Impacts of reduced deposition of atmospheric nitrogen on coastal marine eco-system during substantial shift in human activities in the twenty-first century

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ABSTRACT
The novel infectious disease (COVID-19) took only a few weeks from its official inception in December 2019 to become a global pandemic in early 2020. Countries across the world went to lockdown, and various strict measures were implemented to reduce the further spread of the infection. Although, the strict lockdown measures were aimed at stopping the spread of COVID-19, however, its positive implications were also observed for the environmental conditions across the global regions. The present study attempted to explore the eco-restoration of coastal marine system in response to reduced deposition of atmospheric nitrogen (NO2) emission during the substantial shift in human activities across the global metropolitan cities. Remotely data of NO2 emission were taken from Ozone Monitoring Instrument and the coastal water quality along the marine system was estimated from MODIS-Aqua Level-3 using Semi-Analytic Sediment Model (SASM). The changes in tropospheric NO2 in 2020s were also compared with the long-term average changes over the baseline period 2015 − 2019. A significant reduction in anthropogenic mobility (85−90%) has been observed in almost all countries over

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different places, especially grocery, parks, workplaces, and transit stations. A massive reduction in tropospheric NO$_2$ was detected in Wuhan (53%), Berlin (42%), London (41%), Karachi (40%), Paris (38%), Santiago (35%), and Chennai (34%) during the strict lockdown period of the early 2020 as compared to the last five years. However, after the partial lockdown was lifted, tropospheric NO$_2$ values bounced back and slightly increased over Karachi (6%) and Bremen (12%). For water turbidity, the rate of reduction was found to be the highest along the different coastal regions of the Mediterranean Sea and Black Sea (51%), West Atlantic Ocean (32%), East Atlantic Ocean (29%), and Indian Ocean (21%) from Apr to Jun 2020. The monthly comparison of overland-runoff in 2020 compared to 2019 across the different coastal watersheds indicates that the observed decline in turbidity might have been due to the reduced deposition of atmospheric nitrogen. The findings of this study suggest that the recent decline in tropospheric NO$_2$ and water turbidity might be associated with reduced emissions from fossil fuels and road transports followed by COVID-19 forced restrictions in the twenty-first century. The inferences made here highlight the hope of improving the global environmental quality by reducing greenhouse gas emissions using innovative periodic confinement measures on heavy transport and industries while securing public health and socioeconomics.

1. Introduction

World Health Organization (WHO 2020) reported some cases of novel infectious disease in China in the late December 2019 (Zhu et al. 2020), and at that time, its etiology was unknown (Sohrabi et al. 2020). However, after a few weeks, the infectious disease spread quickly, not only in Wuhan but also in other regions of China (Anderson et al. 2020; Dutheil et al. 2020). Typical symptoms of COVID-19 were reported as fever, dry cough, myalgia, pneumonia, and failure of the respiratory system, and severe illness that may result in death (Huang et al. 2020; Öcal et al. 2020). In late January 2020, the Chinese government claimed that this infectious disease is a new type of coronavirus and named it COVID-19 (Chen et al. 2020; Li et al. 2020b). Government authorities start to implement the different response strategies based on community interventions such as mask-wearing, person-to-person distancing, isolation to reduce the impact COVID-19 spreading (Cvetković et al. 2020). Until 23 January 2020, Wuhan became the first city under quarantine, and subsequently, other regions of the country also went under the COVID-19 forced confinement to prevent further spread of the disease (Wilder-Smith et al. 2020). The Chinese government shut down public transport, parks, educational centers, business centers, and other social places to restrict the transmission rate. WHO declared a worldwide public health emergency on 30 January 2020, after observing the alarming situation of COVID-19 in China. The National Health Commission of China reported more than 81,000 confirmed cases and 3255 deaths until 21 March 2020. The outbreak of COVID-19 spread quickly to many other countries, with the total number of people affected worldwide reaching approximately 3.2 million, and the number of total deaths recorded exceeding 224,300 by 1 May 2020 (WHO 2020). Subsequently, the
epidemic in China turned into a worldwide pandemic, and many countries went into lockdown, constraining major human activities globally (Tosepu et al. 2020). Communications, transportation, culture, education, and industrial manufacturing were among the most affected sectors by the pandemic. While the strict lockdown measures came with social and human health consequences (Bai et al. 2020; Sohrabi et al. 2020) and adverse economic impacts worldwide (Lai et al. 2020), positive effects on the environment were also observed due to the reduction of air pollutants such as tropospheric nitrogen dioxide (NO₂) emission (Dutheil et al. 2020; Shafeeque et al. 2021). Nitrogen dioxide (NO₂) is a highly reactive pollutant of primarily anthropogenic origins, including road traffic and industrial activities (He et al. 2020; Kurz et al. 2014). Several legislations have been executed over the past few decades to diminish the atmospheric pollution level worldwide; however, most of the major cities are still exceeding the WHO air quality standards. The ongoing restrictions and substantial shift in anthropogenic activities during the COVID-19 forced confinement have reduced the emissions of Nitrogen dioxide (NO₂) (Mahato et al. 2020), and thus, resulted in a notable improvement in air quality across the world’s cities (Isaifan 2020; Sharma et al. 2020).

Our study hypothesized that overall atmospheric Nitrogen loading during the COVID-19 forced confinement has significantly declined in the coastal cities, which subsequently may improve the water quality and the marine coastal aquatic system (Mishra et al. 2020). Nitrogen loading to coastal marine systems mainly comprises urban nutrients, atmospheric deposition, coastal upwelling, and agriculture on-farm practices (Voss et al. 2013; Ramesh et al. 2017). However, atmospheric Nitrogen deposition contributed about 40% of coastal marine water pollution (Ramesh et al. 2017). Shreds of evidence were also published about the variations in bioavailable N loadings affect coastal regions’ pollution levels (Mishra et al. 2020). In the coastal marine ecosystem, smaller values of chlorophyll-a (chl-a) and turbidity, a proxy to represent the phytoplankton biomass, indicate a reduced level of water pollution. To better explore the linkage between atmospheric pollution and coastal marine ecosystems, it is necessary to investigate the relationship between NO₂ emissions and coastal turbidity and consider the watershed fluxes (precipitation and overland-surface runoff) to neutralize the effects of nitrogen loading caused by overall runoff. This phenomenon has not been appropriately addressed in the previous studies conducted during global strict lockdown measures in 2020. Therefore, the quantitative assessments to explore the linkage between atmospheric-marine pollution during ongoing "anthropogenic emissions switch off" might be helpful to understand the effectiveness of reduced consumption of fossil fuels.

The current study attempted to (a) investigate the reduced atmospheric NO₂ during COVID-19 forced confinement over the coastal cities scattered along the four continents (Asia, Europe, African, and Americas), and (b) investigate the coastal marine water quality in terms of turbidity along the coastal cities scattered along the Indian Ocean, Baltic Sea, Mediterranean Sea, Euro-Africa East Atlantic Ocean, West Atlantic Ocean along with North and South USA, and (c) address the possible linkage between atmospheric-marine water pollution and reduced deposition of atmospheric nitrogen using hydrological fluxes data (e.g. precipitation and land-runoff). Lack of in


**Figure 1.** Map of study regions, including (a) geographical locations of different cities selected for highlighting the tropospheric NO₂ changes over global scale and (b) coastal regions along the different Oceans for monitoring coastal water quality.

_situ_ observations restricts our ability to investigate real-time changes in tropospheric NO₂ and coastal water quality at the global scale. As a powerful alternative, satellites provide real-time remotely sensed data to analyze the water and atmospheric phenomenon at a large spatial and temporal scale with global coverage (Zhang et al. 2018; Han 2019; Kong et al. 2019; Zhang et al. 2019; Mishra et al. 2020). Ozone Monitoring Instrument (OMI) (Latif et al. 2021) and Sentinel-5 Precursor Tropospheric Monitoring Instrument (TROPOMI) were recently missioned to map air pollution worldwide. Surface Reflectance data from MODIS onboard Aqua/Terra sensors at 250 m resolution and daily temporal scale provide a better understanding of the coastal marine water quality (Yang et al. 2018). Herein, the effects of ongoing restricted anthropogenic activities on the atmospheric NO₂ are investigated based on real-time observations from the OMI satellite by comparing NO₂ in 2020 with the average of past years (2015 – 2019). The impacts of reduced atmospheric pollutants on the coastal marine ecosystem were investigated using overland surface runoff changes across the different coastal watersheds based on data from MERRA-2 v5.12.4 at a spatial resolution of 0.5° × 0.625°.
2. Materials and methods

2.1. Description of the study area

This study analyzed the tropospheric NO\textsubscript{2} variations covering five major study regions, namely North America, South America, Europe, Asia (including South Asia, and East Asia), and Africa, as shown in Figure 1(a). The red boxes represent four continents (Asia, Europe, America, and Africa) selected for the analysis of the tropospheric NO\textsubscript{2} changes on a global scale. We selected 37 cities, most of which are located along the coastal regions, mainly scattered over China, Pakistan, India, Bangladesh, Spain, France, Germany, Poland, Italy, the United Kingdom, the United States, Argentina, and Chile, among others. Moreover, for coastal marine water quality, we selected 36 coastal regions located in the West Pacific Ocean, Indian Ocean, Baltic Sea, Mediterranean Sea, East Atlantic (Europe), East Atlantic (Africa), West Atlantic (North USA), and West Atlantic (South USA) as shown in Figure 1(b). These coastal regions were selected based on their close proximity to the urbanized regions.
areas and watershed discharge outlets. Detailed description of the selected coastal regions is summarized in Table 1.

2.2. Data Collection

Satellites’ instruments in space provide global views of the planet’s air pollution, such as a tropospheric column density of NO₂, which is extremely valuable for health and air quality applications. OMI is a UV–Visible wavelength spectrometer onboard the NASA Aura satellite launched in July 2004. The OMI sensor measures backscattered radiations from the Earth and atmosphere over the broad wavelength of 270 – 500 nm to detect trace gases. It provides data of tropospheric NO₂ columns with global coverage at a daily temporal scale with a spatial resolution of 13 \times 24 \text{km}² (Levelt et al. 2006). The tropospheric NO₂ column is derived from satellite observations based on slant column retrievals using the differential optical absorption spectroscopy (DOAS) technique (Krotkov et al. 2017; van Geffen et al. 2018; Geffen et al. 2020). Daily time series data of tropospheric NO₂ from 2015 to 2020 over selected cities were collected from NASA, Goddard Space Flight Center. We also collected the monthly images of tropospheric NO₂ prepared by NASA, Goddard Space Flight Center for spatial analysis. Daily data of MODIS land surface reflectance band-1 of MYD09GQ product at a spatial resolution of 250 m \times 250 m were collected from the Land Processes Distributed Active Archive Center (LP DAAC) for the year 2019 and 2020. The impacts of reduced atmospheric pollutants on the coastal marine ecosystem were investigated using over-land-runoff and precipitation changes across the different coastal watersheds based on data from MERRA-2 v5.12.4 at a spatial resolution of 0.5° \times 0.625°.

Moreover, time-series data of the human mobility index from Jan – Oct 2020 were obtained from Google mobility reports to account for the anthropogenic mobility and substantial shift in anthropogenic activities during the COVID-19 forced confinement.

2.3. Methodology

2.3.1. Tropospheric NO₂ monitoring

For continental and country scales, we compared the spatial images of tropospheric NO₂ in 2020 (before and after lockdown) with baseline data (2015 – 2019) to shed light on unusual variations in NO₂ under controlled anthropogenic emission during COVID-19 forced confinement. We used daily time-series of NO₂ for the selected global metropolitan cities. The data were averaged over a 15-day window for (a) 2020 (during the epidemic), and (b) averaged over long-term baseline (2015 – 2019). The percentage changes were calculated based on the differences between actual values (NO₂ in 2020) and the long-term baseline average (2015 – 2019). In the present study, pre-assumption behind the baseline period was that the air quality changes in this period reacted to normal states of anthropogenic emissions while the changes noticeable all around from Jan – Oct 2020 were caused fundamentally by impacts of the nations’ strict lockdowns when the majority of the anthropogenic emissions were switched off (Gil et al. 2008; Mahato et al. 2020; Zhang et al. 2020). Moreover,
considering data from the past several years could help to reduce the effects of interannual climatic variability and uncertainties in resulting anomalies (Sicard et al. 2020).

2.3.2. Modeling coastal marine water quality
For modeling coastal water quality in terms of turbidity, we have used a Semi-Analytic Sediment Model (SASM), which was already applied to MODIS Aqua observations (Dorji et al. 2016). Recently SASM model has been used by (Yang et al. 2018) using MODIS Terra observations and found that this model performed better than other linear and exponential models (Dorji and Fearns 2017). Algorithms of the SASM model used in the present study are explained as following (Eq. (1))

\[
\text{Turbidity} = \frac{a \times \left(\frac{x}{1-x}\right)}{1 - b \times \left(\frac{x}{1-x}\right)}
\]  

(1)

The \(a\) and \(b\), are the model calibrated parameters derived using regression analysis between in situ observations and \(x\) is the model parameter and it was calculated by applying the following Eq. (2)

\[
x = \frac{a \times \sqrt{g_1^2 + 4 \times g_2 \times r_s}}{2 \times g_2}
\]  

(2)

where \(g_1\) and \(g_2\) are constant model parameters with values 0.0846 and 0.17, respectively. The \(r_s\) is calculated from surface reflectance data of MODIS onboard Terra sensor as follows:

\[
r_s = \frac{R_s}{0.52 + 1.7 \times R_s}
\]  

(3)

Due to the lack of ground observation data of coastal water quality, we have used already calibrated model parameters values of \(a\) and \(b\) by (Yang et al. 2018). Comparison between in situ observation turbidity and MODIS retrieved turbidity shows higher correlation \((R^2 = 0.89)\) and lower bias (Yang et al. 2018).

3. Results and discussion
3.1. COVID-19 outbreak and substantial shift in human activities
The COVID-19 outbreak began in late December 2019, and in the early phase, COVID-19 cases were detected in Asian countries, while half a month later, it transformed into a global pandemic and began to spread in other regions of the globe. By 24 July 2020, the total number of confirmed COVID-19 cases and deaths worldwide were 15,296,926 and 628,903, respectively (WHO 2020). However, the majority of COVID-19 confirmed cases (and deaths) were recorded in the United States (8,121,700 (325,625)) followed by Europe (3,170,182 (209,421)), and South-East Asia (1,625,564 (38,111)). Various management strategies were implemented by national governments and authorities of each country to minimize the spread of COVID-19, including the
complete lockdown, partial lockdown, home, and mass isolations, restricted domestic and international traveling, prohibited social gatherings, curfews, and declaring a state of emergency (McCurry et al. 2020). These management policies have imposed strong impacts to reduce anthropogenic mobility (Shafeeque et al. 2021).

Figure 2 illustrates the time series of anthropogenic mobility index for grocery, parks, workplaces, rural sites, and transit stations. A substantial shift in human activities could be seen during the COVID-19 lockdown, where overall anthropogenic mobility essentially decreased by 85 – 90% in different places, especially across Poland, Italy, France, and the United Kingdom. In contrast, this mobility trend in residential areas gradually increased by 35 – 50% due to COVID-19 forced confinements (Muhammad et al. 2020). COVID-19 forced confinement dramatically reduced anthropogenic activities, for example, transport and industrial activities, which eventually resulted in a decline in energy consumption and lowered oil demands. These changes significantly impact the environmental quality, particularly over the metropolitan urban communities (Dutheil et al. 2020; Muhammad et al. 2020).

Figure 2. Daily time series of anthropogenic mobility in different countries based on Google tracking reports. Note: vertical lines sketched in red, blue, and green represent the pre-lockdown, strict lockdown, and second wave.
Figure 3. Spatiotemporal variations in airborne nitrogen dioxide (NO$_2$) over America before and after lockdown (2020) compared to the baseline average (2015 – 2019).
Regional changes in tropospheric NO$_2$ were investigated over four continents and five subcontinents, including North America, South America, Europe, East Asia, and South Asia, using satellite imagery from the NASA OMI sensor released. These imageries were taken at a monthly time scale for four different periods such as pre-lockdown stage (Feb 2020), strict lockdown stage (April and May 2020), loosening lockdown stage (Aug 2020), and second-wave (Oct 2020) and compared with the long-term baseline average (2015–2019).

Figure 3 illustrates the monthly spatiotemporal changes in tropospheric NO$_2$ over North America and South America. The tropospheric NO$_2$ shown in the maps was higher in cities in North America, especially New York, Washington, and Atlanta, compared to South America. However, after implementing COVID-19 lockdown and ongoing restricted human activities, a clear drop in tropospheric NO$_2$ could be seen in North America from Apr–Oct 2020 compared to the baseline average (2015–2019). The changes in tropospheric NO$_2$ are not as discernable over South America, even during the lockdown period. This might be because the NO$_2$ level was already much lower over South America compared to North America. However, during the loosening lockdown stage (Aug–Oct), tropospheric NO$_2$ increased in 2020 compared to past years average (2015–2019). The tropospheric NO$_2$ during Mar–Apr 2020 declined about 40% over some regions of Southeast U.S. and about 30% over the Northeast U.S. [https://earthobservatory.nasa.gov/images](https://earthobservatory.nasa.gov/images) (Last access 15 April). Recent improvements in air quality could be explained by "anthropogenic emissions switch off" after various strict lockdown measures were adopted. Reduction in NO$_2$ levels was presumably due to less consumption of fossil fuels associated with the pandemic lockdown (Wang and Su 2020).

Figure 4 shows the spatial changes in tropospheric NO$_2$ during different lockdown stages in 2020 compared to the long-term baseline average (2015–2019) over the European countries. It can be seen that tropospheric NO$_2$ was approximately near baseline average before the 2020 lockdown; however, the post-lockdown tropospheric
NO\textsubscript{2} tended to drop across the European countries, including France, Spain, German, and Italy (Figure 4). A higher drop in tropospheric NO\textsubscript{2} over the United Kingdom (UK) and Germany might be explained by reduced ground transportation during the COVID-19 forced confinement. In European countries, most of the NO\textsubscript{2} is from emissions from road transportation, which experienced a relative decline following COVID-19 lockdown (Zhang et al. 2020; Zhu et al. 2020). For example, the tropospheric NO\textsubscript{2} over the UK and Germany was approximately 8 – 9 \times 10^{15} \text{ molecules/cm}^{2} in 2020, relatively close to the baseline average, before the lockdown, which to <5 \times 10^{15} \text{ molecules/cm}^{2} after the lockdown (especially from Apr – May). Recent imageries published by ESA (European Space Agency) also reported that tropospheric NO\textsubscript{2} during Mar – Apr 2020 had dropped about 54% over France, 48% over Spain, and 49% over Italy compared to the mean of 2019 https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P. The dramatic drop in NO\textsubscript{2} across Europe coincided with the substantial shift in human activities during the lockdown periods (Lal et al. 2020).

Figure 5 presents the variation in tropospheric NO\textsubscript{2} across the Asian subcontinents (South Asia and East Asia), mainly covering four countries, namely China, India, Bangladesh, and Pakistan. The results reflect the dramatic reduction in tropospheric NO\textsubscript{2} during the strict lockdown (Feb – Mar) over East Asia (China), which bounced back to the baseline average after the lockdown was lifted partially. According to NASA https://earthobservatory.nasa.gov/images. (Last access 15 April), the recent improvement in air quality firstly appeared near Wuhan (China) but eventually spread across the country. (Liu et al. 2020) measured the 48% drop through satellite data in tropospheric NO\textsubscript{2} in first 20 days of lockdown period over China. (Li et al. 2020a) studied the air quality during a lockdown of COVID-19 first and second wave in the Yangtze River Delta region, reporting that concentration of SO\textsubscript{2}, NO\textsubscript{2}, and PM2.5 decreased 20.4%, 45.1%, and 31.8% in 1st wave and 7.6%, 27.2%, and 33.2% in second wave, respectively. The NO\textsubscript{2} reduction was higher in both waves at 45.1% and 27.2%.
The recent uneven reduction in NO$_2$ might be associated with a decline in industrial activities and transportation emissions. Coal-fired power generation and air transportation activities in China were reduced by 50% and 80% in by mid-February, respectively. These changes lasted for 35 – 40 days even after the Chinese New Year. However, after this period, a clear bounce-back occurred in coal-fired power generation and air transportation activities, which can be explained by partial lifting of lockdown (Bauwens et al. 2020; Myllyvirta 2020). The results of this study revealed that the tropospheric NO$_2$ substantially dropped over South Asia during the 2020
lockdown (Apr – May; Figure 5). South Asian countries, mainly India, Pakistan, and Bangladesh, have been severely affected by the outbreak of COVID-19. Alarmed by the first case of COVID-19 in early March, these countries imposed a strict lockdown from mid-March. As a result of strict lockdown measures, a remarkable decline in tropospheric NO2 was seen in 2020 over Bangladesh and India. However, the variations over Pakistan were not much apparent, possibly due to fewer restrictions on public activities. Rather than a strict lock-down, Pakistan implemented “smart lockdown” to cause minimal adverse impact on social and economic conditions while reducing the spread of infection successfully. New satellite imageries released by ESA and recently published studies also reported that the average tropospheric NO2 over the Asian counties reduced 40 – 50% in 2020 during the quarantine period compared to the average of last year (Arshad et al. 2020). The recent decline in tropospheric NO2 is associated with less consumption of fossil fuels (Sharma et al. 2020; Wang et al. 2021) due to the sharp reduction in transport and industry, which ultimately resulted in less air pollution (Mahato et al. 2020). (Gautam 2020) also investigated

| Table 2. Percentage changes in tropospheric NO2 changes in different lockdown scenarios over the selected coastal cities. |
|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Continents Countries City | Jan – Mar | Apr – Jun | Jul – Sep | Oct – Nov | Oceans |
| South Asia Pakistan | Karachi | 2.4 | –12.17 | 5.19 | –18.85 | Indian Ocean |
| Pakistan | 1.39 | –15.89 | 13.64 | –21.89 | |
| India | Ahmadabad | 3.21 | –19.45 | –4.57 | –18.77 | |
| India | Chennai | –9.76 | –35.56 | –12.23 | –17.67 | |
| India | Calcutta | 2.01 | –19.83 | 2.78 | –24.34 | |
| Bangladesh | Dhaka | 3.56 | –23.15 | –16.42 | –9.82 | |
| East Asia Vietnam | Hanoi | 16.57 | 3.55 | 15.47 | –28.68 | West Pacific Ocean |
| Vietnam | Ho Chi Min City | 6.88 | 10.28 | 11.64 | –11.62 | |
| China | Guangzhou | –32.19 | –14.14 | –6.39 | –27.22 | |
| China | Shanghai | –37.12 | –9.19 | –4.39 | –15.89 | |
| China | Tianjin | –15.93 | –9.86 | –9.45 | –13.67 | |
| China | Beijing | –20.95 | –21.15 | –11.87 | –13.92 | |
| China | Wuhan | –48.51 | –17.34 | –4.87 | –10.7 | |
| Europe & Africa Spain | Barcelona | 2.78 | –36.2 | –14.59 | –17.56 | Mediterranean and Black Sea |
| Italy | Rome | 6.3 | –23.57 | –11.45 | –14.67 | |
| Italy | Venice | 1.35 | –26.19 | –18.31 | –24.98 | |
| Romania | Bucharest | 18.37 | –4.63 | –9.93 | –16.92 | |
| Pland | Warsaw | 2.67 | –24.44 | –18.43 | –17.92 | |
| Portugal | Lisbon | 5.32 | –15.28 | 2.45 | –19.21 | |
| France | Paris | 7.89 | –38.65 | –18.45 | –7.94 | |
| Netherlands | Amsterdam | 12.56 | –26.18 | –23.35 | –25.92 | |
| Germany | Bremen | –4.3 | –16.66 | –9.67 | –17.07 | |
| Germany | Berlin | –1.89 | –40.75 | –9.78 | –15.89 | |
| UK | London | –3.78 | –32.14 | –28.65 | –34.01 | |
| North America United States | Boston | 4.89 | –12.78 | –6.95 | –12.02 | West Atlantic Ocean (North USA) |
| United States | New York | 2.73 | –31.5 | –17.68 | –31.26 | |
| United States | Washington | –19.58 | –12.94 | –8.89 | –29.38 | |
| United States | New Orleans | 4.12 | 0.83 | –5.55 | –34.56 | |
| United States | Miami | 8.16 | –12.37 | –7.5 | –20.39 | |
| Mexico | Mexico City | –3.92 | –30.66 | –18.3 | –21.78 | |
| South America Argentina | Buenos Aires | 1.32 | –22.8 | –12.7 | –14.23 | West Atlantic Ocean (South USA) |
| Brazil | Belem | –2.23 | 1.29 | 11.03 | 8.38 | |
| Brazil | Saopaulo | 1.08 | –28.75 | –18.79 | –22.55 | |
| Venezuela | Caracas | –10.84 | 12.46 | –12.08 | –39.29 | |
| Mozambique | Maputo | 2.34 | –34.36 | –21.34 | –13.67 | |
| Cameroon | Yaunde | –8.4 | 24.12 | 27.34 | –9.15 | |
| Congo | Brazzaville | –5.66 | 3.85 | 13.35 | –15.42 | |

Note: light to dark red color represents the percentage increase which light to dark green color represents the percentage decrease.
that the NO₂ concentration reduction over India and China during COVID-19 emergency conditions by 20 – 30% and 70%, respectively.

### 3.3. Changes in tropospheric NO₂ along with coastal cities

In this study, changes in tropospheric NO₂ were tracked across the 37 major cities, mostly scattered along the coastal regions (Figure 1(a)). Example time series of 15-day average tropospheric NO₂ in 27 coastal cities (Figure 6) show how NO₂ concentration in 2020 changed over time relative to the baseline average (2015 – 2019). Before the lockdown period, the running means of 2020 and the 2015 – 2019 NO₂ concentration time series coincided, displaying an up and down fluctuation. This confirms that pre-lockdown human activities were continuing normally, releasing NO₂ in the atmosphere following the patterns of past years. After the lockdown was imposed, the daily time series values in 2020 had a lower mean than the long-term baseline average 2015 – 2019 time series. NO₂ in most cities reduced, although abrupt variations occurred across Chennai, London, Barcelona, Venice, Amsterdam, and New York.

Tropospheric NO₂ tends to decline day by day in response to restricted human activities, especially manufacturing and transportation (Sharma et al. 2020). For example, in Lahore city (Pakistan), the mean NO₂ time series in 2020 (before lockdown) is following the patterns of NO₂ time series of the past years 2015 – 2019 with a fluctuating trend; however, after a national lockdown in Pakistan around 25 March 2020, NO₂ starts decreasing gradually, running with a lower mean than that of 2015 – 2019. However, some cities (e.g. Karachi, Beijing, and Wuhan), showed a slight increase in the tropospheric NO₂ and bounced back to past years’ average, which was associated with the partial lockdown being lifted. Other studies also reported that air pollution drastically slowed down within a few days into the lockdown (Isaifan 2020; Mahato et al. 2020) over the major metropolitan and industrialized regions (Chauhan and Singh 2020). The reduced tropospheric NO₂ is associated with the substantial shifts in human activities (Sulaman et al. 2020) following COVID-19 restrictions due to less fossil fuel consumption and other anthropogenic emissions (Dutheil et al. 2020; Muhammad et al. 2020).

Table 2 presents the percentage reduction in tropospheric NO₂ in 2020 compared to the baseline average (2015 – 2019) during different lockdown scenarios over the 36 major metropolitan cities. Before the lockdown period, some cities showed a slight reduction in tropospheric NO₂; however, in the pre-lockdown and strict lockdown stage, a significant drop in tropospheric NO₂ could be seen in all the selected cities. For example, the massive reduction in NO₂ level in 2020 was approximately 34% over Chennai, approximately 35% over Santiago, approximately 38% over Paris, 40% over Lahore, 41% over London, 42% over Berlin, and 53% over Wuhan during the strict lockdown period. However, the rate of decline in tropospheric NO₂ slightly slowed down in all the selected cities during the partial/loosening lockdown period. Meanwhile, some cities, like Karachi and Bremen, also showed a substantial increase in tropospheric NO₂ during this period.

### 3.4. Water quality assessment along the coastal regions

The turbidity of the coastal region was investigated as a proxy of coastal water quality using daily surface reflectance data from MODIS onboard Terra sensor during
different lockdown scenarios in 2020 as compared with the pre-COVID condition in 2019. The turbidity of coastal water quality was estimated over 36 coastal regions scattered mainly in the Indian Ocean, West Pacific Ocean, Mediterranean Sea, Black Sea, East the Atlantic Ocean, and West Atlantic Ocean. During the strict lockdown (SLD) period, turbidity values substantially declined along the coastal regions of the Indian Ocean and West Pacific Ocean, especially changes are much visible over three coastal regions of Karachi, Bombay, and Calcutta in the Indian Ocean, and Haiphong, Shanghai, and Guangzhou in the West Pacific Ocean (Figure 7). Turbidity along some coastal regions was higher in the pre-lockdown stage (PLD) in 2020 and was highly comparable to the past year 2019 with slight variations. A visible decline in turbidity could be seen in most coastal regions after the strict lockdown (SLD) was imposed. For example, the changes are discernable along the coastal regions of Shanghai, China, with an apparent decline in turbidity during the strict lockdown; however, when the lockdown was loosened after mid-March, the turbidity values started to approach the previous year’s average. Again, during the implementation of smart lockdown in the second wave over some countries such as Pakistan, India, and Bangladesh, turbidity values declined over the coastal areas of these countries compared to 2019.

Malabo, Roma, Bcuresti, Veneza, Bremen, Gdansk, London, and Amsterdam in coastal regions of the East Atlantic Ocean, Mediterranean, and the Black Sea show a significant decline in turbidity during the strict lockdown and second wave scenarios
in 2020 (Figure 8). Interestingly, the rate of reduction seems to be higher over the coastal regions of London, Veneza, and Amsterdam. By contrast, coastal regions such as Lisbo and Nantes, showed no significant decrease in turbidity in 2020 compared to 2019, which might be due to the fact that turbidity levels in these regions are already lower than in other coastal areas.

Figure 9 illustrates the time series variations in the 15-days moving average of turbidity in 2020 compared to 2019 for different lockdown scenarios over coastal regions of the West Atlantic Ocean. The turbidity in 2020 is generally lower than 2019 over most of the coastal regions. We can see significant decline of turbidity during the strict lockdown period over the coastal areas of Boston, New York, Port of Spain, and Buenos Aires. Following the lifting of the lockdown, the turbidity level in some coastal areas, such as New Orleans and Charlotte, bounced back and approached the time series of 2019, although the turbidity level in these regions began to decline again during the second wave of COVID-19 (from September to October). Interestingly, there is no visible changes in turbidity observed the along the coastal areas of the Santos and Washington DC even after the strict lockdown measures.

Table 3 presents the percentage changes in coastal water turbidity in 2020 compared to 2019 during the different lockdown scenarios. It can be seen that the rate of reduction was highest along the different coastal regions of Mediterranean and Black
Sea (51%), West Atlantic Ocean (32%), East Atlantic Ocean (29%), and Indian Ocean (21%) during the strict lockdown period from Apr to Jun 2020. This reinforces the assertion that the strict lockdown and second wave periods had a positive feedback effect on the improvement of marine water turbidity along the marine system. Conversely, a rapid increase in turbidity rate was found in Guangzhou (61%), Haiphong (41%), Ho Chi Min City (40%) from the Oct to Nov along the coastal areas of West Pacific Ocean which might be the reason that these regions are heavily urbanized and anthropogenic activities after lifting the lockdown (after May) were running normally. Evidences from literature also indicates a clear decline in water pollution in open water bodies in the same period. For example, (Shafeeqe et al. 2021) reported that water quality along the coastal cities of South Asia improved by 29% over Karachi, 11% over Mumbai, 16% over Calcutta, and 17% over Dhaka. Likewise, (Chakraborty et al. 2021) demonstrated that Chlorophyll concentration in costal water quality decreased from 54 to 99 μg/L before the lockdown to 14 – 39 μg/L during the lockdown. Current improvements in costal water quality during the lockdown are associated with the rapid change in the excursion activities (Muduli et al. 2021).

### 3.5. Association between tropospheric NO2 and water turbidity

Eco-restoration, as a proxy of coastal water quality was investigated through interactions between the air and water pollution along the coastal marine ecosystem. (Wang
et al. 2021) quantified the reduction of NO2 during lockdown conditions in the first and second waves of the pandemic. Major epidemic regions of the world showed a reduction in NO2, especially in China, Europe, and the United States. (Bauwens et al. 2020) used satellite data from TROPOMI and OMI observations to study the COVID-19 lockdown impact on NO2 and found that, NO2 emission dropped about 40% across Chinese cities and 20% to 38% in western Europe and the United States.

The current noticeable decline in turbidity along the coastal areas of the marine ecosystem might be due to the combined effects of reduced urban nutrient pollutants and less deposition of atmospheric nitrogen (N) to the coastal regions during COVID-19 forced confinement (Mishra et al. 2020). Previous studies have also demonstrated that nitrogen dioxide (NO2) generated from anthropogenic emissions such as industries, urban transport, air traffic, urban waste, and agricultural activities play a critical role to affect the coastal water quality (Vasu et al. 1994; Paerl et al. 2002; Stevens et al. 2018). Therefore, there is an important need to eliminate the effects of

Table 3. Percentage changes in coastal water quality in term of turbidity during 2020 compared to last year 2019 in different lockdown scenarios.

| Oceans                  | Coastal regions | % Changes in turbidity |
|-------------------------|-----------------|------------------------|
|                         | Jan – Mar       | Apr – Jun              | Jul – Sep | Oct – Nov |
| Indian Ocean            | Karachi         | -36.88                 | -9.89     | -22.14    | -47.97    |
|                         | Bombay          | 1.56                   | -14.62    | -14.26    | -3.85     |
|                         | Madras          | 12.97                  | 5.78      | -12.36    | -23.24    |
|                         | Calcutta        | 4.87                   | -22.45    | -9.45     | -11.43    |
|                         | Maputo          | -5.73                  | 38.74     | 17.69     | -8.26     |
|                         | Dhaka           | 13.61                  | 9.51      | -4.9      | -11.49    |
| West Pacific Ocean      | Ho Chi Min City | -20.15                 | 12.28     | -1.35     | 40.46     |
|                         | Haiphong        | -21.72                 | -7.39     | 7.7       | 41.77     |
|                         | Guangzhou       | -15.12                 | -18.4     | -5.28     | 67.49     |
|                         | Shanghai        | -32.43                 | -6.87     | -12.54    | 1.34      |
|                         | Tianjin         | -16.49                 | 2.87      | 12.42     | -2.54     |
| East Atlantic (Euro-Africa) | Lisbon        | 57.48                  | -17.51    | -12.21    | -5.41     |
|                         | Porto           | 43.57                  | -6.65     | -28.38    | -19.88    |
|                         | Nantes          | 2.14                   | -2.59     | -3.34     | -28.5     |
|                         | Le Havre        | 11.48                  | -12.02    | -0.99     | 1.84      |
|                         | Amsterdam       | 16.54                  | -21.17    | -7.54     | -15.9     |
|                         | Bremen          | 14.96                  | -12.11    | -19.02    | -15.17    |
|                         | London          | 13.09                  | -29.48    | 16.03     | 0.46      |
|                         | Gdansk          | -20.94                 | 40.24     | 12.28     | -13.54    |
|                         | Matadi          | -14.5                  | 36.63     | -17.02    | -0.75     |
|                         | Malabo          | -1.29                  | -19.81    | 0.27      | -3.32     |
| Mediterranean and Black Sea | Barcelona     | 35.17                  | -6.87     | -4.67     | -2.34     |
|                         | Roma            | -22.1                  | -32.24    | 13.53     | -29.58    |
|                         | Veneza          | 4.89                   | -39.78    | -8.79     | -17.34    |
|                         | Bucuresti       | 11.63                  | -16.33    | -51.47    | -21.39    |
| West Atlantic Ocean     | New York        | -1.37                  | -16.78    | 43.28     | -5.28     |
| (North and South USA)   | Washington DC   | -2.45                  | 34.42     | 39.98     | -4.29     |
|                         | Charlotte       | -2.35                  | -9.56     | -1.67     | -18.45    |
|                         | Boston          | 3.36                   | -19.91    | 53.76     | -13.69    |
|                         | New Orleans     | -2.93                  | -21.68    | 42.73     | -14.33    |
|                         | Tampico         | -13.54                 | -17.82    | 34.87     | -33.2     |
|                         | Miami           | -19.81                 | -4.78     | -14.03    | 17.55     |
|                         | Buenos Aires    | -24.35                 | -8.96     | -12.65    | -16.78    |
|                         | Santos          | 16.53                  | 11.31     | -2.32     | -6.44     |
|                         | Belem           | 13.06                  | -16.63    | -3.67     | 12.47     |
|                         | Port of Spain   | 13.15                  | -31.45    | 3         | 24.03     |

Note: Light to dark red color represents the percentage decrease which light to dark green color represents the percentage increase.
reduced atmospheric nitrogen deposition on coastal water quality. We did not collect the field data to investigate the effects of these pollutants directly. Therefore, we have used an in-direct approach by investigating the watershed fluxes (overland surface runoff and surface precipitation) as a proxy of nutrients loading to coastal regions during the study period. Figure 10 shows a spatial comparison of overland runoff over the study region during 2019 and 2020 in different lockdown periods to investigate the anomalous events affecting the N loading to coastal regions. It is observed that most of the selected coastal regions along the Indian Ocean, West Pacific Ocean,
and West Atlantic Ocean (North and South USA) were receiving a higher amount of runoff in 2020 (mainly from April to Sep) compared to 2019. Conversely, overland runoff in 2020 along the coastal regions of the East Atlantic Ocean (Europe) is highly comparable to the previous year (2019) without significant variations. This phenomenon counterweights and eliminates the effects of land-based nutrients load on coastal regions and shows that the observed decline in Turbidity in East Atlantic coastal regions might be due to the reduced deposition of atmospheric nitrogen. (Shafeeque et al. 2021) evaluated the effect of COVID-19 lockdown on coastal water quality of South Asia, reporting 29% reduction in turbidity in coastal regions, which is associated with the decline in aerosol optical depth (AOD) and NO2 emission over the study area by 45%, and 40%, respectively.

We also assessed the monthly time series variations in surface runoff and precipitation averaged over the different drainage basins along the coastal regions, as shown in Figure 11. Coastal regions along the Indian Ocean, West Pacific Ocean, and West Atlantic Ocean (North and South USA) received higher land surface runoff due to higher precipitation and, hence, a high amount of land-based nutrients to the coastal region. However, the turbidity decreased by 30 – 40% during the lockdown period, which is possibly related to the reduced atmospheric depositions. (Mishra et al. 2020) reported that even though a higher amount of land-based runoff was received in the coastal regions of India during pre-monsoon (Apr – May), the chlorophycal concentration (Chl-a) reduced by 30% during this period. Evidence from the current study
confirms that turbidity along the two Indian coastal regions of Bombay and Calcutta declined by approximately 14% and approximately 22%, respectively, during the strict lockdown (Apr – Jun), which may be associated with less chlorophyll and biomass production followed by reduced deposition of atmospheric nitrogen. The current study found that water turbidity reduced more in coastal areas around the West Pacific Ocean, Mediterranean Sea, and Black Sea. This might be due to the fact that these coastal locations are extensively urbanized, and substantial shift in human activities during the COVID-19 significantly declined the atmospheric pollution (Singh and Chauhan 2020), which in turn play a important role in eco-restoration of coastal water quality (Mishra et al. 2020). Furthermore, agricultural activities continued during the lockdown period, further reinforcing the notion that the drop in coastal phytoplankton biomass and turbidity is driven by less atmospheric deposition.

4. Conclusions

An outbreak of COVID-19 began in late Dec 2019, and a few weeks later, it turned into a global pandemic as the infectious disease spread across many countries in different continents. National government authorities implemented strict lockdown measures to curb the spread of COVID-19 infections. A substantial shift in human activities could be seen during the COVID-19 lockdown, where overall anthropogenic mobility decreased by as much as 85 – 90% at different places such as grocery stores, parks, workplaces, and transit stations. A significant and uneven reduction in tropospheric NO₂ was observed, ranging from 34% to 53% in major metropolitan cities worldwide during the strict lockdown period of 2020. For water turbidity, the rate of reduction was found the highest along the different coastal regions of Mediterranean and Black Sea (51%), West Atlantic Ocean (32%), East Atlantic Ocean (29%), and Indian Ocean (21%) during the strict lockdown period from Apr–Jun, 2020. The monthly comparison of overland runoff over the study region during 2019 and 2020 in different lockdown periods indicates that the observed decline in turbidity might have been due to the reduced deposition of atmospheric nitrogen. The comparison of satellite observations from the last several years against the current data helps to understand the potential effect of anthropogenic changes on environmental pollution. The reduction in tropospheric NO₂ and water turbidity is likely associated with less consumption of fossil fuels, followed by a substantial shift in human activities such as road transportation and industrial activities. It is inferred that environmental pollution can be limited under carefully designed specific fuel use restrictions while also limiting other anthropogenic activities. Developing strategies to implement smart lockdowns over specific periods in a systematic way can offer an effective approach to reduce greenhouse gases and protect the environment.

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Authors’ contributions

Research ideas were conceived by Arfan Arshad, Fasial Mumtaz, and Adil Dilawar. Fasial Mumtaz and Arfan Arshad have jointly performed the experiments, analyzed the results, and drafted the manuscript under the guidance of Yu Tao. Ali Mirchi, Adil Dilawar, Saddam Hussain, Shuaiyi Shi, Rabeea Noor, Rizwana Noor, Andre Daccache, Muhammad Amir Siddique, Barjeece Bashir, Lingling Li, Aqil Tariq, and Dakang Wang provided help in reviewing the manuscript, English editing, and modified the manuscript.

Disclosure statement

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Data availability statement (DAS)

The authors declare that all the data used in this manuscript is available, which was obtained from NASA (National Aeronautics and Space Administration) Atmospheric Chemistry and Dynamics Laboratory (Code 614).

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