitive Groups), 151–200 (Unhealthy), 201–300 (Very Unhealthy), and > 300 (Hazardous).

2.3 Lockdown data

We used various sources, such as media and official government websites and research papers, to define the lockdown period for each of the cities of interest. It should be noted that it's counted from the beginning of lockdown or strict social distancing policy to the date the lockdown started to ease (Table 1), as the reopening is a complex process and could include several steps. In order to compare AQI data during the lockdown period to historical data, we also used the same period of data for 2017, 2018 and 2019. The average AQI of each pollutant was compared to the previous year (2019) and to the 3-year average of the same period to calculate the decrease or increase of each pollutant.

Table 1. Start and end of lockdown period and lockdown policies in 20 selected major cities.

City	Country	Lockdown		Lockdown Policy
		From	To	
Wuhan	China	23-Jan	7-Apr	Full city lockdown with strictest human mobility restrictions, public transportation stopped
Delhi	India	24-Mar	31-May	Full nationwide lockdown, only those who work for "essential services" can move freely, public transportation stopped
Lima	Peru	15-Mar	30-Jun	Nationwide lockdown with gender-based mobility restriction
Madrid	Spain	14-Mar	4-May	Nationwide lockdown, outdoor physical exercise banned
Tehran	Iran	13-Mar	17-Apr	Nationwide lockdown, shops, streets and roads cleared
Moscow	Russia	30-Mar	8-Jun	Nationwide lockdown, digital pass required for car or public transport use
Rome	Italy	9-Mar	3-May	Nationwide lockdown, only allowed to go out alone near home
Paris	France	17-Mar	10-May	Nationwide Lockdown, permit required for going out
London	U.K.	23-Mar	10-May	Nationwide lockdown, only go outside to buy food, to exercise once a day, or go to work if they absolutely cannot work from home
Johannesburg	South Africa	26-Mar	30-Apr	National lockdown, with severe restrictions on travel and movement
Sydney	Australia	23-Mar	27-Apr	National lockdown, stay-at-home except for essential outings
Beijing	China	10-Feb	27-Mar	Partial lockdown, ordering residential communities and villages to limit access for outsiders
New York City	U.S.A	22-Mar	7-Jun	Statewide stay-at-home order
Los Angeles	U.S.A	19-Mar	7-May	Statewide stay-at-home order, social pressure for violations
Mexico City	Mexico	23-Mar	30-May	Statewide lockdown, closing gyms, museums and clubs, banning big gathering, restricting mobility to areas less affected from April 16
Sao Paulo	Brazil	24-Mar	10-May	Statewide/partial lockdown, social distancing measures
Berlin	Germany	17-Mar	19-Apr	Partial lockdown, with rules differing across states. Only go out alone or with a person from same household.
Seoul	South Korea	24-Feb	6-May	No strict lockdown, social distancing applied, no movement restriction
Tokyo	Japan	7-Apr	24-May	State of emergency, encouraged social distancing
Istanbul	Turkey	21-Mar	10-May	Weekend curfew

2.4 Climate data

In order to assess the impact of weather condition on the air quality, we used climate data form the Global Historical Climatology Network - Daily (GHCN-Daily) dataset (www.ncdc.noaa.gov/cdo-web/). This network includes daily land surface observations from around the world. The GHCN-Daily was developed to meet the needs of climate analysis and monitoring studies that require data on a sub-monthly time resolution. The dataset includes observations from the World Meteorological Organization, Cooperative, and CoCoRaHS (Community Collaborative Rain, Hail and Snow) networks.

We used daily rainfall and daily average temperature for the lockdown period of 2020 and the same period of 2019 from the GHCN-Daily dataset. The average temperature was not available for Los Angeles (LA), New York City (NYC) and Sydney, so we used the maximum temperature, as the maximum temperature is important for ozone formation. For Moscow, Mexico City and Berlin, the climate data was not complete; for instance, Moscow had no data for April and May of 2020 and Mexico City was missing 15 days of data in May. We used data from the weather underground website (https://www.wunderground.com) instead of GHCN data for those three locations. From both sources, there is no data for rainfall for Moscow, Mexico City and Berlin. The information about the location (name or/and number of the station) can be found in Suplementary Table S1.

3 Results

3.1 Primary pollutants: NO_2, SO_2 and CO

NO_2 AQI decreased for all cities during the lockdown period, relative to 2019 and the past 3 years average for the same period (Table 2, Figure 2). NO_2 AQI declined in all cities with the highest decrease (60%) in Delhi and the lowest (11.1%) in Sydney in comparison to 2019, and decreased the most (63.3%) in Wuhan and the least in Sydney (15.5%) relative to an average of the past three years. According to ANOVA and Tukey HSD tests with 95% confidence, the decreases were statistically significant for all cities, meaning the 2020 AQI was significantly different to each of past 3 years, expect for Berlin, Tokyo, Istanbul and Sydney. NO_2 continuously decreased from 2017 to 2020 in all Asian cities: Beijing, Wuhan, Tokyo, Istanbul and in South American cities: Lima and Mexico City (Figure 2). This trend of decreasing NO_2 AQI in these cities (that existed prior to 2019) contributed to the small difference between the 2017-2019 average and 2019 value.

Table 2. Percentage (%) decrease in AQI for NO_2, SO_2, CO, ground-level O_3, $PM_{2.5}$, and PM_{10} during lockdown period in 2020 compared to average of 2017-2019, and to 2019 single year for the same period in 20 major cities in the world

Continent	City	Country	NO_2		SO_2		CO		Ground-level O_3		$PM_{2.5}$		PM_{10}	
			To 17-19	To 19	To 17-19	To 19	To 17-19	To 19	To 17-19	To 19	To 17-19	To 19	To 17-19	To 19
Asia	Wuhan	China	**63.3**	**58.3**	28.6	11.2	**17.3**	**13.8**	**+45.6**	**+54.2**	**26.2**	**23.2**	**31.9**	**30.4**
	Beijing		**41.8**	**33.7**	60.3	33.5	7.1	**+92.4**	+10.7	+5.1	15.2	7.2	+0.1	14.8
	Seoul	South Korea	**28.0**	**25.8**	**28.3**	**20.8**	**14.5**	**14.6**	+10.9	+10.2	**21.2**	**19.1**	8.8	+19.5
	Tokyo	Japan	25.8	19.5	**37.6**	**28.1**	3.1	+7.3	5.3	6.7	22.9	11.4	24.1	11.0
	Delhi	India	**57.7**	**60**	**23.7**	**31.7**	22.8	**34.0**	+19.3	**+36.3**	**31.0**	**27.6**	**47.9**	**45.9**
	Tehran*	Iran	NA	**35.2**	NA	NA	NA	NA	NA	NA	NA	**21.9**	NA	**37.9**
	Istanbul	Turkey	36.5	19.9	**+53.8**	**+29.3**	+48.5	+2.9	**8.3**	**43.6**	19.1	3.4	**22.4**	**19.0**
Europe	Moscow†	Russia	**35.8**	**39.8**	**25.5**	**25.8**	**18.8**	**18.7**	NA	+6.4	12.7	**25.9**	29.6	**42.5**
	Berlin	Germany	45.0	17.6	NA	**+29.5**	NA	NA	+16.4	+3.9	**27.4**	**22.5**	15.1	10.3
	Rome	Italy	**45.0**	**36.4**	8.6	3.8	NA	NA	+4.4	+2.9	+0.1	+8.3	6.6	1.8
	Paris	France	**47.8**	**46.4**	20.5	+13.5	NA	NA	**+24.0**	**+26.8**	4.5	13	14.7	22.3
	Madrid	Spain	**56**	**51.6**	+7.1	**54.8**	NA	NA	4.9	9.9	2.4	1.6	17.2	19.8
	London	U. K	**39.6**	**37.8**	+1.3	+0.6	**35.0**	**53.5**	**+47.7**	**+48.0**	8.8	14	4.7	10
North America	New York City#	U. S	**33.7**	**27.5**	NA	NA	**22.0**	**20.7**	+1.0	6.3	**30.8**	**27.6**	NA	NA
	Los Angeles		**29.0**	**24.2**	NA	NA	36.9	7.2	11.7	3.5	20.4	13.7	18.1	+2.0
	Mexico City	Mexico	**35.2**	**24.9**	14.9	+2.2	1.2	+4.0	+7.9	0.1	3.7	**8.3**	8.8	**15.5**
South America	Lima‡	Peru	**63.4**	**50.5**	18.1	**35.2**	**58.6**	**61.8**	28.5	**42.9**	**27.1**	**19.4**	**42.3**	**31.7**
	Sao Paulo	Brazil	**36.0**	**37.8**	**27.3**	**23.2**	**31.8**	**32.7**	**+33.9**	**+24.9**	11.3	**18.3**	5.4	12.9
Africa	Johannesburg§	South Africa	NA	**23.0**	NA	13.9	NA	5.0	NA	+9.0	NA	**31.3**	NA	**33.1**
Oceania	Sydney	Australia	15.0	11.1	NA	NA	**25.5**	**24**	+5.2	+5.6	**34.7**	**29.2**	19.7	**17.0**

Bold red: the change is statistically significant ($p < 0.05$) relative to 2019 or to at least one of the 3 past years, according to ANOVA and Tukey HSD tests. +: increase of AQI. *: No available data in 2019, the comparison was made with 2018. †: the start date is April 3rd instead of March 30th according to the data availability. ‡: the start date is March 29th instead of March 15th according to the data availability. **§:** no available data in 2017 and 2018, only compared to 2019. #: Manhattan area of New York City.

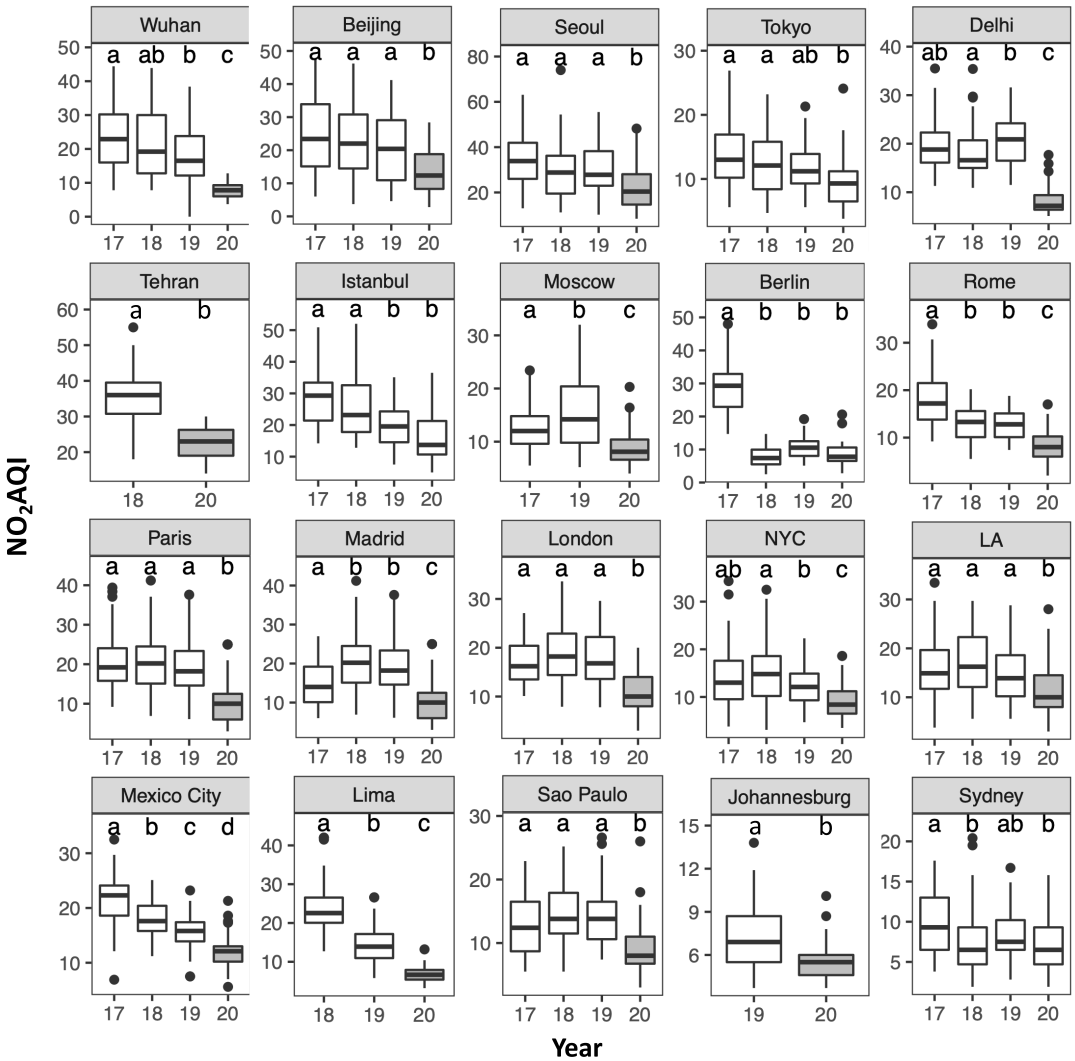


Figure 2. NO_2 AQI in 20 worldwide cities during the lockdown period in 2020 compared to the same period of 2017, 2018 and 2019. Line within the box: the median, box: first and third quartiles, whiskers: non-outlier range, dot: outliers. Years sharing the same letter mean AQI is not significantly different ($p>0.05$). The grey box for 2020: the change in 2020 is significant relative to every previous year.

The SO_2 AQI decreased significantly in 7 cities, compared to each of past 3 years (Table 2). The highest decrease (54.8%) occurred in Madrid relative to 2019, due to a much higher SO_2 level in 2019, for which the cause is unknown. However, as the AQI in 2020 was not statistically different in comparison to those of 2017 and 2018, we suggest that the SO_2 level was stable in Madrid. We also found a significant increase of SO_2 AQI in Istanbul (+29.3%) and Berlin

(+29.5%) (Table 2). For other cities, the changes were not statistically significant, or there was no available data.

Limited CO AQI data was available in the World Air Quality Index project data set. For cities with CO data, the CO AQI decreased significantly in 8 of 15 cities (Table 2), with the maximum decrease in Lima (60%) relative to 2019. In 6 other cities, the AQI changes were not statistically significant, compared to each of past 3 years. In Beijing, where we observed a much higher increase of CO AQI relative to 2019, by excluding the abnormally and unexplained low 2019 concentrations, the level of CO decreased by 26.2% relative to 2017 and 2018.

3.2 Secondary pollutants: Ground-level O_3

Contrary to the trends of decreasing primary pollutants, ground-level O_3 AQI increased (+2.9 - +54.2%) in 12 cities and decreased (0.1 - 43.6%) in the other 7 (no data in Tehran) during the lockdown period for each city relative to 2019 (Table 2 and Figure 3). Comparing each of the past 3 years using an ANOVA with Tukey HSD test, the O_3 significantly increased in Wuhan, Paris, London and Sao Paulo, and significantly decreased in Istanbul. For other cities, the changes were not statistically significant. Wuhan experienced the maximum increase (+54.2%) and Istanbul experienced the maximum decrease (43.6%). Lima also experienced a large decrease (42.9%) relative to 2019, because of the dramatically higher ozone concentration in 2019 than other years (Figure 3). However, the AQI level in 2020 is statistically insignificant in comparison to 2018's level.

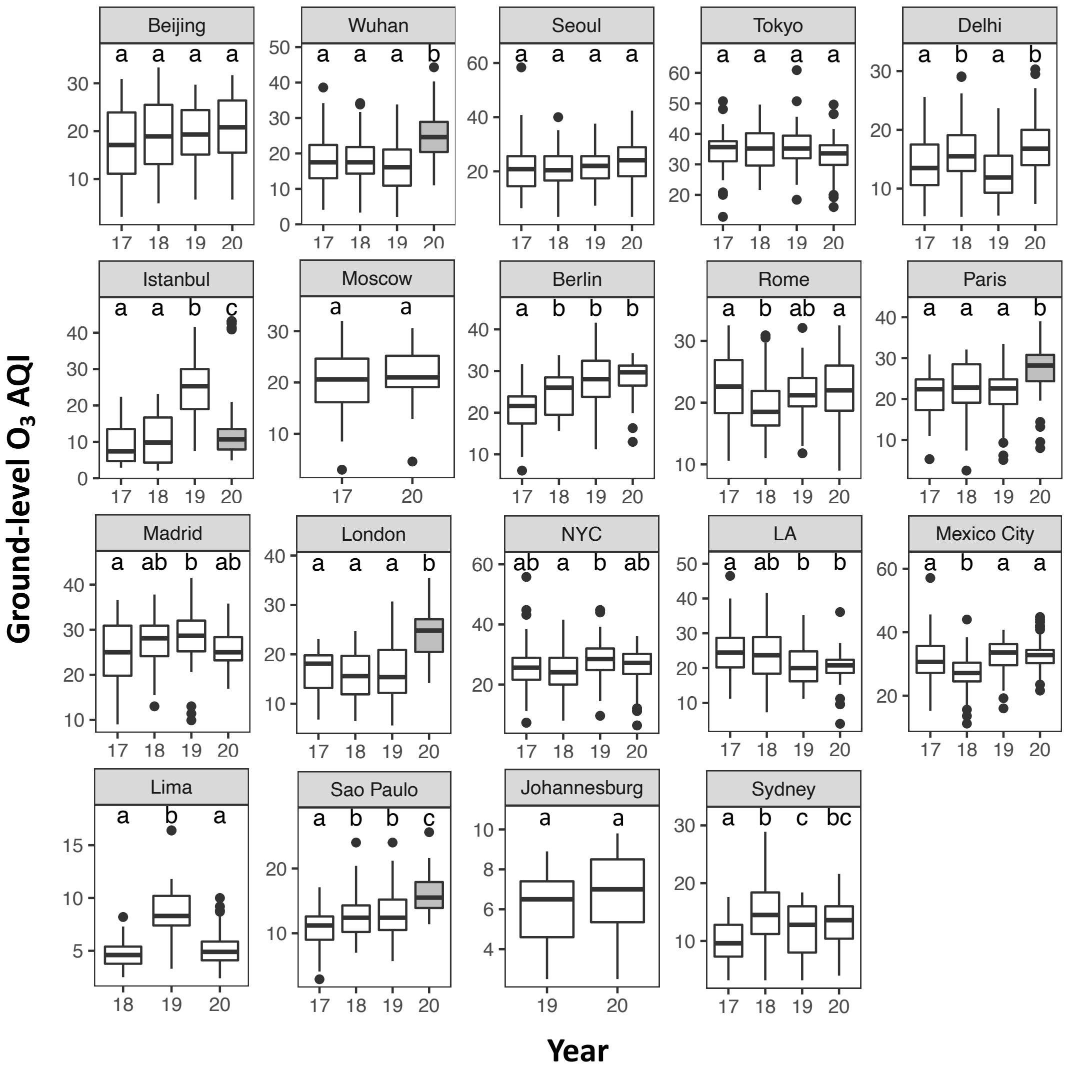


Figure 3. Ground-level ozone AQI in selected worldwide cities during the lockdown period in 2020 compared to the same period of 2017, 2018 and 2019. Line within the box: the median, box: first and third quartiles, whiskers: non-outlier range, dot: outliers. Years sharing the same letter mean not significantly different ($p>0.05$). The grey box for 2020: the change in 2020 is significant relative to every previous year.

3.3 Particulate matter: $PM_{2.5}$ and PM_{10}

$PM_{2.5}$ AQI decreased in all cities (Table 2 and Figure 4), except in Rome with an increase of +8.3%) during the lockdown period relative to 2019 and the 2017-2019 reference, with the maximum decrease in Johannesburg (31.3%) relative to 2019. The decreases are statistically significant in 12 cities relative to 2019, and in 9 cities compared to each of the past 3 years. For other cities, the changes are not statistically significant (see Table 2 and Figure 4). PM_{10} also decreased in all cities, except in Seoul and Los Angeles (insignificant increases), with the maximum decrease in Delhi (45.9%) relative to 2019. The decreases are statistically significant in 9 of 19 cities relative to 2019, and in 4 of 17 cities compared to each of the past 3 years (see Table 2, Figure S3).

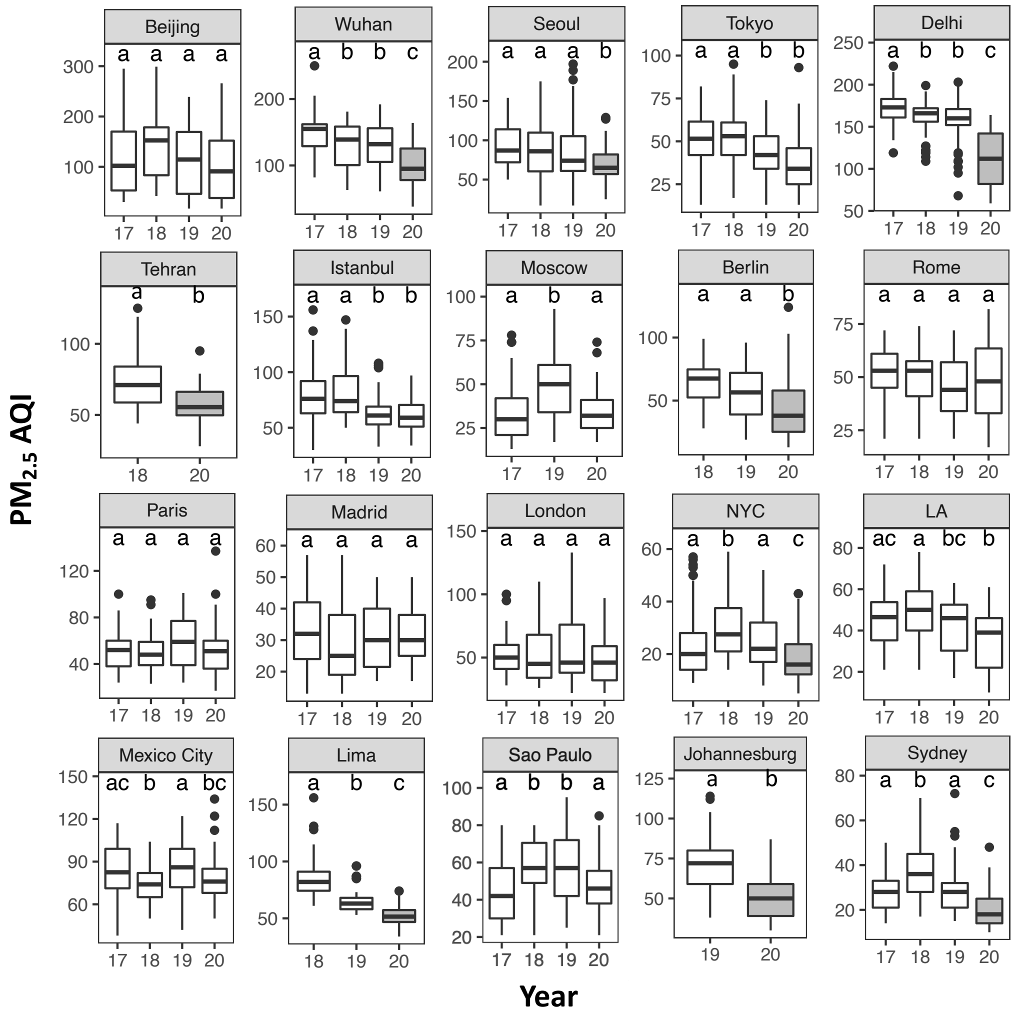


Figure 4. $PM_{2.5}$ AQI in selected worldwide cities during the lockdown period in 2020 compared to the same period of 2017, 2018 and 2019. Line within the box: the median, box: first and third quartiles, whiskers: non-outlier range, dot: outliers. Years sharing the same letter mean not significantly different (p>0.05). The grey box for 2020: the change in 2020 is significant relative to every previous year.

3.4 Temperature and rainfall

Temperatures in 2020 are significantly higher than that observed in 2019 for Moscow and Paris, and significantly lower in 2020 for Delhi, Tehran, NYC and Sao Paulo, with the largest temperature decrease of 2.5 °C in Sao Paulo (Figure 5). For other cities, the temperature changes in 2020 relative to 2019 were not statistically significant. Rainfall was more than two times higher in 2020 than 2019 in Beijing, Istanbul, Johannesburg, LA, Rome, Tokyo and Wuhan (Figure 5).

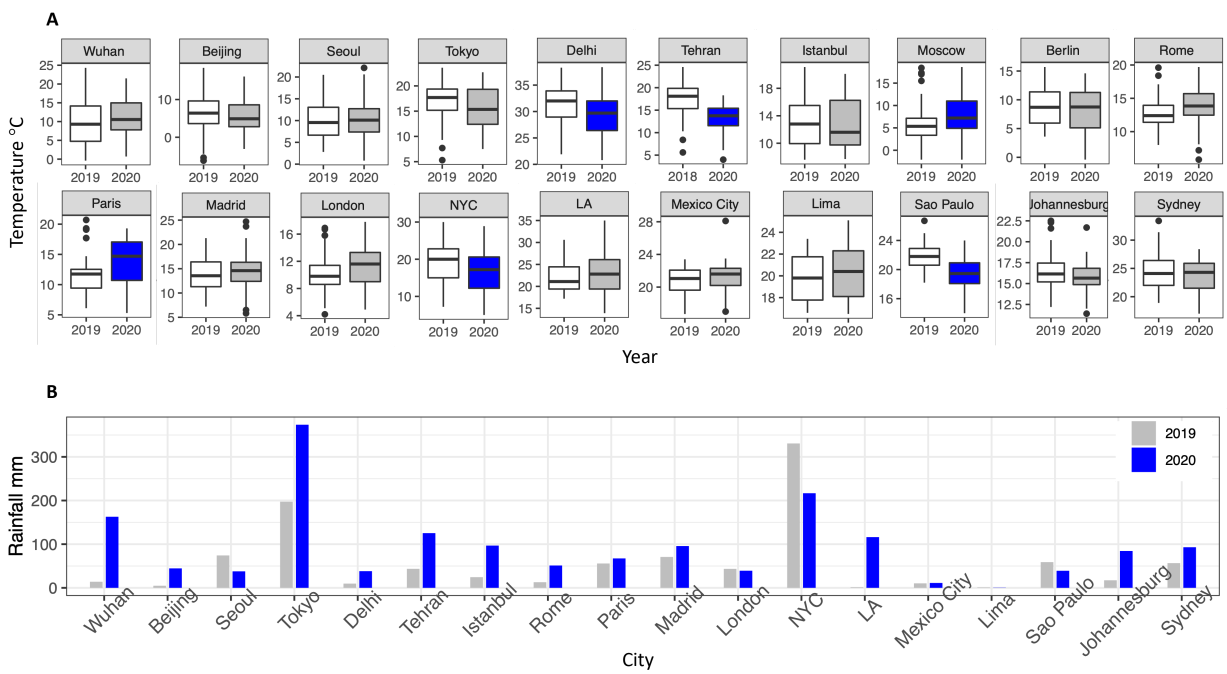


Figure 5. Meteorological condition changes in selected cities during lockdown period in 2020 and the same period in 2019. (**A**) Average temperature, blue boxes mean significant change of average temperature: $p < 0.05$ according to ANOVA and Tukey HSD tests. (**B**) Total rainfall, no rainfall data for Berlin and Moscow from either source.

4 Discussion

4.1 Changes in AQI of main pollutants

We found a significant impact of the COVID-19 lockdown on air quality in 20 major cities, including significant decreases in AQI levels for NO_2, SO_2, CO and PM, and increases of ground-level O_3 AQI in most cities (Table 2). The decrease of primary pollutants NO_2, SO_2, CO during the lockdown period relative to 2019 and to the average of 2017-19 for the same period are due to the reduction of emissions from anthropogenic activities. The transportation reduction is responsible for the declines of NO_2 and CO, due to the restriction of human mobility (e.g., automobile use decreased in all cities during lockdown (Apple, 2020)), and the reduced electricity consumption is responsible for the decrease of SO_2 due to the restrictions of industrial and commercial activities (IEA, 2020) (see section 4.2 for discussion).

For the secondary pollutant ground-level O_3, the AQI level depends on the O_3 formation rate through complex photochemical reactions, in which the three determinizing factors are sunlight, NO_x and VOCs. However, the chemistry of O_3 formation is highly nonlinear, and the effects of precursor concentrations on O_3 production rate can be characterized as either NO_x-sensitive or VOC-sensitive (Sillman, 2003, Tie et al., 2007; Kim et al., 2012; Simon et al., 2015). Under a VOC-sensitive regime (low ratio of VOC/NO_x), an increase in NO_x concentration causes a decrease of ozone with low concentrations of VOCs. On the other hand, under the NO_x-sensitive regime (higher ratio of VOC/NO_x), the reduction of NO_x emissions will lead to an increase in ozone concentrations. As we do not have access to VOC data, we could not define the regime of NO_x-VOC-O_3 sensitivity. However, O_3 levels increased during the lockdown in most cities (Figure 3). Even in the case of Istanbul and Lima, if we exclude the data from 2019, the level from 2020 was also higher than 2017 and/or 2018. Thus, ozone likely formed under a NO_x-sensitive regime in most of cities. Weather conditions are also another important factor, especially solar radiation or temperature.

The decline in PM reflects changes in both primary and/or secondary particles emissions and reactions. The primary PM is from natural and anthropogenic processes including road traffic within urban areas (Charron et al., 2007; Lenschow et al., 2001). The two main species for secondary PM formation are sulfate and nitrate, formed in air from precursor pollutants: SO_2 and NO_2. Thus, the decline of emissions of primary pollutants SO_2 and NO_2 recorded here also indirectly reduced the formation of secondary PM.

4.2 Impact of lockdown strategy on air quality

Lockdown policies reduced transportation and electricity demand, reflecting restricted human mobility, industry and commercial activities (Apple, 2020; IEA, 2020). Since the primary and secondary sources of NO_2 are transportation and combustion in power plants, this led to a reduction in NO_2 (US EPA, 2020; Airparif, 2016; GLA, 2017). We compared the percentage decrease in NO_2 AQI to assess the impact of lockdown policy on air pollution (Figure 6), as NO_2 showed the most significant changes during lockdown. We also used the car driving data (Apple,

2020) to assess the restriction of human mobility, as transportation is the most important source of NO_2.

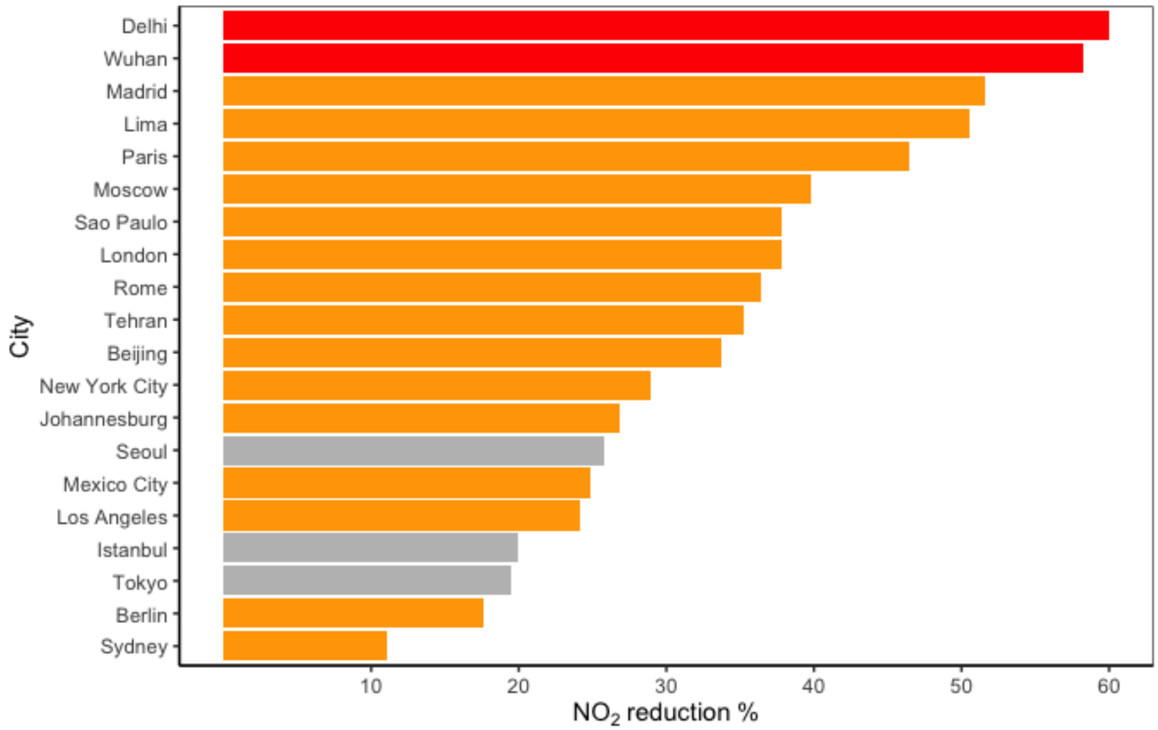


Figure 6. NO_2 reduction percentage during lockdown period in 2020 relative to 2019 for the same period in 20 major cities around the world. Red: cities with strictest lockdown policy (human mobility restriction and stopped public transportation), orange: cities with similar strict lockdown policy (full or partial lockdown, with different social distancing measures), grey: less strict lockdown policy or no lockdown.

In Wuhan, the first epicenter of COVID-19, experienced the strictest lockdown policy (Table 2). All public transport was suspended. The residents of Wuhan were not allowed to leave the city without permission from authorities, and only one person from each household was allowed to leave their house or apartment for two hours every second day for essentials (Wang et al., 2020). A very strict lockdown policy was also applied in Delhi: public transportation was also suspended during the lockdown, and only those who worked for "essential services" could move freely. Due to the strictest lockdown policies, NO_2 reduced the most in Delhi and Wuhan (60.0%, 58.3%, respectively) (Figure 6). Driving in automobiles dropped about 88% in Delhi during the lockdown (Apple, 2020), also the highest reduction in mobility among all cities, consistent with the strictest lockdown policy and the highest reduction of NO_2 among all cities.

As the second epicenter of COVID-19, strict lockdown policies were implemented in hard-hit European countries, which aimed to reduce human mobility, especially in Italy, Spain, France and the UK (Tobías, 2020; Mitjà et al., 2020; Pullano et al., 2020; Hampton et al., 2020). For instance, people could not leave home without a permit in France, citizen mobility reduced by 68% and 79% in the Paris region, respectively, within and leaving the region(Pullano et al., 2020). In the UK, people could only go outside to buy food, to exercise once a day, or go to work if they absolutely could not work from home**(**Hampton et al., 2020**)**. The reduction of NO_2 in Madrid (51.6%), Rome (36.4%), London (46.4%) and Paris (37.8%) (Paris) (Figure 6), agrees with the medium-strict lockdown policies implemented in those countries. Driving of automobiles declined 65-85% in these 4 European cities (Apple, 2020), consistent with the strictness of lockdown policies and the reduction of NO_2.

The Peruvian government implemented the longest lockdown (108 days, Table 2) in the world. The lockdown policy restricted citizen mobility based on gender. Only men could go out on Monday, Wednesday and Friday and only women on Tuesday, Thursday and Saturday. Otherwise, no Peruvian citizens were allowed to leave their homes, and the police and the army were deployed to enforce the lockdown (Perez-Brumer & Silva-Santisteban 2020). Lima experienced fourth highest reduction (51.8%) of NO_2 relative to 2019 for the same period.

The U.S. federal government did not issue a national lockdown, but a national emergency instead. Most states issued their own stay-at-home orders. For example, stay at home orders started on March 17th in California and 22nd in New York. About 60% of the decrease in automobile use (Apple, 2020) was observed during stay-at-home periods in NYC and LA, which is lower than most of European cities and Delhi, meaning less strict policies applied in the U.S. than those in hard-hit European cities. The stay-at-home orders were not legally enforced. This voluntary social distancing led to a 27.5% (LA) and 24.2% (NYC) decrease of NO_2 AQI. This decrease was less than most of the European cities, consistent with the less strict lockdown policies in the U.S. and the lower decrease of human mobility.

The smallest declines in automobile use were observed in Sydney (50%), Berlin (50%), Seoul (45%) and Tokyo (30%) among all cities (Apple, 2020). The least strict lockdown policies were implemented in Seoul and Tokyo. The Japanese government declared a “state of emergency” for seven prefectures, including Tokyo, Osaka, and Fukuoka, and implemented a Japanese version of a social-distancing policy. The government did not impose severe lockdown regulations, but encouraged self-restraint on the part of the public and businesses (Morita et al., 2020). The Korean government handled the COVID-19 crisis by applying intensive testing and contact tracing rather than enhanced social distancing, and since these measures worked to control the COVID-19 spread, a lockdown was never mandated (Aum et al., 2020). Germany implemented a nation-wide social distancing and contact restriction on March 22nd, in contrast to most other European countries, the stringency of measures differs substantially between states (Armbruster & Klotzbücher 2020). For example, in Berlin, people were only allowed to go out alone or with a person from same household. Australia also implemented similar lockdown policies in comparison to most European countries. All Australians were strongly advised to leave their homes only for limited essential activities and public gatherings were limited to two people. Berlin (17.6%) and Sydney (11.1%) experienced the least decreases of NO_2 AQI.

Among all countries, the Turkish government issued a particular policy to fight against the COVID-19 outbreak: weekend curfew for residents under the age of 20, and aged 65 and above, without full or partial lockdown (Kaskun & Ulutas, 2020). However, automobile usedropped ~60%, higher than Berlin and Sydney, where statewide lockdown with human mobility restrictions were implemented. As a consequence, the decrease of NO_2 AQI was also one of the lowest in Istanbul, with a 19.9% decrease, also higher than those in Berlin and Sydney.

In conclusion, the decline of NO_2 related to the drop of automobile usage in most cases, as transportation is the main source of NO_2. The decrease of car use depended on the strictness of lockdown policy, especially the restrictions on human mobility and the forces that were used to control it. However, other social factors also could impact the effectiveness of lockdown policy, such as the voluntariness of citizen on social distancing (Brzezinski et al., 2020) and the trust in government (Bargain & Aminjonov 2020).

4.3 Impact of meteorological conditions on air quality

Year-to-year variations in meteorological conditions impacts air pollution, particularly the formation of secondary pollutants. Higher temperature/solar radiation favors the formation of ozone, and temperature correlates with ground-level ozone (Jacob & Winner, 2009; Lin et al., 2001). Higher temperatures can promote the formation of ground-level O_3. The significant increase of O_3 in Paris and insignificant increase in Moscow in 2020 (Figure 3) could be partially due to the higher temperature (Figure 5). The significantly lower temperature in NYC during lockdown relative to 2019 could be responsible for the slight decrease of O_3. However, in Delhi and Sao Paulo, despite the significantly lower temperature during the lockdown, the O_3 AQI increased significantly in Sao Paulo and insignificantly in Delhi, meaning the increases of O_3 could be higher, if the temperature was the same as in past years.

Enhanced rainfall can wash air pollutants out of the atmosphere, especially particulate matter and water-soluble pollutants, such as NO_2 and SO_2. The decrease in primary pollutants and PM in Beijing, Istanbul, Johannesburg, LA, Rome, Tokyo and Wuhan, where rainfall was more than twice as high in 2020 than 2019, could be partially caused by this higher rainfall during the lockdown. This is especially true in Johannesburg where 4.9 times more rain fell in the 2020 lockdown period than 2019 and could explain the largest decrease of $PM_{2.5}$ (31.3%).

4.4 Impact of environmental policy on air quality

Prior to COVID-19, many countries imposed action plans or policies limiting emissions to the atmosphere to mitigate the impact of air pollution on public health. For instance, the Action Plan on Prevention and Control of Air Pollution in China 2013, the National Clean Air Program (NCAP) in India, the Clean Air Act in the U.S., and the National Air Pollution Control Program in the E.U. all aim to lower air pollution in their country or region. In addition to the lockdown policies and meteorological conditions, these action plans and policies could also play a role in air pollution change. We can assess this role by observing the inter-annual variation of each pollutant prior to the occurrence of COVID.

NO_2 decreased significantly from 2017 to 2019 in Wuhan, Istanbul, Lima and Mexico City (Figure 2) and SO_2 declined significantly in Beijing, Wuhan and Mexico City (see supplementary Figure S1). Significant decreases in $PM_{2.5}$ occurred in Delhi, Wuhan, Tokyo and Lima (Figure 4). These inter-annual declining trends could show the continuous reduction of pollutant emissions due to numerous local environmental policies implemented in these countries, especially in China and Mexico.

China and India, major developing countries in the world with the largest populations, have considerable air pollution issues especially in major cities (Fan et al., 2019; Sharma et al., 2019), due to the high growth in urban population and the increased demand for energy and transportation. After the implementation of different policies to control air pollution, China experienced significant decreases (21-59%) of $PM_{2.5}$, SO_2 and NO_x, since the Action Plan on Prevention and Control of Air Pollution was implemented in 2013 (Zhai et al., 2019; Zheng et al., 2018). For the decrease of air pollutants during the lockdown in 2020, we should take into account this pre-existing decreasing trends of NO_2, SO_2 and $PM_{2.5}$, reported previously in the literature and also observed in this study (Figures 2, 4 and S1) , especially in Wuhan. In contrast, India's SO_2 and

NO_2 levels increased by more than 100% and 50% from 2005 to 2015 respectively, due to the high growth of coal power plants and smelters (Krotkov et al., 2016). The significant increases of NO_2 (Figure 2) and SO_2 (Figure S1) in 2019 relative to 2017 and 2018 confirm this increasing trend in Delhi. In January 2019, India launched a National Clean Air Program aimed to reduce particulate matter pollution by 20-30% by 2024 relative to 2017 levels (MoEFCC, 2019). It is too early to observe the results of this program. The increasing pollution trends of past years could cause an underestimation in the decrease of air pollution during the lockdown period.

In other major developing countries: we also found significant pre-existing decreasing trends of NO_2 and SO_2 in Mexico City during 2017-2019. Since the 1990s, the Mexican government developed and implemented successive air pollution programs that combined regulatory actions with technological changes that resulted in significant improvement to air quality. $PM_{2.5}$ (60%) NO_2 (40%) and SO_2 (90%) decreased dramatically since 1990 to 2018 (Molina et al., 2019). This decreasing trend could partially be responsible for the lower concentrations of NO_2 and SO_2 during 2020 lockdown in Mexico City. In Turkey, according to the regulations, every Provincial Directorate of Environment and Urban Planning has to prepare a clean air plan. The concentration of PM_{10} and SO_2 has decreased by 50% and 98% respectively since 1990s to 2014 (Sevimoğlu, 2020), due to numerous measures included in a clean air action plan. Similar to Mexico City, the decrease of NO_2 could be underestimated in considering the pre-existing decreasing trend of NO_2 in Istanbul. However, we also observed a significant increasing trend of SO_2 from 2017 to 2020 (Figure S1), signifying the increase of SO_2 during 2020 lockdown was a continuous trend, but not specifically caused by the COVID-19 lockdown.

In contrast with Asian and South American countries, air pollution concentrations in European countries and the United States remain stable and at a relatively lower level compared to most Asian and South American countries. This is due to earlier urbanization and implementation of air pollution action plans. In the E.U. countries, the Convention on Long-Range Transboundary Air Pollution (LRTAP) was signed in 1979, aiming to mitigate the air pollution transmitted over long distances by reducing emissions and pollution prevention (CLRTAP, 1979). Since 1980, numerous directives on the limitations of air pollution concentrations have been implemented (Kuklinska et al., 2015), and the air quality has been improved in many European countries. For instance, since 2000 in the Paris region the $PM_{2.5}$ concentration is lower than the World Health Organization suggested limit (25μg/m^3). NO_2 and SO_2 concentrations also remain stable over the past 4 years (Airparif, 2019). The U.S. implemented the Clean Air Act (CAA) in

1970, which dramatically improved air quality in the U.S. nationally, concentrations of air pollutants in 2019 dropped significantly compared to 2000: 92% (SO_2), 62% (NO_2), and $PM_{2.5}$ (43%) (checked on June 20th on https://www.epa.gov/air-trends/). However, in the last 4-5 years, the national annual average of air pollutants is stable. Due to the relatively stable concentrations of air pollutants, especially NO_2, SO_2 and $PM_{2.5}$ in those countries, the impact of environmental policies on short-term air quality should be too low to observe.

5 Conclusions

We found significant decreases in the AQI of NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} during the lockdown period in most of 20 megacities in the world relative to 2019 and to the average of 2017-2019 for the same period. For the primary pollutants: SO_2, NO_2 and CO, the significant decreases were directly due to the reduction of emissions caused by lockdown, as citizen mobility was restricted. The difference of NO_2 reduction between cities was mainly due to the various lockdown policies, and Wuhan and Delhi exhibited the highest decrease of NO_2 due to the strictest lockdown policies. For the secondary pollutants, O_3 increased in most of cities, due to photochemical reactions promoting ozone formation under a potential VOC-sensitive regime. $PM_{2.5}$ and PM_{10} decreased in 19 and 17 of all cities respectively, but the decrease was less than its precursor gases, especially NO_2, as the sources of PM are complex.

Meteorological variability also plays a role in air pollutant concentration: significantly higher rainfall during the lockdown period in Johannesburg could explain the largest decline of $PM_{2.5}$, and the lower temperature and higher rainfall in Istanbul and Tokyo could explain the exceptional decrease of ozone. In addition, environmental policy regulations, especially in Asian cities, such as Beijing, Wuhan, Seoul and Tokyo, reduced pollutant emissions leading to decreasing NO_2, SO_2 and $PM_{2.5}$ concentrations through the past three years prior to the lockdown. Globally, despite the non-negligible impacts of meteorological variability and preceding environmental policy, lockdown explains the large reductions in air pollution.

Acknowledgments, Samples, and Data

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Suplementary

Table S1. Name and number of stations for Meteorological data for 20 selected major cities.

City	Country	Name and number of stations for Meteorological data
Wuhan	China	Wuhan, CHM00057494
Beijing	China	Beijing, CHM00054511
Seoul	South Korea	Seoul, KSM00047108
Tokyo	Japan	Tokyo, JA000047662
Delhi	India	New Delhi Palam, IN022023000
Tehran	Iran	Tehran Mehrabad, IR000407540
Istanbul	Turkey	Istanbul Bolge Kartal, TUM00017064
Moscow	Russia	From https://www.wunderground.com
Berlin	Germany	Berlin Tegel, E00121150
Rome	Italy	Roma Ciampino, IT000016239
Paris	France	Paris Le Bourget, FR000007150
Madrid	Spain	Madrid Getafe, SPE00120296
London	U.K.	Heathrow, UKM00003772
New York City	U.S.A,	NY City central park, USW00094728
Los Angeles	U.S.A.	Los Angeles Downtown USC, USW00093134
Mexico City	Mexico	From https://www.wunderground.com
Lima	Peru	Jorge Chavez International, PEM00084628
Sao Paulo	Brazil	Sao Paulo Aeroport, BR00E3-0520
Johannesburg	South Africa	Johannesburg International, SFM00068368
Sydney	Australia	Canterbury Racecourse Aws, ASN00066194

For Moscow, Mexico City and Berlin: data from weather underground website (https://www.wunderground.com)

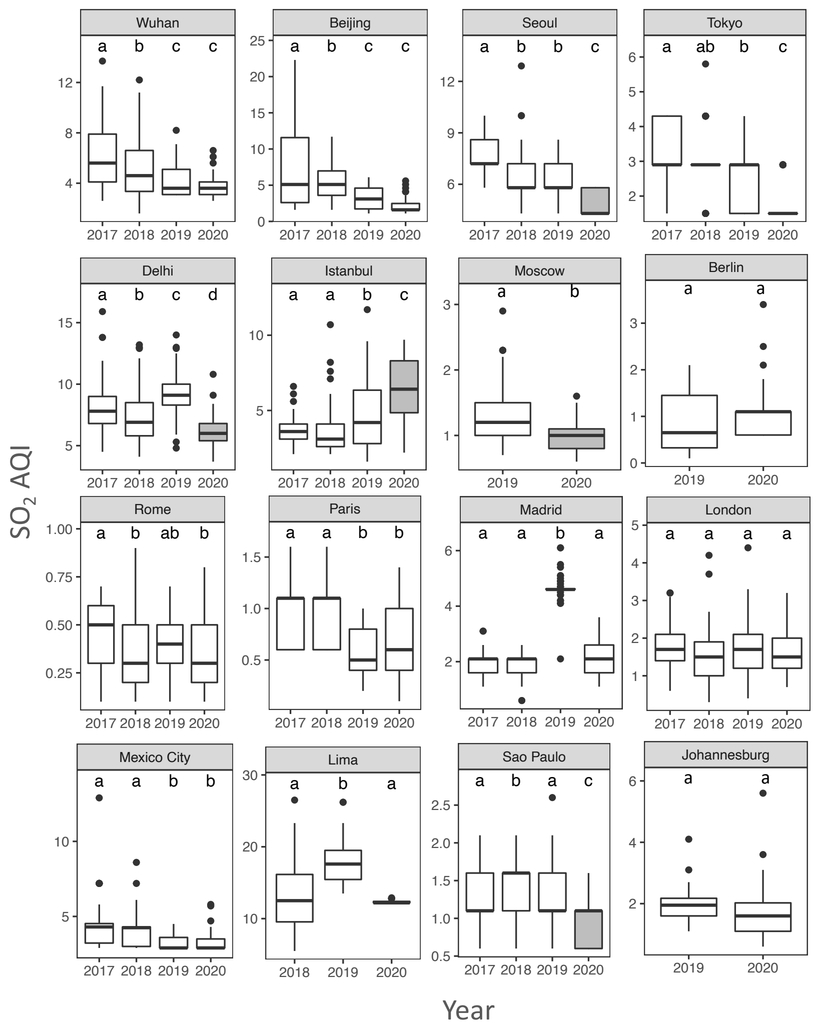

Figure S1. SO_2 AQI in selected worldwide cities during the lockdown period in 2020 compared to the same period of 2017, 2018 and 2019. Line within the box: the median, box: first and third quartiles, whiskers: non-outlier range, dot: outliers. Years sharing the same letter mean not significantly different ($p>0.05$) The grey box for 2020: the change in 2020 is significant relative to every previous year.

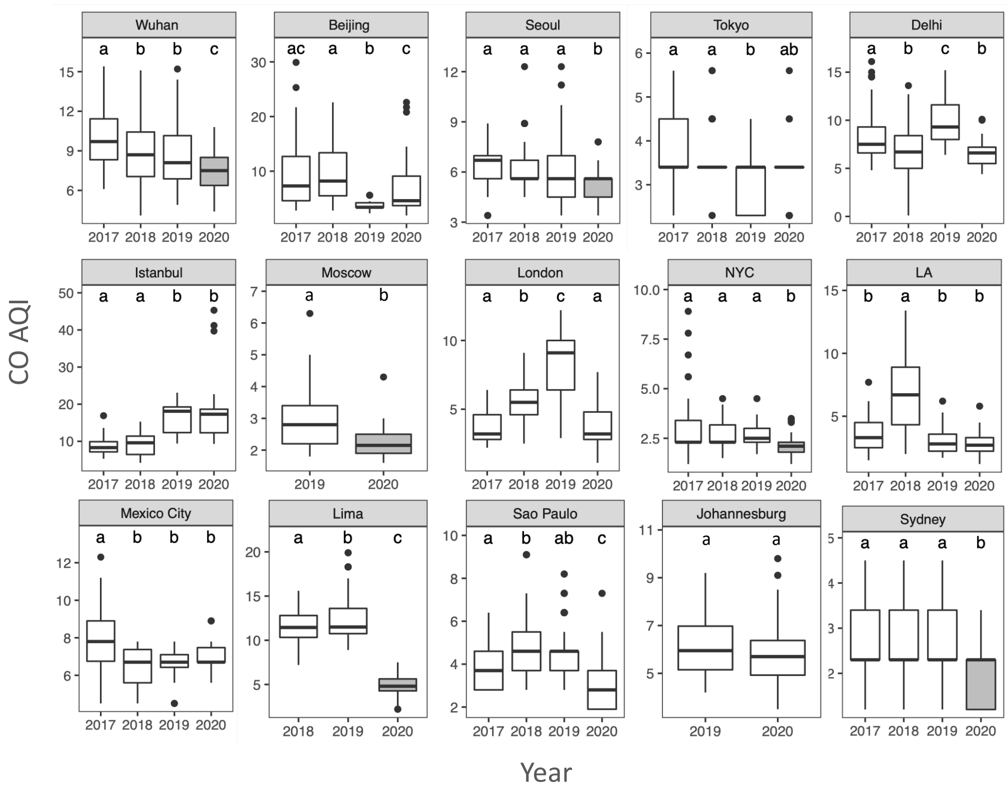

Figure S2: CO AQI in selected worldwide cities during the lockdown period in 2020 compared to the same period of 2017, 2018 and 2019. Line within the box: the median, box: first and third quartiles, whiskers: non-outlier range, dot: outliers. Years sharing the same letter mean not significantly different (p>0.05). The grey box for 2020: the change in 2020 is significant relative to every previous year.

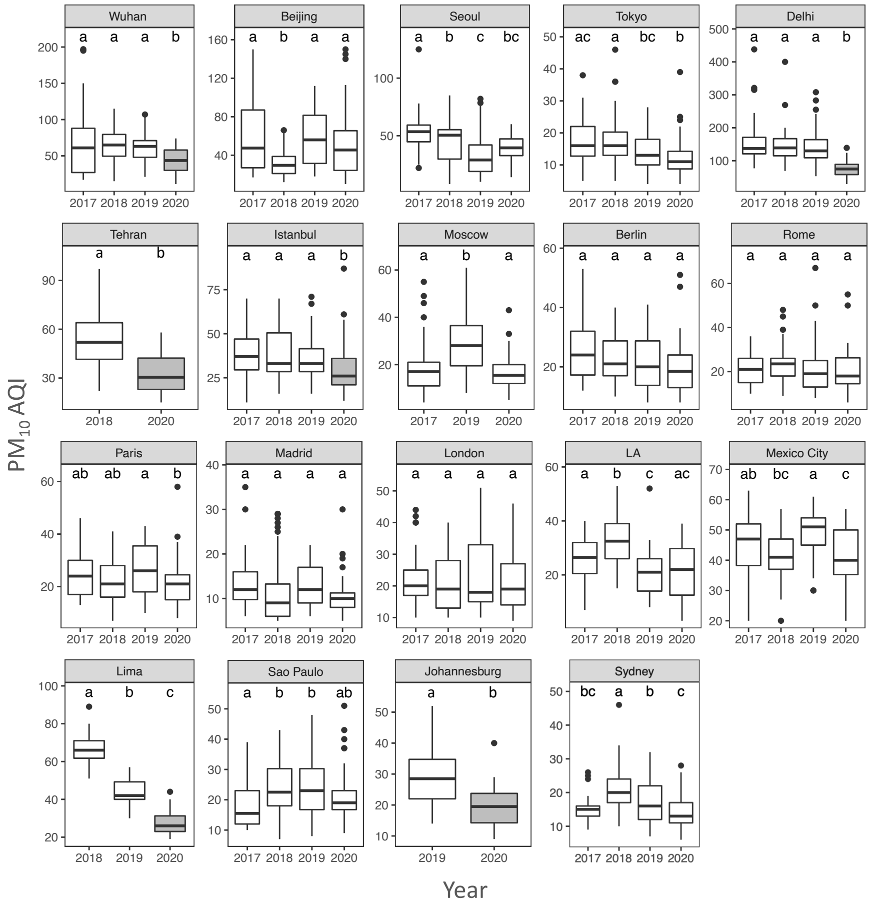

Figure S3. PM_{10} AQI in selected worldwide cities during the lockdown period in 2020 compared to the same period of 2017, 2018 and 2019. Line within the box: the median, box: first and third quartiles, whiskers: non-outlier range, dot: outliers. Years sharing the same letter mean not significantly different (p>0.05). The grey box for 2020: the change in 2020 is significant relative to every previous year.