

# COVID-19 Lockdown: Lessons learnt using multiple air quality monitoring station data from Kolkata city in India

Ghosh Nabanita<sup>1</sup>, Roy Abhisek<sup>2,3\*</sup>, Bose Devdyuti<sup>4</sup>, Das Nandini<sup>4</sup>, Debsarkar Anupam<sup>3,4</sup> and Roy Joyashree<sup>4,5</sup>

1. Global Change Programme, Jadavpur University, Kolkata, INDIA

2. Department of Civil Engineering, Meghnad Saha Institute of Technology, Kolkata, INDIA

3. Department of Civil Engineering, Jadavpur University, Kolkata, INDIA

4. Global Change Programme-Jadavpur University, Kolkata, INDIA

5. Bangabandhu Chair Professor, Asian Institute of Technology, Bangkok, THAILAND

\*abhisekroy22@gmail.com

## Abstract

*On March 16, 2020, Kolkata megacity in India announced partial lockdown due to COVID-19 crisis. This study presents an analysis for multiple pollutants with special focus on NO<sub>2</sub> and O<sub>3</sub> based on data from different monitoring stations located to across Kolkata city for the period from 16 March- 17 May 2020 compared to the pre-lockdown period. Most significant reduction was observed in the concentration of nitrogen dioxide (NO<sub>2</sub>) (- 76.8%), volatile organic compounds (VOCs) (- 69.5%), PM<sub>10</sub> (- 64.6%) and PM<sub>2.5</sub> (- 60.9%). A lower reduction percentage was found for CO, sulfur dioxide (SO<sub>2</sub>) and ammonia (-48.6%, - 41.7% and - 41.1% respectively). However, during partial lockdown, lockdown phase-1, phase-2 and phase-3, surface-level ozone (O<sub>3</sub>) has changed respectively by 31.72%, 31.13%, -14.28% and -14.05% which resulted in an overall increase of 8.17% in the entire study period.*

*The air quality index (AQI) in Kolkata which usually remains poor or very poor, even during lockdown period, failed to attain the 'good' standard. This needs special attention in human health impact assessment and public health management. We recommend additional attention to be drawn towards stickiness in O<sub>3</sub> which had adverse human health and which went up during lockdown period compared to pre-lockdown period. We highlight some major policy implications of the observed trends to combat city air pollution along with climate co-benefits by shifting transport fuel and related infrastructure.*

**Keywords:** COVID-19, Kolkata, Urban Air pollution, Ground-level ozone, NO<sub>2</sub>.

## Introduction

Megacities of India are important cases to study the trend and impact of air pollution because of their population density and high human exposure levels due to the outdoor activity based lifestyle. Notable facts are, unlike many countries, only 10% of city dwellers in India, on an average, have privately owned four-wheelers. Megacities such as

Mumbai and Kolkata are the best representations of public transport dependent lifestyles<sup>54</sup>. Kolkata city which has a population density of 24,000 people per square kilometer, is one of the most densely populated cities in the world and additional day time population load is 6 million<sup>34</sup>. Worldwide city outdoor air quality has been a major cause of concern for a long time<sup>62</sup>.

During pre COVID19 period, Kolkata city's ambient air quality and related disease burden have been in discussion not only in mass media<sup>5</sup> but also in scientific journals<sup>30</sup> and among policymakers and citizens. National Green Tribunal (NGT) imposed a penalty of INR 100 million on the State Government of West Bengal (Kolkata is capital of West Bengal) because it failed to check air pollution in Kolkata and other parts of West Bengal<sup>48</sup>. Air pollution reduction in cities is getting importance not only for human health reason but also for its close link to climate co-benefits. IPCC report has noted that air pollution reduction and climate mitigation actions are synergistic and are also positively linked to multiple SDGs (sustainable development goals)<sup>55</sup>. Like many other countries, India also has national standards defined for local air pollutants (Table 1).

In India, air pollution discussion centres mostly around particulate matters (PM), NO<sub>x</sub> and NO<sub>2</sub> rather than on O<sub>3</sub> and SO<sub>2</sub><sup>21,39,41,51,53,57</sup>. But adverse health impact potential of O<sub>3</sub> is well recognized in the literature in other countries contexts especially regarding respiratory, cardiovascular diseases and mortality<sup>62</sup>. In Kolkata with generally hot and humid climate and high day time temperature, O<sub>3</sub> can have even higher health impact and thus needs special attention.

Sources of air pollution in Kolkata city have been analyzed and studied by scholars<sup>14,27,56,72</sup>. The sources are mostly from automobiles, bio-mass burning and construction-related dust. Till 31st March 2016, the total number of registered vehicles in Kolkata was 7,40,879<sup>46</sup>. AQI is worsening in Kolkata, despite its historical spread and use of public transport service system (one of the first cities in India to have metro, circular and peripheral railway system based transport system). Despite enormous economic loss both in terms of Gross Domestic Product (GDP) and jobs, most positive story that has been communicated both in Indian media as well as in global media is a positive impact on AQI of cities due to Covid-19.

**Table 1**  
**Revised National Ambient Air Quality Standards (NAAQS) vis-a-vis WHO Standards**

S.N.	Pollutants	Time Weighted Average	NAAQS- India (Industrial, Residential, Rural and other Areas)	WHO Standards
1.	Sulphur Dioxide (SO <sub>2</sub> ), µg/m <sup>3</sup>	Annual	50	
		24 hours	80	20
2.	Nitrogen Dioxide (NO <sub>2</sub> ), µg/m <sup>3</sup>	Annual	40	40
		24 hours	80	
3.	Particulate Matter (Size < 10 µm) or PM <sub>10</sub> µg/m <sup>3</sup>	Annual	60	20
		24 hours	100	50
4.	Particulate Matter (Size < 2.5 µm) or PM <sub>2.5</sub> µg/m <sup>3</sup>	Annual	40	10
		24 hours	60	25
5.	Ozone (O <sub>3</sub> ) µg/m <sup>3</sup>	8 hours	100	100
		1 hour	180	

Source: 8, 74

The irony is no one was on the streets to breathe fresh air when AQI improved. However, on a serious note, many other city-level data<sup>62</sup> showed that one of the worst pollutants in terms of health impact O<sub>3</sub> showed an increase during lock-down period. In this study, we also try to analyze the evidence for Kolkata city as we feel this will provide not only comparable evidence but will also help in public health policy advisory design and for finding techno-economic policy solution as well as to highlight areas of multiple open-ended research questions of high priority

#### Rapid Review of Covid-19 and Pre-existing Air Pollution-related Literature

**On Air Pollution Levels:** According to the most recent studies<sup>59,61,71</sup>, ever since lockdowns are enforced in response to the COVID-19 outbreak, the levels of criteria air pollutants have reduced significantly around the world<sup>61,71</sup>. An anthropogenic holiday effect in ambient air quality during public holidays like the Chinese New Year has been reported in various studies<sup>67,68</sup>. Gaseous pollutants such as carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), volatile organic compounds (VOCs) or non-methane hydrocarbon (NMHC), sulfur dioxide (SO<sub>2</sub>) and particulate pollutants such as PM<sub>10</sub>, PM<sub>2.5</sub> were reported to be lower on public holidays. Table 2 shows the comparative results.

However, one significant greenhouse gas i.e. ground-level ozone (O<sub>3</sub>) concentration has substantially increased<sup>60,70</sup> during those lockdown days. Ground-level ozone (O<sub>3</sub>), one of the important criteria air pollutants as well as greenhouse gas<sup>16,63</sup>, is a key element to control the chemical composition of the troposphere and plays an adverse role on human health (respiratory disease and short-term mortality)<sup>2,38,62</sup>, agricultural productivity<sup>35,44</sup> and climate change<sup>7</sup>. In the troposphere, this greenhouse gas is coming from two basic processes<sup>17</sup>: (a) tropospheric/stratospheric exchange that causes the transport of stratospheric rich O<sub>3</sub> air into the troposphere and (b) production of O<sub>3</sub> occurring within the

troposphere during photochemical reactions. NO<sub>x</sub> (NO and NO<sub>2</sub>) plays a key role in the formation of tropospheric O<sub>3</sub>. Indeed, O<sub>3</sub> is a secondary photochemical oxidant produced by the photolysis of nitrogen dioxide (NO<sub>2</sub>) at wavelengths less than 424 nm<sup>37</sup>.

O<sub>3</sub> is greatly influenced by predominant meteorological conditions (temperature, solar flux, wind speed and relative humidity). Many studies have shown that O<sub>3</sub> concentration increases with an increase in solar flux and temperature<sup>24</sup>. Furthermore, the observed concentration of O<sub>3</sub> variation is higher in clear days as compared to cloudy days. The transport of O<sub>3</sub> precursors over long distances in the presence of favourable meteorological conditions results in O<sub>3</sub> formation far from the emission sources<sup>10,11</sup>.

Ambient ground-level O<sub>3</sub> pollution contributes to negative health impacts and premature death. In 2011, the premature mortalities due to exposure to PM<sub>2.5</sub> (~570,000) and ozone (31,000) caused an annual economic cost of about USD 640 billion in India, which was ten times higher than the total expenditure by public and private expenditure on health<sup>23</sup>. O<sub>3</sub> can cause adverse respiratory effects such as shortness of breath, chronic respiratory symptoms (i.e. coughing and sore or scratchy throat, phlegm, wheezing and inflammation of the airways) in the general population<sup>75</sup>.

These respiratory symptoms can further aggravate lung diseases such as asthma, emphysema, chronic obstructive pulmonary disease (COPD) and cardiovascular disease<sup>33</sup>. Children are at increased risk from O<sub>3</sub> exposure as long-term exposures to ozone have been associated with lower lung function and abnormal lung development in children<sup>20</sup>. In India's northern region, it was estimated that 37800 adults die prematurely each year from O<sub>3</sub> pollution<sup>32</sup>. Among the different polluted areas, the largest share of premature mortalities is in the Indo-Gangetic plain region with about 45% for O<sub>3</sub> exposure. For O<sub>3</sub>-related mortalities by COPD,

the greatest premature mortalities are found in Uttar Pradesh with about 5500 excess cases (about 18%) followed by Bihar (11%) and West Bengal (9.5%)<sup>23</sup>.

**On Economic Costs of Health Impact for India:** The primary sources of air pollution in cities of India are vehicular emissions, industrial emissions, coal combustion, biomass burning, road dust and waste burning, construction activities, oil combustion etc.<sup>28</sup> There exists a strong linkage

between air pollution and adverse health impacts. The total Disability Adjusted Life Years (DALYs) and the total number of deaths attributable to outdoor air pollution in India in 2012 were 20506015 and 621137 respectively<sup>73</sup>. The deaths and DALYs due to non-communicable diseases like Acute Low Respiratory Infection (ALRI), Ischaemic Heart Disease (IHD), Chronic Obstructive Pulmonary Disease (COPD), Lung cancer and Stroke are shown in table 3.

**Table 2**  
**Literature review on air quality during the lockdown**

Country/ Region	% Change in pollutant concentration
27 countries across the world (including Mexico, Taiwan, Slovakia Sweden, China, India) <sup>71</sup>	NO <sub>2</sub> : -29 % with 95% confidence interval -44% to -13%, Ground-level O <sub>3</sub> : -11%; -20% to -2% Fine particulate matter (PM <sub>2.5</sub> : -9%; -28% to 10%) during the first two weeks of lockdown
40 major cities around the world (Including Bangalore, Beijing, Bangkok, Delhi, Nanjing, New York, London, Paris, Seoul, Sydney and Tokyo) <sup>61</sup>	Max decline of PM <sub>2.5</sub> and PM <sub>10</sub> in Feb in Vienna (-57.1% and -60.7% respectively), Mixed trends for NO <sub>2</sub> - Wuhan (+62.0% in Feb, +11.3% in, Nanjing (+35.1% in Feb, +62.4% in Mar), Chengdu (+30.9% in Feb, +73.9% in Mar), where Madrid (-33.3% in Feb, -47.5% in Mar) and other 4 cities also shows downwards trend. O <sub>3</sub> decrease only in 3 cities - Lima (-42.5%) has a maximum decrease followed by Bangkok (-17.6%) and Bangalore (-10.6%).
44 cities, North China <sup>6</sup>	Average, the air quality index (AQI) decreased by 7.80% and five air pollutants (i.e., SO <sub>2</sub> , PM <sub>2.5</sub> , PM <sub>10</sub> , NO <sub>2</sub> and CO) decreased by 6.76%, 5.93%, 13.66%, 24.67% and 4.58%, respectively.
Southern European cities (Nice, Rome, Valencia and Turin) and Wuhan (China) <sup>62</sup>	Compared to the same period in 2017–2019, O <sub>3</sub> increase in all cities (17% in Europe, 36% in Wuhan) during the lockdown in 2020. A substantial reduction in NO <sub>x</sub> in all cities (~ 56%) Reductions in PM were much higher in Wuhan (~ 42%) than in Europe (~ 8%)
China <sup>60</sup>	Average, levels of surface PM <sub>2.5</sub> and NO <sub>2</sub> have decreased by approximately 35% and 60%, respectively, mean O <sub>3</sub> concentration has increased by a factor 1.5–2 between the period 1 and 22 January 2020 and the period 23 January and 29 February 2020.
Barcelona (Spain) <sup>70</sup>	Black carbon and NO <sub>2</sub> (-45 to -51%), PM <sub>10</sub> (-28 to -31.0%). O <sub>3</sub> levels increased (+33 to +57% of the 8 h daily maxima)
22 cities in India <sup>59</sup>	Overall, around 43, 31, 10 and 18% decreases in PM <sub>2.5</sub> , PM <sub>10</sub> , CO and NO <sub>2</sub> in India - during the lockdown period compared to previous years. 17% increase in O <sub>3</sub> and negligible changes in SO <sub>2</sub> . The air quality index (AQI) reduced by 44, 33, 29, 15 and 32% in north, south, east, central and western India, respectively.
Delhi, India <sup>40</sup>	In compare to 2019 (-60%) PM <sub>10</sub> and (-39%) PM <sub>2.5</sub> , NO <sub>2</sub> (-52.68%) and CO (-30.35%) during-lockdown phase. About 40% to 50% improvement in air quality is identified just after four days of commencing lockdown. About 54%, 49%, 43%, 37% and 31% reduction in AQI have been observed in Central, Eastern, Southern, Western and Northern parts of Delhi.

**Table 3**  
**Deaths and DALYs in India by disease**

	ALRI	COPD	IHD	Lung Cancer	Stroke
Deaths	39914	110500	249388	26334	195001
DALYs	3663274	3282841	7455375	813674	5290851

Source:<sup>73</sup>

The health costs of the population exposed to air pollution can be estimated by different methods like use of household health production function models<sup>1,26</sup>, dose-response function<sup>49</sup>, concentration-response function<sup>29,52</sup> and benefit transfer approach<sup>41</sup>. The cost of illness (COI) approach to measure health cost incurred due to exposure to air pollution includes loss in wages due to workdays lost from work and the expenditure incurred on mitigating activities.

In India, the annual health cost of outdoor air pollution has been estimated to be INR 1103 billion (14.7 billion USD) in 2009 which accounts for about 1.7% of the country's GDP and it is mainly attributable to the air pollution-related mortality in urban areas<sup>43</sup>.

Although particulate matter concentration is high in Delhi, as compared to Mumbai, the economic cost of health impact has increased in both the cities from 1995 to 2015 due to increasing pollution. The economic cost of health impact in Delhi and Mumbai was USD 6394.74 million and USD 4269.60 million respectively in 2015<sup>41</sup>. It is generally observed that the residents of Kolkata perceive the severity of air pollution problem by the health effects of the pollutants like allergic rhinitis, sore throat, chronic cough, bronchitis, sinusitis, chest dyspnoea, bronchial asthma etc.<sup>15</sup>

The annual benefits to all the citizens of Kolkata and Delhi for reducing particulate matter concentration from 2002 level to safe level have been estimated as INR 2999.7 million (39.72 million USD)<sup>1</sup> and INR 4896.6 million (64.84 million USD)<sup>1</sup> respectively<sup>47</sup>.

Majumdar<sup>42</sup> has found that the monthly cost of illness of the sampled households of Kolkata city due to air pollution is INR 4625.42 (60.13 USD). Various studies on economic costs of health impacts were conducted from time to time in other cities of India other than Kolkata<sup>26,41,57</sup> and suggested that ambient air pollution poses a serious concern to the

worsening health in various cities as reflected in high annual economic costs of health impacts, varying across cities and across time, ranging from USD 430 million (2007-2008)<sup>29</sup> to USD 2.2 billion (2013)<sup>18</sup>. Thus, mitigation of air pollution can yield monetary gains in the medical expenditure of the population.

In this backdrop, this present study aims to evaluate the lockdown effect on tropospheric levels  $O_3$ ,  $NO_x$ ,  $PM_{10}$ ,  $PM_{2.5}$  and  $SO_2$  for the lockdown period from 16<sup>th</sup> March 2020 to 14<sup>th</sup> May 2020 in the ambient air of Kolkata, India. The study by Sharma et al<sup>59</sup> looks into among other cities as well but only for the time period of March 16<sup>th</sup> to April 14<sup>th</sup> and compares the results with past 3 years (2017 – 2019) data. The current study has a larger data set compared to the previous study and also adds additional value compared to Gude et al<sup>23</sup> by linking the study with possible policy and future research implications.

## Material and Methods

**Study Locations, Data and Study Period:** Kolkata (22°34'N and 88°24'E) is an Indian megacity with about 4.5 million people and 14.1 million suburb inhabitants. It is the third-most populous megacity of India after Mumbai and Delhi but most densely populated in India and is an important business hub of the eastern and north-eastern part of India. It is characterized by its sub-tropical climate with annual mean rainfall and temperature of 1400-1600 mm per year and 26.8°C respectively. The temperature may drop to 10°C in winter and rise to 40°C in summer<sup>2</sup>.

The West Bengal State Pollution Control Board (WBPCB) has set up air-quality monitoring network across West Bengal to report hourly air quality on daily basis in conformity with the revised National Ambient Air Quality Standards (NAAQS) (Table 1), notified on 18 November 2009.



Figure 1: Distribution of air quality monitoring stations (Source: OpenStreetMap)

Our study covered data from six stations located in central zones within a radius of 6.6 km i.e. Ballygunge (BA), Bidhannagar (BI), Esplanade area - Fort William (FW), B.T. road area - Rabindra Bharati University (RBU), Rabindra Sarobar (RS) and Park Street -Victoria (VI) of Kolkata (Figure 1). The hourly NO, NO<sub>2</sub>, NO<sub>x</sub>, O<sub>3</sub>, VOCs (Benzene, Toluene, O-Xylene, MP-Xylene and Eth-Benzene), particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>), CO and ammonia (NH<sub>3</sub>) concentrations are measured and reported by the WBPCB for all ambient air quality stations. 1hr interval ambient temperature data has been collected from WBPCB ambient air quality stations for those six respective stations.

In West Bengal due to COVID19 outbreak, a partial lockdown was implemented from 16<sup>th</sup> March 2020 to 24<sup>th</sup> March 2020. Government of India (GoI) implemented the first phase of nationwide lockdown from 25<sup>th</sup> March 2020 to 14<sup>th</sup> April 2020, which was further extended to phase – 2 (15<sup>th</sup> April 2020 to 3<sup>rd</sup> May 2020) and phase -3 (4<sup>th</sup> May 2020 to 17<sup>th</sup> May 2020). To study the effect of lockdown in diurnal variation of pollutant concentration for all the previously mentioned six stations, the station-specific air quality data were obtained from the Central Pollution Control Board (CPCB) online portal for a duration of 1<sup>st</sup> February 2020 to 17<sup>th</sup> May 2020 where air quality data from 1<sup>st</sup> February 2020 to 15<sup>th</sup> March 2020 has been considered as the pre-lockdown phase. The pollutants concentration data during different lockdown phase has been compared with the pre-lockdown phase.

However, in this comparison the variation in pollutants concentration will be due to two factors: 1) effect of lockdown and 2) seasonal variation. To encounter the problem associated with seasonal variation, overall air quality data of Kolkata district from 1<sup>st</sup> January to 17<sup>th</sup> May of this year was compared with 2019. For this purpose, the air quality data for overall Kolkata district were collected from the WBPCB online portal. It is worth mentioning that the pollutants concentration of the before mentioned six-station was not available from 1<sup>st</sup> January to 17<sup>th</sup> May 2019 period, hence, we cannot compare this data with the data of 2020.

## Results and Discussion

**Comparative Analysis:** Overall air quality data of Kolkata district for January to May of 2020 is compared with 2019 and presented in figure 2. The data presented in figure 2 have much wider land surface coverage. They are not the average of the above mentioned six stations which represent city core, rather it is the average data of Kolkata district collected from WBPCB online portal.

Apart from socio-economic activity and fossil fuel based automobility, meteorological factors (temperature, wind speed, relative humidity, atmospheric pressure and solar insolation) play an important role<sup>13</sup> in influencing in criteria pollutant levels. The concentrations of NO<sub>2</sub> and ozone are presented by box and whisker plot which include the

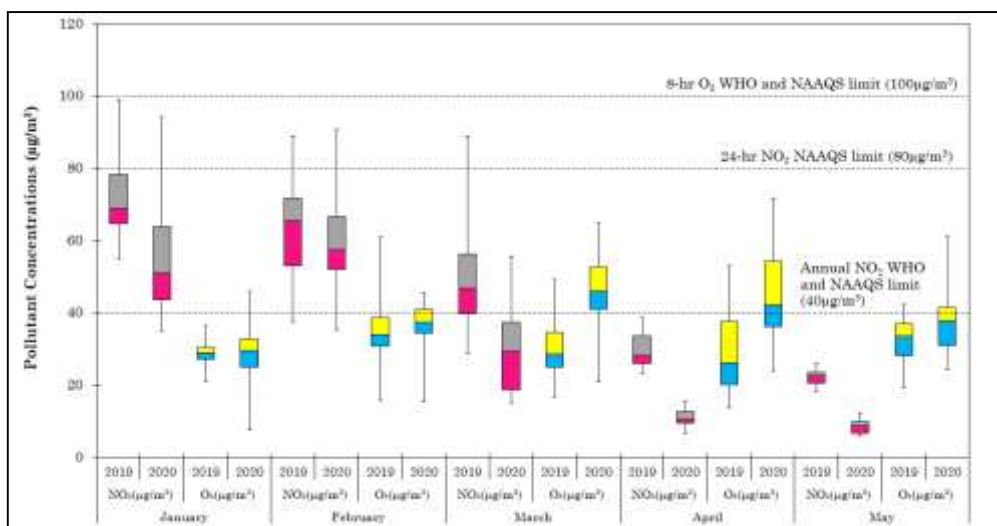
monthly averages, maximum, minimum, 25% quartile and 75% quartile value from 1<sup>st</sup> January to 17<sup>th</sup> May for the year of 2019 and 2020. In health impact context, what is more important to note, is the maximum value.

In both the years, average NO<sub>2</sub> concentration was above annual average NAAQS limits during (pre-lock down period comparison) January and February and maximum even crossing 24 standard. However, point to be noted is during March to May, 2019, mean concentration was gradually declining and was below the annual NAAQS limit with maximum also varying and coming down despite all regular economic activities as that is the control year compared to 2020. This declining trend we consider is because during January and February temperature in Kolkata is lower, being winter months compared to the temperature in March to May. It needs to be noted that temperature and NO<sub>2</sub> concentration are inversely related keeping all other things constant while temperature and O<sub>3</sub> are positively correlated. This is explained usually by thermal stability level of the atmosphere<sup>25,50</sup>.

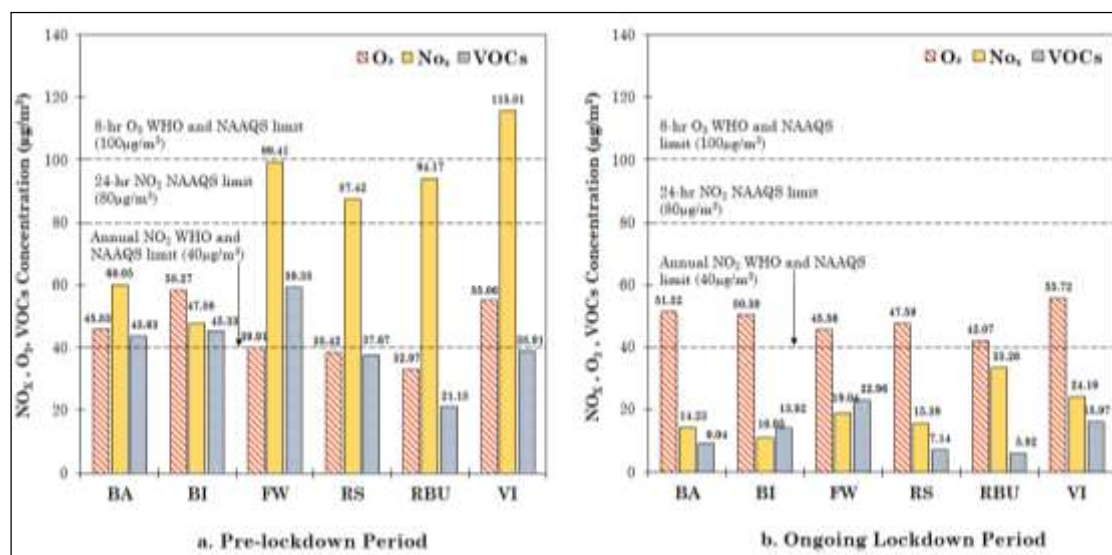
In figure 2 if we focus on only 2019, we see this relation clearly as well as in 2020 independently. What is additional to look into is the lock down effect during March-May in 2020 compared to 2019. If we compare the average NO<sub>2</sub> concentration during pre-lockdown phase 2020 with the similar time frame in 2019 (January and February), we can observe there is not much difference but whatever difference we see is due to rain in January 2020 which we assume resulted into decrease of mean NO<sub>2</sub> concentration relative to 2019 as there was no deviation from business as usual economic activities went on. In February, the average NO<sub>2</sub> concentration and range are almost the same for both the years as the metrological parameters (mainly temperatures and rain) are more or less within regular variability range.

March 16<sup>th</sup> onwards lock down was implemented and movement of automobiles on the roads impacted which is observed from the average as well as maximum and minimum concentration, as well as the range of NO<sub>2</sub>, as it has decreased progressively in 2020 compared to that of 2019. The reason is lesser vehicular pollution, the major source of NO<sub>2</sub> in Kolkata. The effect of lockdown in pollution concentration is more visible in April and May as there is complete lockdown during this period whereas in March the lockdown has been partial. On the contrary, during lock down the average monthly concentration and the range for ground-level ozone have been increasing in March to May of 2020 in comparison to the same period of 2019.

Concentration of ground level ozone is highly dependent on NO<sub>x</sub> and volatile organic carbons (VOCs). Normally, any urban region like Kolkata is considered as predominantly VOC limited chemical region. In any VOC limited chemical region, the decrease in NO<sub>2</sub> concentration results in the short-term increase in the ground-level ozone concentration<sup>31,36,50,58,64</sup>.



**Figure 2: Comparative analysis of  $\text{NO}_x$  and  $\text{O}_3$  pollutant concentration for the years 2019 and 2020**  
(Data Source: West Bengal Pollution Control Board (WBPCB), Air Quality Information System)



**Figure 3: Station wise pollutant concentration variation between (a) Pre-lockdown and (b) lockdown period**  
(Data source: Central Pollution Control Board (CPCB), Central Control Room for Air Quality Management)

**Table 4**

Mean concentrations, concentration range and variation of  $\text{NO}_x$  ( $\text{NO}$  and  $\text{NO}_2$ ),  $\text{O}_3$  and VOCs (Benzene, Toluene, O-Xylene, MP-Xylene and Eth-Benzene) pre-lockdown and during lockdown in sample location Kolkata, India.

Type of air pollutant	Pre-Lockdown (1/2/2020 – 15/3/2020)		During lockdown (16/03/2020–17/05/2020)		Variation	
	Mean	Range	Mean	Range	$\mu\text{g}/\text{m}^3$	(%)
$\text{NO}_x$	84.11	167.93 – 29.44	19.51	65.06 – 7.21	- 64.60	(-76.80)
a. NO	33.61	109.68 – 6.94	5.77	19.52 – 2.91	- 27.84	(-82.83)
b. $\text{NO}_2$	52.93	89.80 – 22.24	13.70	46.10 – 4.06	- 39.23	(-74.11)
$\text{O}_3$	45.08	64.05 – 17.78	48.76	76.30 – 10.10	+ 3.68	(+8.17)
VOCs	41.01	90.18 – 14.17	12.49	40.97 – 7.80	- 28.52	(-69.54)
a. Benzene	11.12	22.71 – 3.88	2.76	11.51 – 1.06	- 8.36	(-75.19)
b. Toluene	19.54	40.56 – 7.88	7.46	19.09 – 5.39	- 12.07	(-61.79)
c. O-Xylene	2.87	5.92 – 0.82	0.78	2.74 – 0.27	- 2.09	(-72.88)
d. MP-Xylene	5.88	14.15 – 1.64	1.24	5.5 – 0.50	- 4.64	(-78.94)
e. Eth-Benzene	3.68	7.69 – 0.64	0.71	3.39 – 0.32	- 2.98	(-80.85)

(Data source: Central Pollution Control Board (CPCB), Central Control Room for Air Quality Management)



In our case also, maximum ground-level ozone concentration during March to May increased to  $71.6 \mu\text{g}/\text{m}^3$  in 2020 from  $52.99 \mu\text{g}/\text{m}^3$  in 2019, although the average temperatures during March to May for both the year is nearly the same. This increase in ozone concentration poses a serious health concern.

**Station wise Pollutant Variation and AQI:** It needs to be mentioned that six monitoring stations are located in the cross-section of city streets of core economic district of the city, which have business as usual. Heavy transport/traffic load and population densities both during day and night with some variation across stations are observed. During the lockdown period, all socio-economic activities such as schools, colleges, restaurants, shopping malls and a large number of industries, companies and administrative centres were all closed; and people were not allowed to be on the roads. Figure 3(a, b) shows that in the pre-lockdown period the 24-hr average  $\text{NO}_x$  concentration is relatively higher in most of the stations and especially in four stations FW, RS, RBU and VI.

Transport is the major contributor to  $\text{NO}_x$  pollution. About 44.3 MT  $\text{NO}_x$  is emitted per day in Kolkata city<sup>3</sup>. Lockdown in Kolkata meant closure on the mobility of all kinds except for essential services; so the concentration of  $\text{NO}_x$  declined visibly after the implementation of lockdown. During the lockdown,  $\text{NO}_x$  concentration is still relatively higher (24-hr avg.  $33.26 \mu\text{g}/\text{m}^3$ ) in station RBU because it is a highway through which essential service cargo movement in trucks happened.

We also present the station wise air quality index (AQI) reported using the standard Indian AQI procedure i.e. sub-indices method<sup>9</sup>. From figure 4 and table 5, it is observed that in the pre lockdown scenario, overall air quality is poor to moderate with responsible parameters being  $\text{PM}_{2.5}$  for the station BA, FW, RBU and VI; and  $\text{PM}_{10}$  and  $\text{NO}_x$  for station BI and RS respectively. But due to lockdown, the scenario has changed. In more than 45% of lockdown days,  $\text{O}_3$  leads as a responsible parameter with AQI ranging from good to satisfactory level.

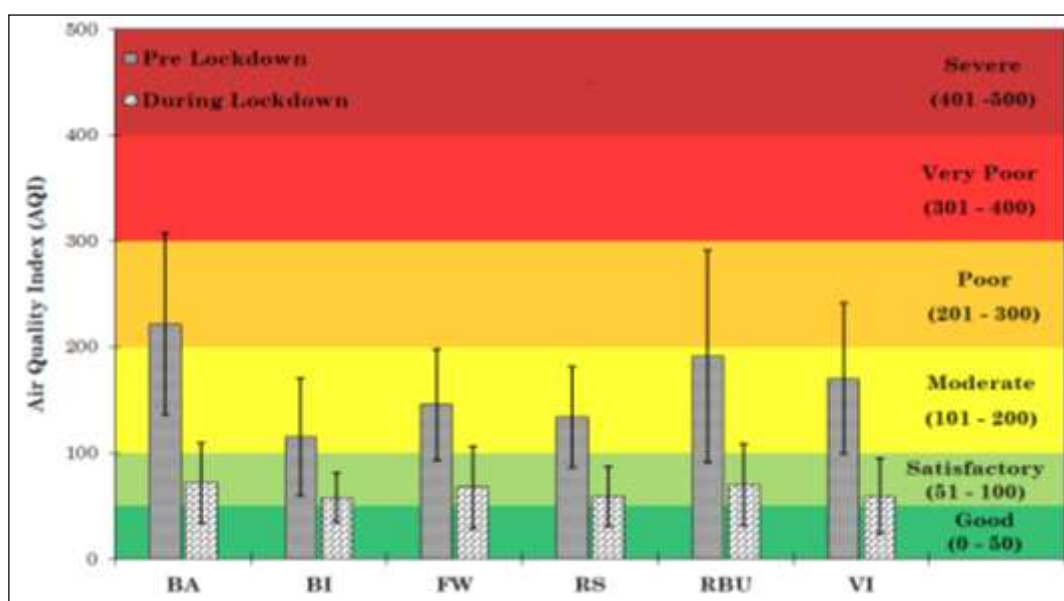


Figure 4: Station wise AQI during pre-lockdown and ongoing lockdown period

Table 5  
Station wise AQI variation between pre-lockdown and ongoing lockdown period

Station Name	Air Quality Index (AQI) [M $\pm$ SD] (Responsible Parameter)	
	Pre-Lockdown	During Lockdown
BA	222 $\pm$ 86 [(24%) $\text{PM}_{10}$ & (76%) $\text{PM}_{2.5}$ ]	71 $\pm$ 39 [(51%) $\text{PM}_{10}$ , (39%) $\text{O}_3$ & (10%) $\text{PM}_{2.5}$ ]
BI	120 $\pm$ 50 [(56%) $\text{PM}_{10}$ , (7%) $\text{O}_3$ , (35%) $\text{PM}_{2.5}$ & (2%) $\text{NO}_2$ ]	58 $\pm$ 23 [(37%) $\text{PM}_{10}$ , (58%) $\text{O}_3$ & (5%) $\text{PM}_{2.5}$ ]
FW	146 $\pm$ 53 [(33%) $\text{PM}_{10}$ , (47%) $\text{PM}_{2.5}$ & (20%) $\text{NO}_2$ ]	69 $\pm$ 39 [(30%) $\text{PM}_{10}$ , (38%) $\text{O}_3$ & (32%) $\text{PM}_{2.5}$ ]
RS	134 $\pm$ 48 [(36%) $\text{PM}_{10}$ , (36%) $\text{PM}_{2.5}$ , & (29%) $\text{NO}_2$ ]	60 $\pm$ 28 [(43%) $\text{PM}_{10}$ , (46%) $\text{O}_3$ , (10%) $\text{PM}_{2.5}$ & (2%) $\text{CO}$ ]
RBU	210 $\pm$ 83 [(27%) $\text{PM}_{10}$ , (71%) $\text{PM}_{2.5}$ & (2%) $\text{NO}_2$ ]	70 $\pm$ 39 [(31%) $\text{PM}_{10}$ , (44%) $\text{O}_3$ , (19%) $\text{PM}_{2.5}$ & (6%) $\text{NO}_2$ ]
VI	174 $\pm$ 67 [(16%) $\text{PM}_{10}$ , (55%) $\text{PM}_{2.5}$ , (5%) $\text{CO}$ & (25%) $\text{NO}_2$ ]	64 $\pm$ 33 [(18%) $\text{PM}_{10}$ , (54%) $\text{O}_3$ , (11%) $\text{PM}_{2.5}$ , (11%) $\text{CO}$ & (7%) $\text{NO}_2$ ]

\*Abbreviation: M = Arithmetic mean, SD = Standard Deviation

(Data source: Central Pollution Control Board (CPCB), Central Control Room for Air Quality Management)

Average values mask the details which are very important in understanding the densely populated areas in the cities and in understanding the human health impact.

**Diurnal Variation and Lockdown Effect:** Levels of criteria air pollutants got temporarily reduced during lockdown, especially the primary pollutants. The most significant variation was observed for NO<sub>x</sub> and VOCs level. Urban NO<sub>x</sub> and VOCs are emitted during combustion processes, especially diesel and to lesser extent gasoline. NO<sub>x</sub> and VOCs are the precursors of ground-level O<sub>3</sub> formation. Ground-level O<sub>3</sub> concentration depends negatively on the NO<sub>2</sub> concentration<sup>13,31</sup>.

The diurnal variations of air pollutant concentrations averaged from six air quality monitoring stations in Kolkata for the periods ranging from pre lockdown and lockdown period presented in figure 5 and 6. We also show the temperature variation curve in the graph.

Figure 5 shows the mean diurnal variability of the observed dataset of NO<sub>x</sub>, O<sub>3</sub> and VOC during the pre-lockdown phase. The concentration of any pollutant in atmospheric air depends mainly on four factors: i) Influence of emission source, ii) Solar intensity, iii) Wind pattern and iv) Planetary boundary layer (PBL)<sup>4,12,19,45,65,66</sup>, which is a widely used concept. PBL is the portion of the troposphere or friction layer which is directly influenced by the combined action of mechanical as well as thermal turbulence or force<sup>50,66</sup>. NO, NO<sub>2</sub>, NO<sub>x</sub> and VOCs have double-peak patterns as in figure 5. NO<sub>x</sub> are at their highest levels during the morning (6:00 hrs – 8:00 hrs) and in the evening (19:00hrs – 21:00 hrs), which describe the effect of peak vehicular emission. By regulation on traffic movement in these hours, heavy duty trucks move within city core business district from 20.00 hrs to 8.00 hrs and inner city passenger movement peaks are in the evening hours ~19.00 hrs.

We relate the lower level of concentration of NO<sub>x</sub> observed during the daytime 10:00 – 17:00, which is mainly due to the effect of PBL as well as due to regulations on traffic movement as mentioned above. Also, as day time temperature is higher (25.5°C to 27.67°C), earth surface heating produces buoyant convective turbulence. Along with this, during the daytime, the effect of wind speed and mechanical turbulence induced by vehicles or other moving objects increases the turbulence in PBL, which has direct effect in the depth of PBL.

In the daytime, this planetary boundary layer could be extended up to several kilometres. Due to this high PBL value, amount of air available for mixing is large and the concentration of the NO<sub>x</sub> is lower.

In night time (21:00 – 02:00), the lower temperature and unavailability of mechanical turbulence result in lower value of PBL. Value of PBL in night time could be as low as few tens of meters, which results in a high concentration of NO<sub>x</sub>

in the night time. Also, in night time, the mobility of the diesel operated heavy-duty vehicles further contributes to the higher NO<sub>x</sub> concentration.

A strong negative correlation between temperature and concentration of NO<sub>x</sub> can be observed from figure 5 as well as from the Pearson correlation analysis ( $r = -0.82$ ) justifying the above explanations.

It can be observed from the figure that during day time (10:00 – 17:00), concentration of O<sub>3</sub> is higher, whereas during night time concentration of NO<sub>x</sub> is higher. A strong negative correlation was observed between O<sub>3</sub> concentration and NO<sub>x</sub> concentration ( $r = -0.88$ ), which is in line with the findings of the previous researchers. Tropospheric/ground-level ozone formation depends mainly on: ozone precursors (like NO<sub>x</sub> concentration) and meteorological parameters (like temperature, wind speed, relative humidity and solar radiation). The figure and the Pearson correlation analysis ( $r = 0.96$ ) suggest a strong positive correlation between temperature and ozone concentration. Normally, high-temperature resulting from strong solar radiation promotes the photolytic dissolution of NO<sub>2</sub> and hence produces ground-level ozone.

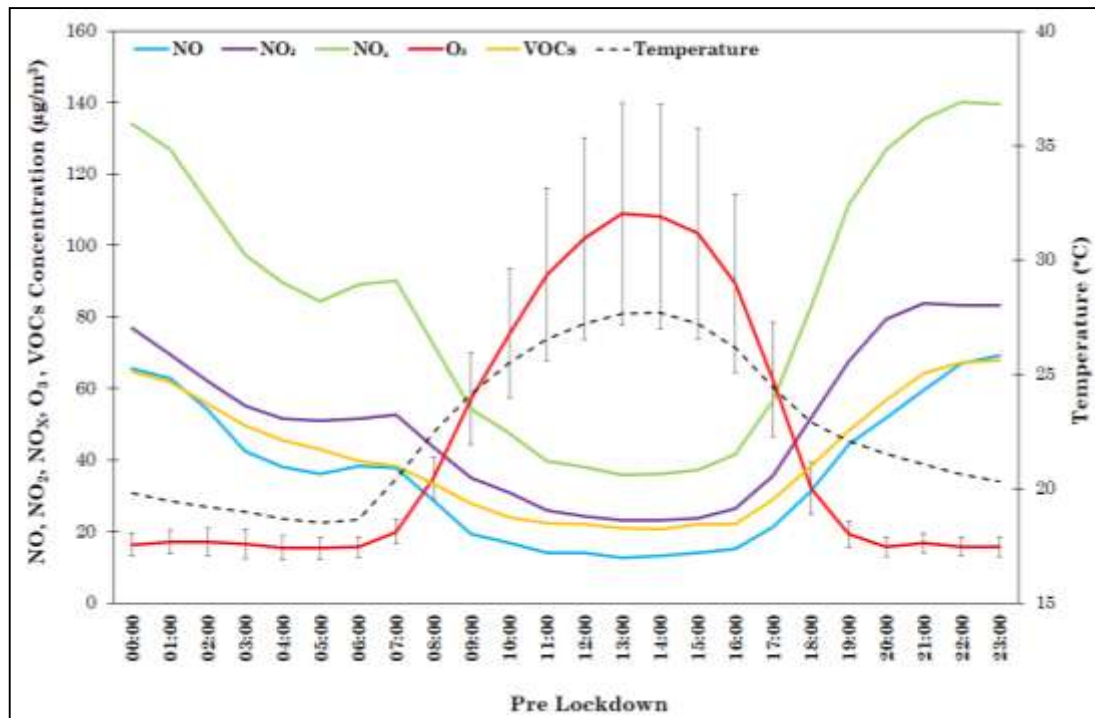
Like figure 5, a similar trend of diurnal NO<sub>x</sub> and VOCs variation was observed during a partial lockdown phase when night time traffic movement was not stopped completely (Figure 6a), although the concentrations are at much lower level. This can be described by the facts that in this period, the school, colleges and all the educational institutes were closed and hence the vehicular traffic within city core was less. In the lockdown period (Figure 6b, 6c and 6d), the concentration of NO<sub>x</sub> does not show significant diurnal variation like pre-lockdown phase which is obvious due to the absence of the source.

No peak was observed for NO<sub>x</sub> during these three lockdown periods due to complete stop of interstate mobility of trucks. However, for ozone strong +ve correlation was observed with temperature ( $r$  varies in between 0.949 to 0.987). Peak ozone concentration was observed in the day time (10:00 – 17:00) (similar to the pre lockdown case). The peak concentration of tropospheric ozone during the lockdown phase decreases from the pre-lockdown phase in the absence of precursor NO<sub>x</sub>.

However, the average concentration of ozone increases from pre-lockdown phase to partial lockdown phase, lockdown phase-1, phase-2 and phase-3 by 31.72%, 31.13%, -14.28% and -14.05% respectively which resulted in an overall increase of 8.17%. This may be due to the combined effect of two important factors:

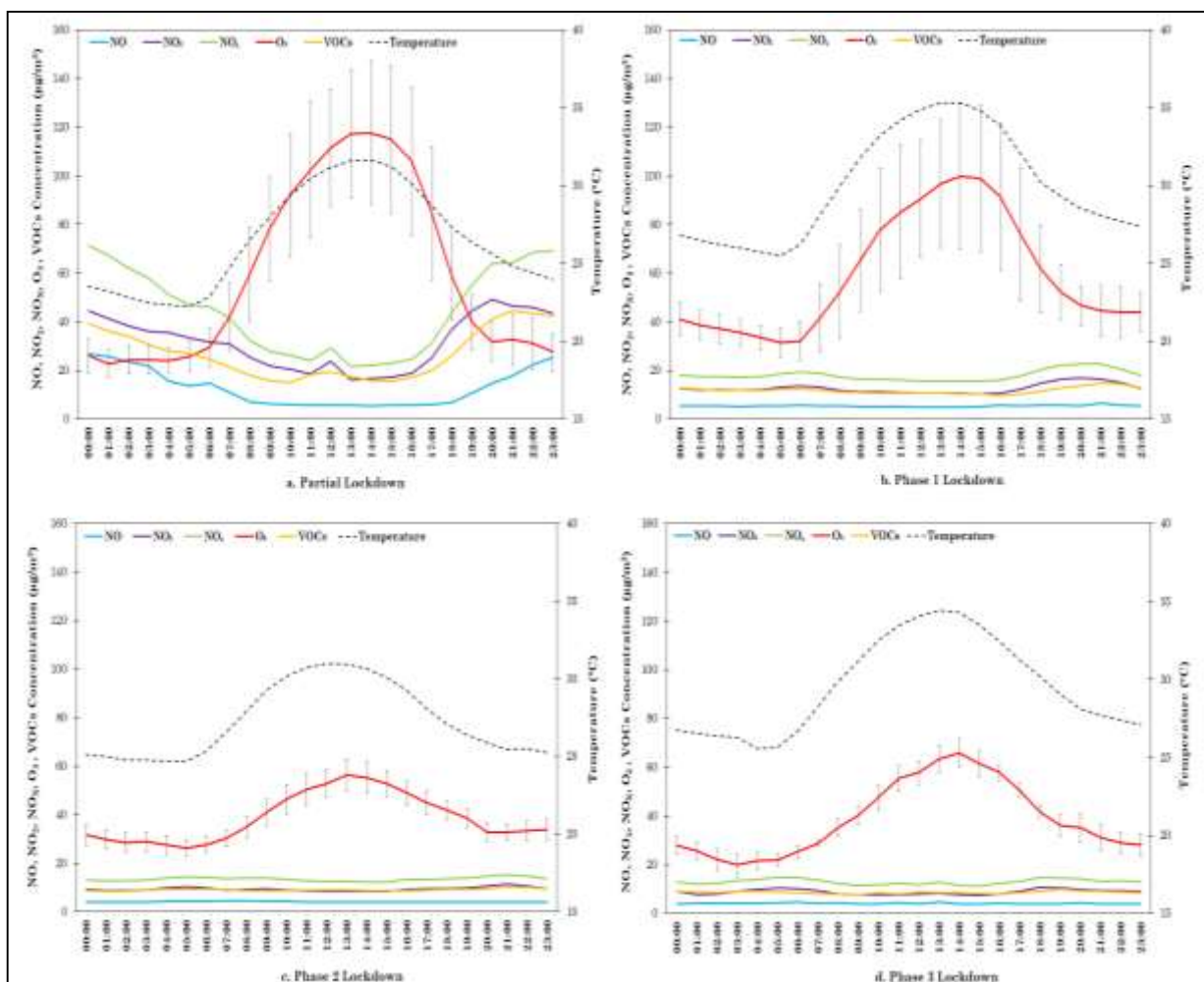
**1. Ozone concentration increasing factor:** In the VOCs limited chemical regime (as most urban areas are), decrease in NO<sub>x</sub> increases the average ground level ozone concentration.





**Figure 5: Diurnal cycle of pollutant during Pre lockdown period**

(Data source: Central Pollution Control Board (CPCB), Central Control Room for Air Quality Management)



**Figure 6: Diurnal cycle of pollutant during the lockdown period (a) Partial (b) Phase 1 (c) Phase 2 (d) Phase 3**

(Data source: Central Pollution Control Board (CPCB), Central Control Room for Air Quality Management)

The result of this effect is distinctly visible in partial lockdown phase and lockdown phase-1 where ozone concentration increased by 31.72% and 31.13% respectively.

Also, the high temperature and high solar isolation during this period increased the photochemical reaction and produce ozone.

**2. Ozone concentration decreasing factor:** The lesser availability of precursor of tropospheric ozone like NO<sub>x</sub> concentration progressively reduces the tropospheric ozone concentration. Effect of this factor is clearly visible with the progress of the lockdown as in lockdown phase -2 and 3, ozone concentration decreased by 14.28% and 14.05% from the pre-lockdown phase. So these two mixed effects result in lower peak in ozone concentration but the average ozone concentration was increased by 8.17% (Table 4). This increase in average concentration in Kolkata is high compared to the other cities in India.

Like in Delhi, the average concentration increase in the partial lockdown and first phase of the lockdown (3<sup>rd</sup> March 2020 to 14<sup>th</sup> April 2020) was +0.78%<sup>40</sup> compared to increase of 31% in Kolkata. This might be due to the higher temperature and solar radiation in this lockdown period (March to May) in Kolkata compared to New Delhi. In the absence of NO titration effect, VOCs limited chemical regime condition and lower fine particulate matter concentration might have been responsible for the formation and accumulation of ground-level O<sub>3</sub> which needs further investigation.

## Conclusion and Policy Implications

COVID-19 lockdown response strategy led to business as usual, city automobility on halt for all non-essential services. Kolkata city residents had the privilege of having non-motorized mobility services such as cycle driven vegetable carts, cycle rickshaws service for localised essential service provision for vegetable supply etc. As a result of that, fossil fuel combustion went down to an unprecedented lower level. Cycle rickshaws, which on a business as usual day carry passengers, started to serve in the residential areas with vegetables and other essential services. The average peak NO<sub>x</sub> level came down from ~140 µg/m<sup>3</sup> to below ~20 µg/aum<sup>3</sup>, which is below national and WHO standards. This provided an opportunity to answer a long standing policy question scientifically- how much city air quality can be improved through regulation on fossil fuel driven traffic movement?

If choice is to be made between halting of all socio-economic activities like lock down period and shift away from fossil fuel combustion within the city limits, then definitely latter will be preferred to avoid economic hardships, livelihood loss, unmeasured mental wellbeing impact which city dwellers have been undergoing due to lock down of economic activities. Since this economic activity loss due to

lock down is neither feasible nor a desirable solution, the question which the multidisciplinary research teams need to answer is how this experience can be related to future science-driven policy and actions in city air quality management to improve the health outcome and minimise health damage costs mentioned above, advocacy and awareness building programmes and citizen's education programmes.

A scientific assessment is needed to find out why city's average air quality could not reach the 'good' AQI standard in none of the six stations during lockdown period. Researchers need to look at if this is related to emissions from essential service vehicles like Police service, ambulance and medical service, some long distance selective food delivery services, online essential food delivery services. The remaining average positive emissions as shown in figure 5 and 6 are below ~20 µg/m<sup>3</sup> but almost at the same level combined with O<sub>3</sub> level the city is treated 'good'.

AQI still unattainable during lock down period needs more careful study. This might mean analysis of the maximum emissions which are not shown here on a day to day basis, granular data matching of traffic movement and air quality measurements at their maximum values and not average values. But, at least this can still be concluded that even essential service delivery by fossil fuel driven mobility services cannot be allowed to ensure good AQI in Kolkata city.

A possible post-COVID recovery path for Kolkata can very well be transformative shift in city's mobility sector. Transport sector needs to undergo a transformation, given the challenges of new-normal social practices. In such situation, apart from the pollution abatement policies, there are many pollution mitigation options in the road transport sector, like use of alternative fuels, modal shifts, behavioural change etc. which if implemented, can yield multiple ancillary benefits or co-benefits including climate benefit. Fuel switch fits well into the India's EV policies<sup>1</sup> which need massive push for early penetration in the post-COVID-19 recovery phase.

Our estimates of Levelized Cost of Carbon Conserved (LCCC) by an electric AC bus in Kolkata city is respectively around INR 2.35 (0.031 USD) per kg CO<sub>2</sub> eq. and INR 1.6 (0.021 USD) per kg CO<sub>2</sub> eq. for 9 meter and 12 meter bus lengths, relative to a conventional BS IV diesel AC bus. On the other hand, LCCC for electric car is INR -0.726 (- 0.0096 USD) per kg CO<sub>2</sub> eq. relative to a BS IV conventional diesel car. A push towards increased cleaner fuel use in public transport and car pool/sharing system will reduce this abatement cost even further which makes good economic sense from investor point of view.

From user point of view, during lockdown period and as lockdown is easing out, a modal shift towards increased use

of non-motorized transport means has gained prominence. An increasing number of people in Kolkata and in other parts of India are commuting to their workplaces by bicycle because of unavailability of regular transport service and also to abide by social distancing norms. It needs mention that in pre-COVID time by regulation in Kolkata, bicycles were not allowed on the main roads because of the road safety issues.

In post-COVID scenario, if transport sector needs to transform more sustainably a separate bicycle lane can be very transformative and people friendly. This infrastructure investment in favour of active transport mode will not only help in healthy lifestyle but also will address climate benefit by sustaining pandemic induced behavior change. At present many of the cyclist associations are already voicing their suggestions for pop-up cycle lane.

It is clear that this transformation would mean technological, institutional, policy and social innovation. Briefly, technological innovation would imply appropriate infrastructure building for accelerated penetration of electric mobility to unlock fossil fuel driven vehicular movement, transport equipment retrofit, new purchase and appropriate incentive design for making a shift from fossil fuel compared to electricity use as transport fuel.

The Government of West Bengal has already taken several policy measures to introduce electric mobility in the State including a complete shift towards electrification of public buses by 2030. The Department of Transport in Kolkata has planned the phasewise launch of 80 AC electric buses and out of which 30 buses are currently plying on road<sup>69</sup>.

In the past also, a public policy initiative involving multiple Government departments working with auto-mobility association successfully shifted the city's mobility by banning the 15 year old four-wheelers and shifted to 4-stroke auto-rickshaw which also shifted from kantatel fuel (an adulterated product mix containing petrol, naphtha and kerosene) to LPG based fuel. That led to reduction in emission generated by the 15 year old autos, which accounted for 60% of vehicular pollution<sup>22</sup>.

The benefit was later taken back by increase in number of four wheeler fleets on the road using gasoline/diesel. Electric mobility compatible infrastructure design can act as nudging strategy also for consumers and mobility service providers.

Currently multiple institutions which act independently such as multiple academic institutions within the city, pollution control board, transport department, power utility and oil supply and distribution companies will need strategic coordination. Social innovation to enhance social acceptance for accelerated shift to cleaner fuel and necessary consumer specific cost sharing mechanism will depend how social science research generates knowledge and plays a role in articulation and coordination in institution and policy

innovation in collaboration with scientists and engineers. Inclusive policy and implementation plan design should be the core of such strategy with public debate and transparency in knowledge generation and dissemination involving multiple stakeholders in the process. It cannot be done through current practice of fragmented top down policy silos. Goal of policy sequencing and policy portfolio development can be attached the highest priority in this systemic change design. While financial recovery packages are getting planned, Kolkata city can be a very fertile ground for shift in mobility regime to achieve cleaner air quality for ensuring higher human wellbeing outcome.

## References

1. Alberini A. and Krupnick A., Cost-of-illness and Willingness-to-pay estimates of the benefits of improved air quality: evidence from Taiwan, *Land Economics*, **76**, 37-53 (2000)
2. Amoatey P. et al, Short and long-term impacts of ambient ozone on health in Ahbazi, Iran, *Human and Ecological Risk Assessment: An International*, **25**, 1336-1351 (2019)
3. AQMC, Comprehensive Air Quality Action Plan for Kolkata by Air Quality Monitoring Committee (AQMC), Government of West Bengal (2019)
4. Arakawa A., A personal perspective on the early years of general circulation modeling at UCLA, *Int. Geophys.*, **70**, 1-65 (2000)
5. Bandyopadhyay K., The Times of India. Retrieved from Kolkata's air, 65% laden with PM2.5, deadlier than that of Delhi's: Study, <https://timesofindia.indiatimes.com/city/kolkata/kolkatas-air-65-laden-with-pm2-5-deadlier-than-that-of-delhis-study/article72921350.cms> (2019)
6. Bao R. and Zhang A., Does lockdown reduce air pollution? Evidence from 44 cities in northern China, *Science of the Total Environment*, **731**, 139052 (2020)
7. Barnes P.W. et al, Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future, *Nature Sustainability*, **2**, 569-579 (2019)
8. Central Pollution Control Board, MoEFCC, National Ambient Air Quality Status & Trends-2012 (2014)
9. Central Pollution Control Board, MoEFCC, National Ambient Air Quality Status 2009 (2011)
10. Chandra A. and Chandra H., Impact of Indian and imported coal on Indian thermal power plants, *Journal of Scientific and Industrial Research*, **63**, 156-162 (2004)
11. Chandra S., Ziemke J.R., Bhartia P.K. and Martin R.V., Tropical tropospheric ozone: Implications for dynamics and biomass burning, *Journal of Geophysical Research*, **107**(D14), 4188 (2002)
12. Charlson R.J., The atmosphere, *Int. Geophys.*, **72**, 132-158 (2000)
13. Chen K.S., Ho Y.T., Lai C.H., Tsai Y.A. and Chen S.J., Trends in Concentration of Ground-Level Ozone and Meteorological

Conditions during High Ozone Episodes in the Kao-Ping Airshed, Taiwan, *Journal of the Air & Waste Management Association*, **54**, 36-48 (2004)

14. Chowdhury A.K., Debsarkar A. and Chakrabarty S., Assessment of combined Noise-Air quality and combined exposure to Noise-Air pollution at the curbside open-air microenvironment of Kolkata city, India, *Pollution*, **2**, 35-47 (2016)

15. Dasgupta M., Economic Analysis of Health Benefits from Air Pollution Reduction: A Comparative Case Study of Delhi and Kolkata, International Human Dimensions Programme (IHDP) 6<sup>th</sup> Open Science Meeting held in Bonn, Germany (2005)

16. Denman K.L. et al, Couplings Between Changes in the Climate System and Biogeochemistry, In Climate Change 2007, The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and USA (2007)

17. Duen˜as C., Fern˜andez M. C., Can˜ete S., Carretero J. and Liger E., Assessment of ozone variations and meteorological effects in an urban area in the Mediterranean Coast, *The Science of the Total Environment*, **299**, 97-113 (2002)

18. Etchie T.O. et al, The health burden and economic costs averted by ambient PM2.5 pollution reductions in Nagpur, India, *Environment International*, **102**, 145-156 (2017)

19. Fluxes S., Chapter 7 Parameterization-averaged subgrid-scale fluxes, *Int. Geophys.*, **78**, 164-209 (2002)

20. Gauderman W.J. et al, The Effect of Air Pollution on Lung Development from 10 to 18 Years of Age, *The New England Journal of Medicine*, **351**, 1057-67 (2004)

21. Gautam S. and Berma J., Spatio-temporal variation in the concentration of atmospheric particulate matter: A study in fourth largest urban agglomeration in India, *Environmental Technology & Innovation*, **17**, 100546 (2020)

22. Ghosh P. and Somanathan R., Improving Urban Air Quality in India Lessons from the Kolkata Clean Air Regulations of 2009, Int. Growth Cent. Work. Pap. (2013)

23. Ghude S.D. et al, Premature mortality in India due to PM2.5 and ozone exposure, *Geophysical Research Letters*, **43**, 4650-4658 (2016)

24. Gorai A.K., Tuluri F., Tchounwou P.B. and Ambinakudige S., Influence of local meteorology and NO2 conditions on ground-level ozone concentrations in the eastern part of Texas, USA, *Air Quality, Atmosphere & Health*, **8**, 81-96 (2015)

25. Guo D., Zhao P., Wang R., Yao R. and Hu J., Numerical simulations of the flow field and pollutant dispersion in an idealized urban area under different atmospheric stability conditions, *Process Saf. Environ. Prot.*, **136**, 310-323 (2020)

26. Gupta U., Valuation of Urban Air Pollution: A Case Study of Kanpur City in India, *Environmental Resource Economics*, **41**, 315-326 (2008)

27. Gupta A.K., Karar K. and Srivastava A., Chemical mass balance source apportionment of PM10 and TSP in residential and industrial sites of an urban region of Kolkata, India, *J. Hazard Mater.*, **142**, 279-287 (2007)

28. Guttikunda S.K. and Calorib G., A GIS based emissions inventory at 1 km × 1 km spatial resolution for air pollution analysis in Delhi, India, *Atmospheric Environment*, **67**, 101-111 (2013)

29. Guttikunda S.K. and Kopakka R.V., Source emissions and health impacts of urban air pollution in Hyderabad, India, *Air Quality, Atmosphere & Health*, **7**, 195-207 (2014)

30. Haque S.M. and Singh R.B., Air Pollution and Human Health in Kolkata, India: A Case Study, *Climate*, **5**, 77 (2017)

31. Jhun I., Coull B.A., Zanobetti A. and Koutrakis P., The impact of nitrogen oxides concentration decreases on ozone trends in the USA, *Air Qual. Atmos. Heal.*, **8**, 283-292 (2015)

32. Karambelas A. et al, Urban versus rural health impacts attributable to PM2.5 and O3 in northern India, *Environmental Research Letter*, **13**, 064010 (2018)

33. Karthik B.L., Sujith B., Rizwan S.A. and Sehgal M., Characteristics of the Ozone pollution and its Health Effects in India, *International Journal of Medicine and Public Health*, **7**, 56-60 (2017)

34. KMC, Kolkata Municipal Corporation, Basic Statistics, Retrieved June 8, 2020, from <https://www.kmcgov.in/KMCPortal/jsp/BasicStatistics.jsp> (2018)

35. Lanzi E., Dellink R. and Chateau J., The sectoral and regional economic consequences of outdoor air pollution to 2060, *Energy Economics*, **71**, 89-113 (2018)

36. Li Y., Lau A.K.H., Fung J.C.H., Zheng J. and Liu S., Importance of NOx control for peak ozone reduction in the Pearl River Delta region, *J. Geophys. Res. Atmos*, **118**, 9428-9443 (2013)

37. Lu X., Zhang L. and Shen L., Meteorology and Climate Influences on Tropospheric Ozone: a Review of Natural Sources, Chemistry and Transport Patterns, *Current Pollution Reports*, **5**, 238-260 (2019)

38. Lu X. et al, Rapid Increases in Warm-Season Surface Ozone and Resulting Health Impact in China Since 2013, *Environmental Science & Technology Letters*, **7**, 240-247 (2020)

39. Madala S., Prasad K.H., Srinivas C.V. and Satyanarayana A., Air quality simulation of NOx over the tropical coastal city Chennai in southern India with FLEXPART-WRF, *Atmospheric Environment*, **128**, 65-81 (2016)

40. Mahato S., Pal S. and Ghosh K.G., Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India, *Science of the Total Environment*, **730**, 139086 (2020)

41. Maji K.J., Dikshit A.K. and Deshpande A., Disability-adjusted life years and economic cost assessment of the health effects related to PM2.5 and PM10 pollution in Mumbai and Delhi, in

India from 1991 to 2015, *Environmental Science and Pollution Research*, **24**, 4709-4730 (2017)

42. Majumdar C., The Health Cost of Air Pollution in Kolkata, *The Indian Economic Journal*, **58**, 95-109 (2010)

43. Mani M., Markandya A., Sagar A. and Strukova E., An Analysis of Physical and Monetary Losses of Environmental Health and Natural Resources in India, World Bank (2012)

44. Miao W., Huang X. and Song Y., An economic assessment of the health effects and crop yield losses caused by air pollution in mainland China, *Journal of Environmental Sciences*, **56**, 102-113 (2017)

45. Moeng C.H. and Stevens B., Chapter 19 Representing the stratocumulus-topped boundary layer in GCMs, Academic Press, 577-604 (2000)

46. MRTHTRW, Road transport year book (2015-16) by Government of India Ministry of Road Transport & Highways Transport Research Wing (MRTHTRW), 15 (2018)

47. Murty M., Gulati S. and Banerjee A., Health Benefits from Urban Air Pollution abatement in Indian subcontinent, Institute of Economic Growth, Delhi (2003)

48. NGT, National Green Tribunal (NGT), 1-11 (2019)

49. Ostro B., Estimating the health effects of air pollutants: A method with an application to Jakarta, World Bank (1994)

50. Pancholi P., Kumar A., Singh D. and Chourasiya S., An observation of seasonal and diurnal behavior of O<sub>3</sub> - NO<sub>x</sub> relationships and local / regional oxidant (OX = O<sub>3</sub> + NO<sub>2</sub>) levels at a semi-arid urban site of western India., *Sustain. Environ. Res.*, **28**, 79-89 (2018)

51. Pant P. et al, Monitoring particulate matter in India: recent trends and future outlook, *Air Quality, Atmosphere & Health*, **12**, 45-58 (2019)

52. Pope III C.A., Cropper M., Coggins J. and Cohen A., Health benefits of air pollution abatement policy: Role of the shape of the concentration-response function, *Journal of the Air & Waste Management Association*, **65**, 516-522 (2015)

53. Ravindra K., Singh T., Pandey V. and Mor S., Air pollution trend in Chandigarh city situated in Indo-Gangetic Plains: Understanding seasonality and impact of mitigation strategies, *Science of the Total Environment*, **729**, 138717 (2020)

54. Roy J., Chakravarty D., Dasgupta S., Chakraborty D., Pal S. and Ghosh D., Where is the hope? Blending modern urban lifestyle with cultural practices in India, *Current Opinion in Environmental Sustainability*, **31**, 96-103 (2018)

55. Roy J. et al, Sustainable Development, Poverty Eradication and Reducing Inequalities, In Global Warming of 1.5°C., An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways (2018)

56. Roy A., Chakraborty A., Thakur B. and Chakraborty S., Interrelating Air Quality and Transport near a Heritage Structure :

Victoria Memorial , Kolkata, *Int. J. Res. Advent Technol.*, **5**, 45-55 (2017)

57. Sacratees J., Measuring Benefits From Reduced Air Pollution in Manali Industrial area of Chennai using Contingent Valuation, *Journal of Economic & Social Development*, **9** (2013)

58. Sadanaga Y., Shibata S., Hamana M., Takenaka N. and Bandow H., Weekday/weekend difference of ozone and its precursors in urban areas of Japan, focusing on nitrogen oxides and hydrocarbons, *Atmos Environ.*, **42**, 4708-4723 (2008)

59. Sharma S., Zhang M., Anshika G.J., Zhang H. and Kota S., Effect of restricted emissions during COVID-19 on air quality in India, *Science of the Total Environment*, **728**, 138878 (2020)

60. Shi X. and Brasseur G.P., The Response in Air Quality to the Reduction of Chinese Economic Activities During the COVID-19 Outbreak, *Geophysical Research Letters*, doi:10.1029/2020gl088070 (2020)

61. Shrestha A., Shrestha U., Sharma R., Bhattarai S., Tran H. and Rupakheti M., Lockdown caused by COVID-19 pandemic reduces air pollution in cities, Retrieved June 28, 2020, from EarthArXiv Preprints: <https://eartharxiv.org/edt4j/> (2020)

62. Sicard P. et al, Amplified ozone pollution in cities during the COVID-19 lockdown, *Science of the Total Environment*, **735**, 139542 (2020)

63. Solomon S. et al, Technical Summary. In: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth, Cambridge University Press, UK and USA, 19-92 (2007)

64. Steinfeld J.I., Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, *Environ. Sci. Policy Sustain. Dev.*, **40**, 26-26 (1998)

65. Stensrud D.J., Coniglio M.C., Knopfmeier K.H. and Clark A.J., Numerical Models: Model Physics Parameterization, Second Edi., Elsevier, 167-180 (2015)

66. Stull R.B., An Introduction to Boundary Layer Meteorology, Roland B. Stull, Ed. Springer Netherlands (1988)

67. Tan P.H., Chou C., Liang J.Y., Chou C.C.K. and Shiu C.J., Air pollution "holiday effect" resulting from the Chinese New Year, *Atmospheric Environment*, **43**, 2114-2124 (2009)

68. Tan P.H., Chou C., Liang J.Y. and Chou C.C.K., Impact of urbanization on the air pollution "holiday effect" in Taiwan, *Atmospheric Environment*, **70**, 361-375 (2013)

69. TERI, Successful Operation of Electric Bus Fleet – A Case Study of Kolkata, New Delhi (2020)

70. Tobías A. et al, Changes in air quality during the lockdown in Barcelona (Spain) onemonth into the SARS-CoV-2 epidemic, *Science of the Total Environment*, **726**, 138540 (2020)

71. Venter Z.S., Aunan K., Chowdhury S. and Lelieveld J., COVID-19 lockdowns cause global air pollution declines with implications for public health risk, *medRxiv* (2020)

72. WBPCB, West Bengal Pollution Control Board (WBPCB) Report, Clean Air is Our Birth Right, Fight for Right **(2019)**

73. World Health Organisation, Ambient air pollution: A global assessment of exposure and burden of disease, Geneva **(2016)**

74. World Health Organization, WHO Air quality guidelines for particulate matter, ozone, nitrogen, dioxide and sulfur dioxide, Global update 2005, Summary of risk as **(2006)**

75. Zhang J., Wei Y. and Fang Z., Ozone Pollution: A Major Health Hazard Worldwide, *Frontiers in Immunology*, **10**, 2518 **(2019)**.

(Received 26<sup>th</sup> January 2021, accepted 03<sup>rd</sup> April 2021)