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Gauging the effects of the COVID-19 pandemic lockdowns on atmospheric pollution content in select countries

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1. Introduction

The swift spread and ensuing community transmission of the COVID-19 pandemic since its inception often overwhelmed local healthcare services quite quickly and left the aged and those with existing health issues particularly vulnerable (MacConnachie et al., 2007). Healthcare officials and governments introduced and widely propagated the concept of 'social distancing' (Manderson and Levine, 2020) and 'lockdowns' to limit the spread of the virus, with cancellations of major sporting and cultural events (Munoz and Meyer 2020; Farnell et al., 2020) and diplomatic gatherings (Sharfuddin, 2020), closure of religious institutions (Alyanak, 2020), industries and commercial establishments and the suspension of academic conferences and teaching activities (Gallo and Trompetto, 2020). Such lockdowns sought to heavily restrict the movement of those possibly carrying the contagion and stop healthy people from coming into contact with pre-symptomatic/asymptomatic individuals (Imdad et al., 2020). The Chinese government declared its lockdown period in late January 2020, to slow down the spread of infection (Wilder-Smith and Freedman, 2020). The United States and countries in Western Europe also went into lockdown by early March 2020. Nations like India, where the outbreak became potentially threatening after its initial rampage in East Asia and Western Europe, were somewhat quicker to impose such lockdown measures in late March 2020 (The Lancet, 2020).

Such a complete shutdown of industry and vehicular movements and the substantial decrease in all but essential services inevitably left its imprint on the environment. The European Space Agency (ESA, 2020) and the National Aeronautics and Space Administration (NASA, 2020) released a few satellite image products in April 2020 that showed the marked improvement in air quality as a result of the COVID-19 induced lockdowns and Muhammad et al. (2020) briefly highlighted the global scenario in this respect. There have also been a number of studies that have examined the localized impact of the above lockdowns in different parts of the world and particularly across large cities and regions on the environmental (primarily air) quality (Mahato et al., 2020; Kumari and Toshniwal, 2020; Anil and Alagha, 2020; He et al., 2020c; Singh and Chauhan, 2020; Collivignarelli et al., 2020; Kerimray et al., 2020; Kumar and Managi, 2020; Menut et al., 2020; Baldasano, 2020; Giani et al., 2020; Sahoo et al., 2020; Patel et al., 2020; Wang et al., 2020; Mandal et al., 2021) or brought forth the strong correlation between the improvement of air quality and the COVID-19 induced lockdown (Ghosh and Ghosh, 2020; Mahato and Ghosh, 2020; Sarkar et al., 2020). However, there have been relatively fewer studies (e.g. Acharya et al., 2021) that have mapped and analyzed the lockdown’s effect on the air quality at the entire country level, while at the same time comparing its relative impact across different nations.

An attempt has thus been made here to draw attention to the multiple-country-level spatial impacts of this occurrence across the globe within one succinct account, based on the available NASA satellite datasets of Nitrogen Dioxide (NO2) and the Aerosol Optical Depth (AOD). Aerosols are the solid and liquid particles suspended in the atmosphere and their major sources are windblown dust, sea salts, volcanic ash, smoke from wildfires and pollution from factories and vehicular combustion (NASA, 2020). Traffic pollution is the primary source of tropospheric NO2 (He et al., 2020a, 2020b). Such air pollutants generate short term as well as long term morbidity, with about seven million people worldwide dying from such respiratory induced illnesses (WHO, 2020), and it markedly impacts upon the economies of the most affected nations. Therefore, discerning the extent in reduction of these pollutants is important, as it can provide insights into the how much the local atmosphere can self-purify if no/lesser proportions of pollutants are constantly added to it. This can help frame guidelines to periodically curtail such emissions and achieve some measure of sustainability that less affects the health of the residents of these regions.
2. Material and methods

2.1. Data sources

To investigate the environmental effects of the coronavirus quarantine periods across the globe on the atmospheric quality, two parameters, i.e. NO$_2$ and AOD, have been considered here. Six of the most polluting countries worldwide, where the impact of the virus was notable initially, were chosen. These were- China, India, Italy, France, Germany and the United States (Fig. 1). The various periods examined for each of these countries were -the pre-lockdown phase (the two prior weeks before the lockdown was imposed in each country in 2020), the lockdown itself (held during 2020), the post-lockdown (the two weeks after lockdown measures were lifted in each country in 2020), and the previous year (the same time windows as the respective nations-wise lockdowns but in 2019- regarded as the normal period) (Table 1). The NO$_2$ and the AOD datasets were obtained from the NASA GIOVANNI web portal (https://giovanni.gsfc.nasa.gov/giovanni/). The NO$_2$ Tropospheric Column (30% cloud screened) daily level 3 global 0.25° latitude/longitude grid product of the Aura/Ozone Monitoring Instrument (OMI) and the AOD 550 nm (Deep Blue, Land only) daily L3 global 1° latitude/longitude grid product of the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) were employed here (Table 2). Moreover, the NO$_2$ and the AOD datasets were also obtained for the period of 2005–19 to examine the spatio-temporal concentration of these substances across the globe in more normal times (i.e. over the last 15 years, which is as far back till when both these datasets can be obtained). This longer term view thus depicted the actual usual picture of the pollutants’ distribution across the globe, unaffected by lockdowns. The OMI/Aura sensor was launched in 2004 while the Terra/MODIS sensor was launched in 1999. To have similarity between the datasets, we used the period from 2005 to 2019 for analysis of the pre-lockdown period.

To evaluate the accuracy of classified image files obtained from the NASA GIOVANNI web portal, we used samples of the ground station data of NO$_2$, PM$_{2.5}$ and PM$_{10}$ of the studied countries. This ground level pollution data was collected from the Air Pollution in the World (Real-time Air Quality Index/AQI) web portal (https://aqicn.org/city/all/). Two ground data stations were selected for each country, viz. Beijing and Wuhan for China; R.K. Puram and Victoria for India; Cornale and Milano Sinato for Italy; Ajaccio-Canetto and Pompidan-Tours for France; Wetzlar and Marburg for Germany; and New York and Ware for the United States. These stations were also chosen keeping in mind the previously ascertained most polluted zones of each studied country from

Fig. 1. The six countries studied.

### Table 1

The selected countries and their pre-lockdown, lockdown, and post-lockdown durations.

| Sl. No. | Country       | Normal period, 2019          | Pre-lockdown period, 2020 | Lockdown period, 2020 | Post-lockdown period, 2020 | Population, 2020a | Urban Populationb (%) | World Shareb (%) |
|---------|---------------|------------------------------|----------------------------|-----------------------|---------------------------|-------------------|------------------------|-------------------|
| 1       | China         | 23 January-25 March          | 9 January-22 January      | 23 January-25 March   | 26 March-8 April          | 1,439,323,776     | 61                     | 18.47             |
| 2       | India         | 24 March-14 April            | 11 March-23 March        | 24 March-14 April     | 15 April-28 April         | 1,380,004,385     | 35                     | 17.7              |
| 3       | Italy         | 9 March-18 May               | 24 February-8 March      | 9 March-18 May        | 19 May-1 June             | 60,461,826        | 69                     | 0.78              |
| 4       | France        | 17 March-11 May              | 3 March-16 March         | 17 March-11 May       | 12 May-25 May             | 65,273,511        | 82                     | 0.84              |
| 5       | Germany       | 23 March-20 April            | 9 March-22 March         | 23 March-20 April     | 21 April-4 May            | 83,783,942        | 76                     | 1.08              |
| 6       | United States | 3 March-22 April             | 18 February-2 March      | 3 March-22 April      | 23 April-6 May            | 331,002,651       | 83                     | 4.25              |

an as per Worldometer (2020) based on the latest United Nations Population Division data.

### Table 2

Dataset details.

| Parameter | Agency | Instruments/Platforms | Spatial resolution | Temporal resolution |
|-----------|--------|-----------------------|--------------------|--------------------|
| NO$_2$    | NASA   | OMI/Aura              | 0.25°              | Daily              |
| AOD       | NASA   | Terra/MODIS           | 1°                 | Daily              |

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2.2. Uncertainties of MODIS data

The uncertainties of MODIS data, such as sensor zenith angle and cloud cover are the major limitations in its spatio-temporal analysis. Few researchers (Li et al., 2016, 2019; Muhammad and Thapa, 2020, 2021) have effectively discussed these uncertainties in MODIS data. The present study was conducted on the datasets collected over a 15 year time period, which were primarily the 15-years averaged maps of NO$_2$ and AOD, which seemingly decreases the uncertainty to some extent. For most of the lockdown periods in the respective countries, clear skies were present. Urban and industrial regions are the major source-areas of atmospheric pollutants in contrast to the more sparsely populated rural and mountainous regions.

2.3. Methods

To detect the normal (i.e. usual) spatial-temporal concentration of the NO$_2$ and AOD attributes across the globe, the 15-year (2005–19) time averaged images were prepared from the NASA web portal (Krotkov et al., 2019). The same respective datasets/images of the six countries mentioned above, for the previous year, pre-lockdown phase, lockdown, and post-lockdown periods, were also prepared from the same web portal. The downloaded averaged images were analyzed using the ESRI ArcGIS 10.3 platform. For visual interpretation of the images at the country level and for the world as a whole, these datasets were properly stretched using a fixed range of NO$_2$ and AOD values. As per the dataset legends provided by the NASA portal, areas denoted with dark red and blue tones would represent the maximum and minimum concentrations of NO$_2$. On the other hand, the dark red and yellow tones

![Fig. 2. 15-years averaged map of NO$_2$ distribution across the globe.](image-url)

![Fig. 3. Status of NO$_2$ concentration over China, in - (a) Previous year (23 January - 25 March 2019), (b) Pre-lockdown phase, (c) During lockdown phase, and (d) Post-lockdown phase.](image-url)
would depict the maximum and minimum concentration of the AOD, respectively, in a region.

3. Results and discussion

3.1. Spatio-temporal concentration of NO$_2$ across the globe

The 15-years time averaged map of NO$_2$ concentrations worldwide is shown in Fig. 2. The United States, China, India, France, Germany and Italy, all have a high concentration of NO$_2$, with this being particularly high in a few pockets within each of these countries. These areas thus pose considerable risk for human health. China was the worst affected country, having the highest NO$_2$ concentration levels, followed by India, United States, Italy, France, and Germany (Fig. 2). The tropospheric NO$_2$ column amount has particularly increased during this time period over the newly and rapidly developing regions of China and in other parts of South Asia (Ghude et al., 2009). NO$_2$ is usually added to the tropospheric air column through vehicular emission, industrial activities and from domestic fuel burning. Since, the COVID-19 lockdowns in each of these countries had effectively halted vehicular movement and industrial activity, it was expected that a discernible improvement in the air-quality would likely be observed in each of their most affected regions.

3.2. Spatio-temporal concentration of NO$_2$ in the six nations

The eastern part of China, i.e. the areas of Beijing, Tianjin, Hebei, Shandong, Shanghai, Anhui, Henan, Jiangsu, Shanxi, Shaanxi and Heijian were highly polluted, with more than 2.001 $\times 10^{15}$ molecules/cm$^2$ NO$_2$ levels in the previous year (Fig. 3a) and pre-lockdown periods (Fig. 3b). This concentration level had reduced significantly in the lockdown period (Fig. 3c) but had then also increased sharply in the post-lockdown era (Fig. 3d). However, the contaminant levels in the Tianjin and Shanghai areas were still quite notable, even during the lockdown period, being markedly higher than the levels in the other regions mentioned above. Overall, up to 85% reduction in the NO$_2$ levels was witnessed in the country during the lockdown period but the falling pollutant levels increased soon thereafter (a nearly 35% increase) just after the lockdown. Most countries recorded a 50% reduction of NO$_2$ in their urban areas with the built-up neighbourhoods characterizing a reduction of 33% during the restriction phase (Singh et al., 2021). The reopening of industries and resumption of vehicular movement no doubt added more pollution in the post-lockdown period. On the other hand, there was almost a 75% less concentration of this pollutant during the lockdown as compared to the same time period the previous year.

A few pockets in the eastern part of India (primarily its states along/around the Ganga plains, e.g. Uttar Pradesh, Chhattisgarh, Jharkhand,
West Bengal, Madhya Pradesh, Orissa and Delhi), were the notable polluted zones (Fig. 4). This region witnessed an up to 65% reduction in the concentration of NO$_2$ during the lockdown period. India had also witnessed a remarkable fall in the NO$_2$ column density in 2020 compared to the 2017–2019 average for the month of April–May (Biswas and Ayantika, 2020; Pathakoti et al., 2020; Sharma et al., 2020; Singh et al., 2021). Similar inferences, showing a fall in the NO$_2$ emissions over South Asia were elicited by Shafeeque et al. (2021). This diminished level was also about 40% less than what had existed in the denoted normal period of 2019. The NO$_2$ level remained almost the same even after two weeks of the post-lockdown phase (Fig. 4d). Only, one pocket was witnessed with a more than $2.001 \times 10^{15}$ molecules/cm$^2$ NO$_2$ level in the pre-lockdown period, which reduced up to $0.825 \times 10^{15}$ molecules/cm$^2$ thereafter. The partial relaxation in the transport and industrial sectors in the unlock period obviously added to the air pollution subsequently.

Italy had reported just a nominal amount (below $0.825 \times 10^{15}$ molecules/cm$^2$) of NO$_2$ concentration in its previous normal year period of 2019 and also during the pre-lockdown period, with the post polluted areas being the northern provinces of the country, e.g. Lombardia and

![Fig. 5. Status of NO$_2$ concentration over Italy, in - (a) Previous year (9 March - 18 May 2019), (b) Pre-lockdown phase, (c) During lockdown phase, and (d) Post-lockdown phase.](image-url)
Veneto. About 55% reduction in the contaminant level was noted in the lockdown period (Fig. 5), while the post-lockdown scenario had remained quite similar to the lockdown phase. Similar inferences for major cities of European countries were drawn by Singh et al. (2021).

The northern part of France, i.e. the provinces of Nord-Pas-de-Calais, Picardie and Ile-de-France were the most polluted with respect to NO$_2$ concentration in the previous normal year and in the pre-lockdown phase (Fig. 6a and b), with levels ranging from $0.825 \times 10^{15}$ molecules/cm$^2$ to $1.238 \times 10^{15}$ molecules/cm$^2$. This concentration level had reduced significantly in the lockdown period (Fig. 6c), with the entire country reporting an overall 50% decrease. The continued post-lockdown reduction in the NO$_2$ concentration is shown in Fig. 6d.

In the United States, the states in its eastern part and in the upper mid-east, such as New York, New Jersey, Pennsylvania, Michigan and Connecticut were considerably polluted as per the ambient NO$_2$ concentration levels in the normal and pre-lockdown periods (Fig. 8). These

![Fig. 6. Status of NO$_2$ concentration over France, in - (a) Previous year (17 March - 11 May 2019), (b) Pre-lockdown phase, (c) During lockdown phase, and (d) Post-lockdown phase.](image-url)
levels dropped by up to 65% once the lockdown ensued. The highest concentration in one pocket was noted to be about $1.238 \times 10^{15}$ molecules/cm$^2$ in the normal period while the remaining areas were near $0.413 \times 10^{15}$ molecules/cm$^2$. The lockdown had reduced about $0 \times 10^{15}$ molecules/cm$^2$ of NO$_2$ concentration on average overall in the US.

3.3. Spatial pattern of AOD worldwide

Fig. 9 shows the spatial distribution (based on the 15-year averaged datasets) of the aerosol amounts in the troposphere. Higher aerosol amounts occur over African countries and over the countries of South-east Asia. As this map consists of datasets taken for the whole year,
the aerosol amounts reported were linked to different processes in different places that generated them and at different times of the year (NASA, 2020). Land clearing and agricultural fires were the major contributors for aerosol formation in Africa and South America (Tosca et al., 2013; Martin et al., 2010; De et al., 2019; Morgan et al., 2019), along with the dust particles being blown off the Sahara, Arabian and other deserts. Such dust storms transport particles to the troposphere in the Arabian countries and elevate the aerosol levels along the fringes of the Thar desert in India (Ghosh et al., 2019) and the periphery of the Gobi desert in eastern China (Yang et al., 2017). The burning of field stubble also raises the dust content in the winter months along the foothills of the Himalayan region in the Gangetic plains and across China (Chen et al., 2017; Sharma et al., 2017). These elevated aerosol amounts worsen the pollution effect, adding to that being produced by vehicular and industrial exhausts and severely impair respiration and health (NRC, 2010).

3.4. Spatio-temporal concentration of AOD across the six examined countries

Fig. 10 represents the aerosol amounts in the normal and pre-lockdown phases and during the lockdown and post-lockdown in China. The AOD concentration reduced significantly during the lockdown due to the complete shutdown of the industry and transport sectors. The eastern part of the country, i.e. the provinces of Hebei, Beijing, Henan, Shandong, Shanghai, and Jiangsu recorded AOD values of

![Fig. 8. Status of NO2 concentration over United States, in - (a) Previous year (3 March - 22 April 2019), (b) Pre-lockdown phase, (c) During lockdown phase, and (d) Post-lockdown phase.]

![Fig. 9. 15-years averaged map of AOD concentration across the globe.](image-url)
nearly 1, while Shanxi, Shaanxi, Liaoning, Jilin, Heilongjiang, Guangxi and Sichuan had lower values, around 0.619 AOD. Overall, China witnessed about 70% reduction in its AOD levels during the lockdown period compared to the normal (i.e., same period in 2019) and pre-lockdown phase. There was a 50% reduction over Shanghai, parts of South Korea, Beijing and regions around Xi’an in East Asia in the lockdown period (Singh et al., 2021). A massive reduction in the AOD was similarly observed in the northern part of South Asia in April 2020 (Shafeeq et al., 2021; NASA, 2020). The reopening of industries and renewed movement of vehicles expectedly added more pollution in the post-lockdown phase and hence, a revival of the AOD level was detected (Fig. 10d).

Fig. 11 represents the aerosol concentration over India during the aforementioned four phases. The Gangetic Plains usually record the highest amounts of aerosol concentration during normal times, i.e. in the previous year and pre-lockdown phases, due to industrial pollution, field stubble burning and heavy vehicular emissions (Sharma et al., 2017; Ghosh et al., 2019). Thus, the northern to eastern states of Haryana, Delhi, Uttar Pradesh, Bihar, West Bengal and Assam showed high AOD aerosol concentrations (AOD being nearly 1), while Orissa, Chattisgarh and Andhra Pradesh also reported quite elevated levels (Fig. 11a and b). During the lockdown period, the AOD reduced by about 75% while the post-lockdown increase in this amount was of about 60%. Similar reduction in the AOD over India in the pre-monsoon period of 2020 was detected by Biswas and Ayantika (2020) and Pathakoti et al. (2020).

In Italy, France and Germany, the respective AOD levels were very low in both the normal and pre-lockdown phases (Figs. 12–14). The northern part of Italy and the north-west parts of both France and Germany recorded slightly more AOD concentrations than the remaining areas of these respective countries and the normal-time AOD concentration was also the highest in Germany compared to the other two nations. Slight improvements in the above were noted in the lockdown phase. The post-lockdown scenario is almost similar to that during the lockdown times.
In the United States, the states in its northern part, such as Utah, South Dakota, Colorado and Maine had relatively higher concentrations of AOD in the normal period in 2019 (Fig. 15a). Only a partial dataset was available for the pre-lockdown period. During the lockdown period the AOD reduced by about 45% while the post-lockdown levels had remained similar to those during the lockdown phase (Fig. 15c and d).

3.5. Comparison of satellite derived parameter trends with ground measured information

For an added examination of whether the satellite image captured information regarding the decrease in the NO$_2$ and the AOD levels was truly reflected in the ground conditions, we examined similar data of a
Fig. 12. Status of AOD concentration over Italy, in - (a) Previous year, (b) Pre-lockdown period, (c) During lockdown period, and (d) Post-lockdown period.

Fig. 13. Status of AOD concentration over France, in - (a) Previous year, (b) Pre-lockdown period, (c) During lockdown period, and (d) Post-lockdown period.
select few stations in each of the examined countries/regions. The ground-based NO\textsubscript{2} measurements also showed the sharp decrease in this pollutant’s levels during the lockdown phase with a slight increase once the lockdown was lifted (see Table S1 in the Supplementary Information file). Some of the sharpest reductions in this regard were noted for the R. K. Puram station in New Delhi, India and also for the Victoria station in Kolkata, India. Lesser degrees of change were apparent for stations in China, USA, Italy and France. Strangely, the Wetzlar station in Germany actually reported an increase in the NO\textsubscript{2} levels during the lockdown while that country’s Marburg station also reported only a very slight decline in this pollutant, possibly due a partial operation of the industries herein as they are centres of precision engineering and manufacturing. What was observed across the board however was that in the post-lockdown period, NO\textsubscript{2} levels had immediately not gone back up to their pre-lockdown levels but had continued to mostly remain near the levels attained during the lockdown or even declined slightly in some cases. This is significant as it highlights the marked effect of cleansing the atmosphere that a short lockdown period can have and is also indicative of the window for which this condition can last. Therefore, temporary such stoppages of short duration at the regional level could be a sustainable way of partially improving the ambient air quality.

For the AOD comparison, we used the PM\textsubscript{2.5} and PM\textsubscript{10} data that was available for the above stations. Again, it was apparent that the aerosol or atmospheric particulate matter had declined in concentration during the lockdown period in almost all the observed stations and that their respective values were at lower levels than before even in the post-lockdown phase. Thus, there was a significant declining trend in both the pollutants’ level between the pre-lockdown and the lockdown as well as post-lockdown periods. This reveals the similarity of trends recorded between the compared datasets and validates our analysis.

4. Conclusion

The present study has assessed the extent to which the improvement in two parameters of air quality occurred as a result of the COVID-19 induced shutdowns across the world. Before such lockdowns were put in place, China had the highest levels of tropospheric air pollution, followed by India, United States, Germany, France and Italy. Despite using quite coarser resolution datasets and having some dataset limitations, an overall nearly 60% reduction in the pollutant levels was witnessed worldwide during the lockdown period. These levels varied for the individual nations examined in this study as well as the rate at which the contaminants reached close to their pre-lockdown levels after restrictions were lifted. Therefore, such a recession or lockdown for 3–5 days every month (possibly through extended weekends) could be quite fruitful towards checking air pollution levels, thereby saving many lives (Srivastava et al., 2020) and having a more sustainable environment (PTI, 2020). This may allow nature to essentially ‘reboot’ and enable a better standard of living all round. From the perspective of geographical philosophy, it can be further mentioned that such improvements in the air quality as a result of these lockdowns quite tallies with the old concept of ‘neo-determinism’ or ‘stop-and-go determinism’ as postulated by Griffith Taylor (Hardin, 2009). In this, nature reacts and exacts a price as per the human use of the environment (Lewthwaite, 1966) or again revitalizes itself when external anthropogenic perturbations do

Fig. 14. Status of AOD concentration over Germany, in - (a) Previous year, (b) Pre-lockdown period, (c) During lockdown period, and (d) Post-lockdown period.
not exceed the ecological thresholds, thereby showing the most sustainable path development (Minshull, 2014).

CRediT authorship contribution statement

Jayatra Mandal: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. Priyank Pravin Patel: Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2021.100551.

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Fig. 15. Status of AOD concentration over United States, in - (a) Previous year, (b) Pre-lockdown period, (c) During lockdown period, and (d) Post-lockdown period.
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