



A study on variation of atmospheric pollutants over Bhubaneswar during imposition of nationwide lockdown in India for the COVID-19 pandemic

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Abstract

The nationwide lockdown in India to flatten the pandemic COVID-19 curve has resulted in the reduction of anthropogenic emission sources to a great extent. This study reports change in air quality and its impact on the environment during the unique lockdown scenario at Bhubaneswar, a coastal smart city in east India. The urban air shows a remarkable reduction in the mean pollutant levels influenced by traffic emission viz. NO_x (~ 67 %) and BC (~ 47 %) during lockdown over the pre-lockdown. Comparatively, a lower reduction of CO (~ 14 %) is attributed to the dominance of natural atmospheric chemical regulation and biogenic sources in addition to anthropogenic contributions. In addition to the lockdown, frequent rain events due to depression in the Bay of Bengal (BoB) also had a significant role in the reduction of the primary pollutants over the study site. An enhancement of secondary pollutant viz. O₃ (~ 3%) with a distinct diurnal pattern was observed during the first phase of lockdown over the pre-lockdown period. An anti-correlation between O₃ and NO_x during pre-lockdown points to a higher O₃ production potential with decreasing NO_x. While a reduction in the titration of O₃ due to suppression of fresh NO emissions led to accumulation of O₃ in the first phase of lockdown, inhibited photochemistry due to cloudy skies as well as reduction in precursors led to lower O₃ values during the later phases of lockdown.

Keywords Lockdown · Air quality · CO · NO_x · BC · O₃

Introduction

The spread of novel coronavirus (COVID-19) was initially identified in Wuhan city of China, in early December 2019, and then was successively transmitted across the world with 4 million cases in the first 4 months. While the first case of the COVID-19 pandemic was confirmed on 31 January 2020 in

India, it was detected on 16 March 2020 in Odisha, an eastern coastal state in India. The country saw a sudden jump in COVID-19 cases during mid of March (<https://www.mohfw.gov.in/>). In order to stem the spread of novel coronavirus, the Indian government called for a 14-h voluntary public curfew called as *Janta Curfew* on 22 March 2020. Besides, the Odisha Government called for an early lockdown of five districts of the state from 22 March 2020 to 29 March 2020 together with Bhubaneswar (20.30° N, 85.82° E), the state capital, and a globally acclaimed smart city. However, after 3 days of *Janta Curfew*, the Indian Government enforced a complete nationwide lockdown for 21 days from 25 March to 14 April 2020 (lockdown 1.0) then extended it further until 03 May 2020 (lockdown 2.0). Thus, the lockdown limited the movement of the entire 1.3 billion population of India in an effort to flatten the infection/transmission curve during the pandemic. Confinement of population, shutting off a large portion of industrial activity, and bringing public transport to a standstill led to a considerable decrease in anthropogenic emissions and, consequently, in the level of urban air pollution. However, essential services such as electricity, water, municipal sanitation bodies, hospitals, banks and financial

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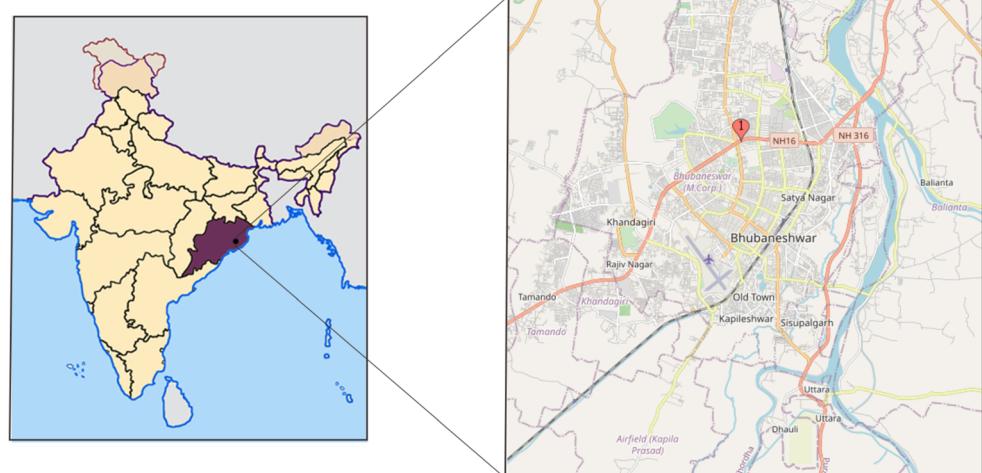
services, shops dealing with food and medicines, and movement of essential goods trucks and trains were exempted from lockdown. With the rising tolls of COVID-19 cases, the Government of India further extended the lockdown two times until 31 May 2020 with some conditional relaxation. Moreover, night curfews were imposed during the entire May (lockdown 3.0 and lockdown 4.0) month from 7 PM to 7 AM. The pandemic outbreak has caused a large economic disruption in India. So, the Indian Government has allowed restarting various industrial and other commercial activities with 50 % of workforce called Unlock-1 during 01 June–30 June 2020 with strict guidelines. However, to tackle the emergency and curb the dispersion of COVID-19, the Odisha Government continued the night curfew from 7 PM to 5 AM with an addition of complete shutdown of weekends during entire June month of 2020.

The sudden change in emissions is expected to have a drastic impact on air quality, and the situation can be used as a natural experiment to simulate the sensitivity of certain pollutants prevailing in ambient air. In this context, air quality parameters such as carbon monoxide (CO), oxides of nitrogen ($\text{NO}_x = \text{NO} + \text{NO}_2$), black carbon (BC), and ozone (O_3) are analysed. The measurements were carried out at CSIR—Institute of Minerals and Materials Technology (IMMT) located in the heart of Bhubaneswar city during March–June 2020 (Fig. 1). Bhubaneswar, the capital city of Odisha state in eastern coastal India, is home to more than 8 lakhs people (<https://www.census2011.co.in/census/city/270-bhubaneswar.html>). The city, enlisted in the Government of India smart city program, is undergoing significant development in the construction of roads, shopping malls, residential areas around the city, and the consequent anthropogenic emissions. According to the 2018 RTO database, a total of 76,946 vehicles were registered in the Bhubaneswar city out of which 70% are personal vehicles.

Furthermore, the city is fenced with numerous point sources of pollution like the thermal power plants, steel plants, cement industries, mines, metallurgical plants, and manufacturing industries in the north and north-west direction and two major shipping harbours, one (Paradeep Port) ~ 100 km towards the eastern direction and the other (Dhamra Port) ~ 159 km towards the north-eastern part (Mahapatra et al. 2018). Despite nationwide lockdown, the thermal power plants, steel processing industries, mining activities, production and distribution of thermal and coking coal, limestone, dolomite, manganese, and chromite in and around Odisha were operational, as a part of essential services (<http://www.ecoti.in/tQMoEb80>). However, there was a reduction of ~ 60% of production capacity due to a fall in the number of workers.

Apart from this, the study site is considered to be a strategic location as it is a gateway of most of the polluted air mass that reaches the BoB from the Indo Gangetic Plains (IGP), and the heavily industrialised Chotta Nagpur Plateau region as well as the western part of India (Mallik et al. 2019). Therefore, in the current pandemic situation as various phases of lockdown were imposed over this region, it was indeed a unique scenario to understand the behaviour, source, and concentration of primary and secondary ambient air pollutants like CO, NO_x , BC, and O_3 . The data has been presented here to understand the variation of measured pollutants in the perspective of the environment when anthropogenic emissions are curtailed. While CO can give an insight into both anthropogenic and biogenic emissions together with chemical processing in the atmosphere, NO_x and BC can give a direct insight into the emission scenario w.r.t. gas and aerosol phases. Furthermore, O_3 variations can give an insight into the photochemical processes operating in the atmosphere. Thus, the primary goal of this study is to evaluate and understand the change in the air quality of the region with a sudden reduction in anthropogenic emissions. The change in emission regime provided an

Fig. 1 Location map pf sampling site in CSIR-IMMT, Bhubaneswar, Odisha (marked as '1')



opportunity to generate baseline data for the region, which will help to adopt new strategies to ensure better air quality.

Methodology

Measurement techniques

The in situ measurements of near surface CO was made in Bhubaneswar using an online CO analyser (Horiba, APMA-370). The analyser is based on cross modulation-type non-dispersive infrared absorption at 4.67 μm vibration band and has a detection limit of 50 ppb for a 60 s response time (Mahapatra et al. 2014a). Simultaneously, the measurement of NO_x and O₃ was carried with a chemiluminescence NO_x analyser (Thermo fisher scientific, 42i), and UV photometric O₃ analyser (Thermo fisher scientific, 49i) respectively. The NO_x analyser works on the principle of chemiluminescence effect produced due to oxidation of NO by O₃ molecule at 630 nm and has a detection limit of 50 ppt with a response time of 50 s. The O₃ analyser works on the principle of absorption of UV radiation by atmospheric O₃ at 254 nm. The lower detection limit is 1 ppb with a response time of 20 s. All instruments were periodically calibrated using NIST traceable calibration standards and multi-channel calibrator. The analysers drew ambient air samples in using a 2-m-long polytetrafluoroethylene (PTFE) tubing placed at a height of 20 m above the ground level. Besides, PTFE filters were placed at the sampling inlet of each analyser to remove dust and larger particles. A more detailed description can be found in Mahapatra et al. (2014a, 2019), Mallik et al. (2019).

In addition, BC measurements were performed using a seven-channel (370, 470, 520, 590, 660, 880, and 950 nm) optical wavelength Aethelometer (Magee Scientific, AE33). The instrument was equipped with 2.5- μm cut point of PM_{2.5}-cyclone along with a rain/insect guard, and was operated continuously at a flow rate of 2 L min⁻¹. The 880-nm wavelength was used to derive the BC concentration, as described by the previous studies (Babu and Moorthy 2002).

Surface level meteorological parameters viz. temperature (T), rainfall, relative humidity (RH), wind speed (WS), and wind direction (WD) were continuously monitored and recorded during the study period with the help of an Automatic Weather Station (AWS) mounted at the rooftop of CSIR-IMMT.

Analysis of lockdown periods

This study adopts an intra-comparative approach to analyse the impact of COVID-19 lockdown on the environment during March–June 2020. The study period was divided into the following phases:

- Pre-lockdown (PL: 01-21 March 2020)
- Lockdown 1.0 (L1: 22-14 April 2020)
- Lockdown 2.0 (L2: 15 April-03 May 2020)
- Lockdown 3.0 (L3: 04-17 May 2020)
- Lockdown 4.0 (L4: 18-31 May 2020)
- Unlock 1.0 (UL: 01-30 June 2020)

Furthermore, a weekend shutdown was imposed by the Odisha Government during the unlock period. Hence, the unlock period has been further sub divided into unlock weekdays (UL-WDy) and unlock weekends (UL-WEd).

Results and discussion

Meteorology

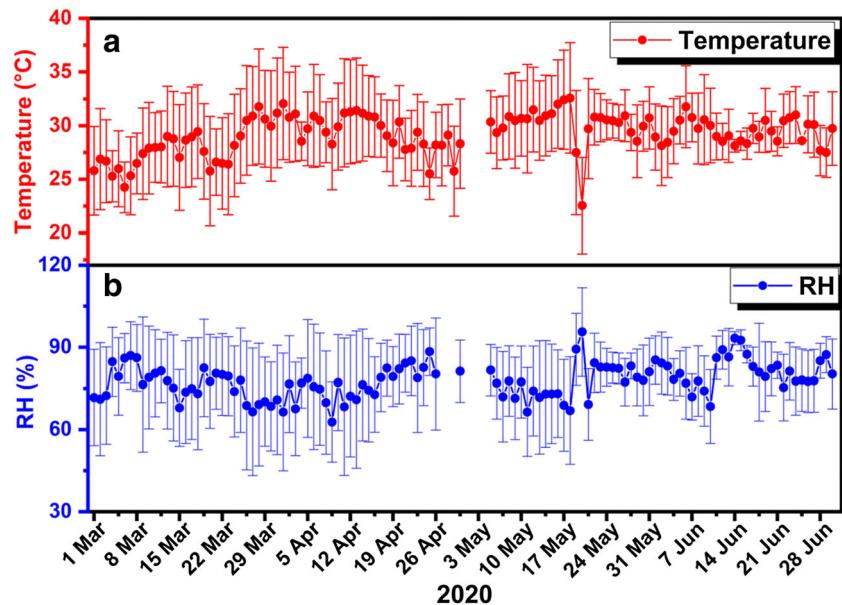
Meteorology plays a key role in the formation and transport of air pollutants (Bao and Zhang 2020; Yen et al. 2013). Hence, surface T, rainfall, RH, WS, and WD were analysed for the study period. Bhubaneswar experiences a tropical weather condition with a hot and humid climate during the summer months. Figure 2 shows the day to day variation of T and RH observed during the study period. The daily mean surface T varied in the range of 23–32 °C, whereas RH varied in the range of 63–95%.

A total rainfall of ~ 11 mm was recorded during pre-lockdown days while ~ 1 mm, ~ 32 mm, and ~ 9 mm during L1, L2, and L3, respectively (Fig. S1). The increased rain event during the end of April is attributed to a depression in the BoB (Mahapatra et al. 2019; Fadnavis et al. 2011). However, the maximum rain events resulting in ~ 76 mm during L4 is due to cyclonic storm “Amphan”, which hit Odisha coast on 20 May 2020.

Wind pattern

The wind rose plot shows the dominance of wind patterns from the south direction indicating the profound influence of marine air mass during the study period (Fig. 3). The 5-day-backward air masses arriving at Bhubaneswar were tracked using NOAA Air Resource Laboratory (ARL) Hybrid Single-Particle Model at 100 m agl for different phases of the study period (Draxler and Hess 1998; Draxler 1999; Dutkiewicz et al. 2009; Tiwari et al. 2013; Stein et al. 2015) (Fig. S2). Moderate Resolution Imaging Spectroradiometer (MODIS), aboard Aqua, and Terra satellites (C6 version), derived from NASA FIRMS, were used to understand the impact of biomass and crop residue burning over the study site (Giglio et al. 2003, 2016). Fires with 80% and above detection confidence were only considered to side step any bias due to false fires. Although distinct fire events were observed in central India during L1 and L2, the prevailing air mass mostly of marine

Fig. 2 Variation in daily average temperature and daily average relative humidity in Odisha during March–June 2020



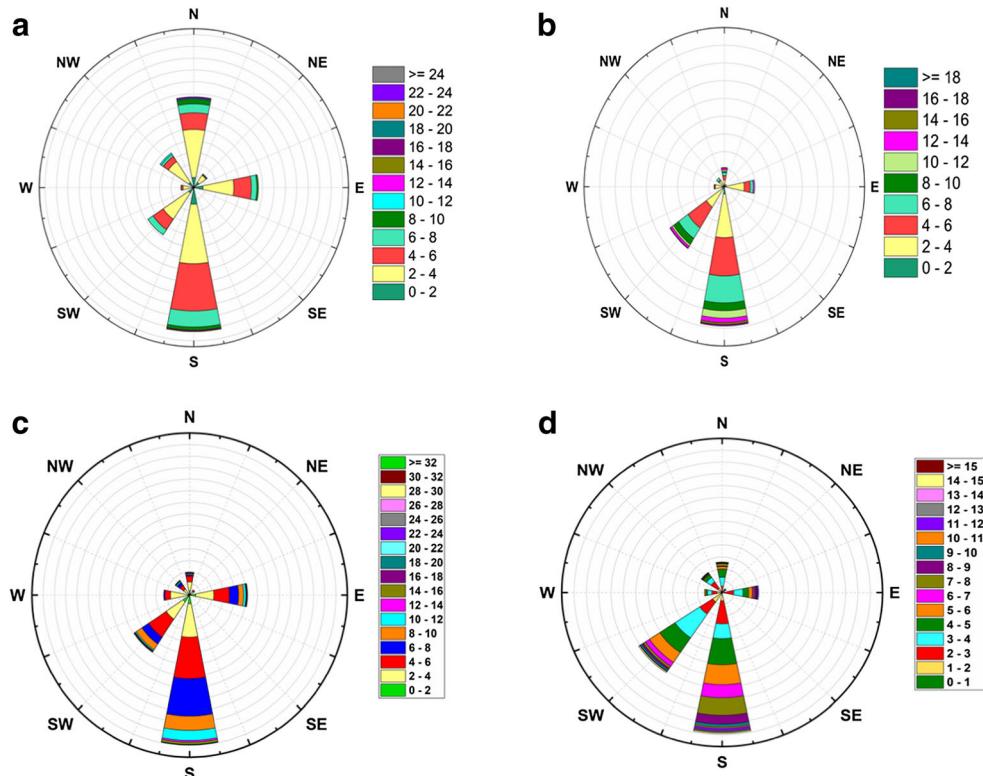
origin indicates the inconsequential impact of regional fire events over the study site (Fig. S2).

Diurnal variability of air pollutants

The average diurnal variation of surface CO, NO_x, BC, and O₃ over the study site is shown in Fig. 4. The diurnal variation of CO, NO_x, and BC show a bi-modal pattern during PL. The primary pollutants showed a build-up during the morning, and

late evening due to an increase in emission sources (mostly traffic-related as the study site situated close to National Highway-16) and suppressed boundary layer that helps trap the pollutants in the lower troposphere. Conversely, higher dilution leads to lower value of these species during noon (Nair et al. 2002; David and Nair 2011). Furthermore, photochemical consumption of NO_x and CO also results in their lower value during the daytime. Previous reports also observed a distinct bi-modal peak in almost all the seasons for

Fig. 3 Wind rose plot showing local wind direction and distribution of wind speed (m/s) over the study site (Bhubaneswar) for **a** March, **b** April, **c** May, **d** June month respectively



CO, NO_x (Xie et al. 2016; Zhao et al. 2016; Yadav et al. 2016; Jang et al. 2017; Zheng et al. 2017), and BC (Babu et al. 2002; Beegum et al. 2009; Mahapatra et al. 2014b; Kompalli et al. 2014; Talukdar et al. 2015; Vaishya et al. 2017; Rana et al. 2019) depicting the influence of anthropogenic emissions in urban areas. In addition, analysis of tropospheric CO by Ghude et al. (2011) and Girach and Nair (2014) over Indian subcontinent have revealed that CO emissions in eastern India is mostly dominated by coal combustion from the thermal power plants along with biofuel and biomass burning. However, during the current lockdown phases, we could not observe prominent bi-modal peaks for CO, NO_x, and BC. Thus, the suppressed rush hour peaks for three pollutants is a direct indication of lockdown effects, and such suppression have not been observed during similar time periods in previous years over the study site (Mahapatra et al. 2014a, b). The suppressed peaks for CO and NO_x during the various lockdown phases can be attributed to curtailment in vehicular movements. Furthermore, for species like NO_x, which have strong local sources and short residence times, the reduction is much more drastic with high pre-lockdown to lockdown ratios compared to a pollutant like CO with regional sources and a much longer residence time (more than 30 times that of NO_x). Similarly, the residence time of BC of a few days to a week is intermediate between NO_x and CO, and hence BC can provide a wider coverage compared to NO_x in terms of source contributions. The lifetimes of these pollutants are in the order CO > BC > NO_x. The L1/PL values for these gases are 0.98, 0.73, and 0.32, respectively. Likewise, Jain and Sharma (2020) also highlighted a statistically significant plummet in NO₂ (~ 51%) in five megacities of India viz. Delhi, Mumbai, Chennai, Kolkata, and Bangalore. However, unlike the pollutants discussed above, the diurnal pattern of surface O₃ shows a distinct noon peak during PL and L1 (Fig. 4a), a notable feature of an urban region (Lal et al. 2000; Nishanth et al. 2012; Gaur et al. 2014; Yadav et al. 2016). The O₃ concentration starts building up immediately after sunrise, attains maximum value (PL, 30 ppbv; L1, ~ 34 ppbv) during noontime, and then decreases. The daytime increase in concentration is attributed to the photo-oxidation of precursor gases such as CO, CH₄, and NMHCs in the presence of NO_x (Lal et al. 2000). However, lower O₃ concentration during the night is due to inhibition of photochemistry, titration of O₃ by surface emissions of NO, and loss due to surface deposition (Mallik et al. 2015). The pronounced elevated diurnal pattern during L1 suggests a higher rate of photochemical production of O₃ from precursors compared to O₃ destruction (Resmi et al. 2020). The O₃ chemistry during L1 could be due to locally/regionally emitted precursors along with atmospheric transport from the Chota-Nagpur region and the north-western parts of Odisha state (Fig. S2). This is evinced by very similar background concentration observed during night time in PL and lockdown periods. A cloudy sky due to rain events (Fig.

S1) on several days during L2, L3, L4, and UL along with reduced precursor levels inhibits photochemical production of O₃ leading to the suppressed diurnal variation of O₃ (Ghosh et al. 2015). Furthermore, the standard deviation (SD) in O₃ values during the current study is of the order of less than 20% while the year to year changes in O₃ is of the order of 36–45%, implying the impacts of lockdown (Table 1).

Day-to-day variability of air pollutants

The daily (24 h) averaged temporal variation of air pollutants viz., CO, NO_x, BC, and 8 h averaged surface O₃ are shown in Fig. 5. An overall average reduction of ~ 14%, ~ 67%, ~ 47%, and ~ 14% for CO, NO_x, BC, and O₃ respectively, are observed during the entire lockdown phase, compared to the pre-lockdown period. However, the decline in the concentration of pollutant level in the UL period is attributed to change in meteorology due to the onset of monsoon. The minimum, maximum, mean, and standard deviation of the pollutants during different study phases are summarised and presented in Table 1.

The mean CO and BC levels show a notable reduction from L1 (CO, 526.95 ± 136.19 ppbv; BC, $1.31 \pm 0.34 \mu\text{g m}^{-3}$) to L4 (CO, 368.24 ± 131.44 ppbv; BC, $0.93 \pm 0.37 \mu\text{g m}^{-3}$), revealing a change of ~ 30% and 29% respectively. However, a two-sample *t* test shows an insignificant ($p > 0.8$) decline in the concentration of CO during L1 as compared to PL. CO is released during incomplete combustion processes viz. burning of fossil fuel, biomass, garbage as well as from photo-oxidation of methane (CH₄), and other hydrocarbons (Fishman and Seiler 1983; Cros et al. 1988; Mahata et al. 2018). Furthermore, the ozone monitoring instrument (OMI) time series of area-averaged methane (CH₄) mole fraction in the air for March–June 2020 over 20–21° N, 85–86° E (<https://giovanni.gsfc.nasa.gov/giovanni/>) shows no substantial change in CH₄ concentration during the observation period (Fig. S3). This can be attributed to the much longer lifetime for CH₄ and sources like agriculture, waste, biomass, and biofuel as well as natural sources, making a much larger contribution to CH₄ emissions compared to fossil fuels (Bousquet et al. 2011; Saunois et al. 2016; Kavitha et al. 2018). All these sources in and around Bhubaneswar might result in a build-up of CO concentration during L1. Furthermore, CO has a longer lifetime due to a combination of CO production and loss chemistry, being controlled by OH radical, which is mostly well buffered (Mallik et al. 2018). Nonetheless, a significant reduction in mean CO during L2 over PL could be due to the extended lockdown phase, across the entire country, resulting in a continuous fall in anthropogenic emissions over the study region. CO concentration decreased further from 219.29 ± 66.62 ppbv during weekdays to 177.29 ± 66.62 ppbv during the weekend of UL period due to the imposed curfews, along with the change

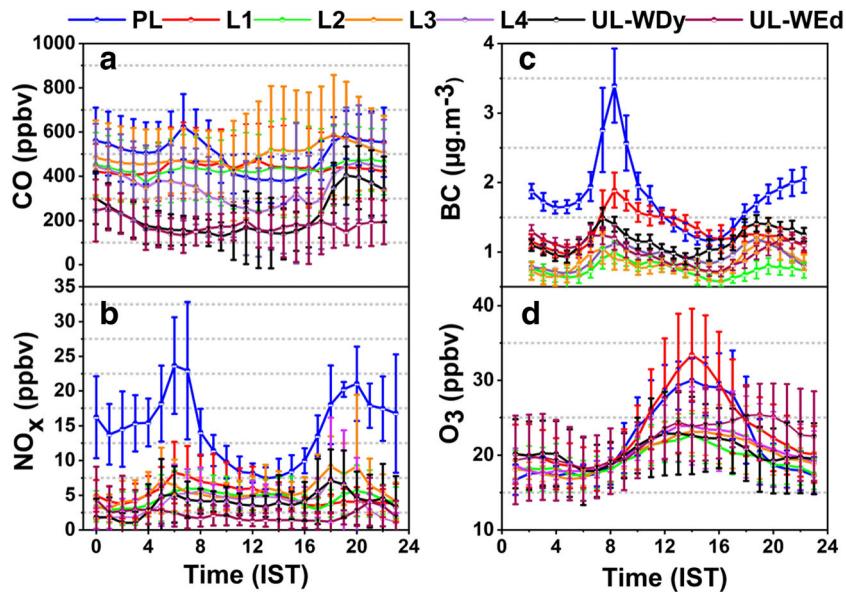
Table 1 Statistics of measured O₃, NO_x, CO and BC during March–April 2020 at Bhubaneswar (PL, pre-lockdown; L1, lockdown 1.0; L2, lockdown 2.0; L3, lockdown 3.0; L4, lockdown 4.0; UL, unlock 1.0)

Phases (date 2020)	CO (ppbv)			
	Minimum	Maximum	Mean	SD
PL (01/3–21/3)	367.08	660.85	535.41	84.74
L1 (22/3–14/4)	276.06	837.67	526.95	133.19
L2 (15/4–03/5)	219.07	620.42	445.44	101.47
L3(04/5–17/5)	198.13	673.96	493.41	126.08
L4 (18/5–31/5)	178.54	527.71	368.24	131.44
UL (01/6–30/6)	93.54	395.00	208.09	64.41
Weekday during UL	93.54	395.00	219.29	66.62
Weekend during UL_shutdown	99.77	252.50	177.29	66.62
NO _x (ppbv)				
PL (01/3–21/3)	Minimum	Maximum	Mean	SD
L1 (22/3–14/4)	8.63	25.49	16.00	5.08
L2 (15/4–03/5)	2.57	10.86	5.13	1.96
L3 (04/5–17/5)	2.72	7.38	4.58	1.33
L4 (18/5–31/5)	3.33	9.31	5.61	1.65
UL (01/6–30/6)	1.54	15.55	5.97	4.56
Weekday during UL	0.97	7.39	3.44	1.72
Weekend during UL_shutdown	1.51	7.39	3.88	1.55
BC ($\mu\text{g m}^{-3}$)				
PL (01/3–21/3)	Minimum	Maximum	Mean	SD
L1 (22/3–14/4)	0.84	2.83	1.79	0.51
L2 (15/4–03/5)	0.86	2.09	1.31	0.33
L3 (04/5–17/5)	0.45	1.17	0.75	0.19
L4 (18/5–31/5)	0.56	1.36	0.85	0.24
UL (01/6–30/6)	0.68	2.06	0.93	0.37
Weekday during UL	0.62	2.04	1.11	0.33
Weekend during UL_shutdown	0.64	2.04	1.16	0.34
O ₃ (ppbv)				
PL (01/3–21/3)	Minimum	Maximum	Mean	SD
L1 (22/3–14/4)	20.86	32.76	27.45	3.53
L2 (15/4–03/5)	21.06	40.15	28.34	5.46
L3 (04/5–17/5)	17.70	24.44	21.10	2.11
L4 (18/5–31/5)	19.02	30.58	21.88	2.86
UL (01/6–30/6)	16.95	28.34	22.83	3.84
Weekday during UL	17.23	34.06	22.15	3.91
Weekend during UL_shutdown	18.01	29.42	23.39	3.84

in seasonal meteorology, i.e., transition between pre-monsoon to monsoon season. CO and NO_x, which share many common anthropogenic emission sources (Mallik et al. 2015) were found to be weakly associated ($r = 0.4$) over Bhubaneswar (Fig. 6). The low CO/NO_x values imply the predominance of vehicular emissions compared to point sources which corroborated by a significant reduction of NO_x level during the lockdowns.

However, there is a notable reduction of $\sim 47\%$ in BC during the entire lockdown as compared to PL. This could be due to curtailment of vehicular emission, which is considered to be dominant source over the study site (Mahapatra et al. 2014b). The BC concentration during UL weekdays ($1.16 \pm 0.34 \mu\text{g m}^{-3}$) was observed to slightly increase in comparison to L4 due to relaxation in vehicle movement during daytime (7 AM to 7 PM); however, a slight decrease in BC

Fig. 4 Diurnal variation of **a** surface CO, **b** surface NO_x, **c** BC, and **d** surface O₃ during pre-lockdown, lockdown 1.0, lockdown 2.0, lockdown 3.0, lockdown 4.0, and unlock-1 at Bhubaneswar



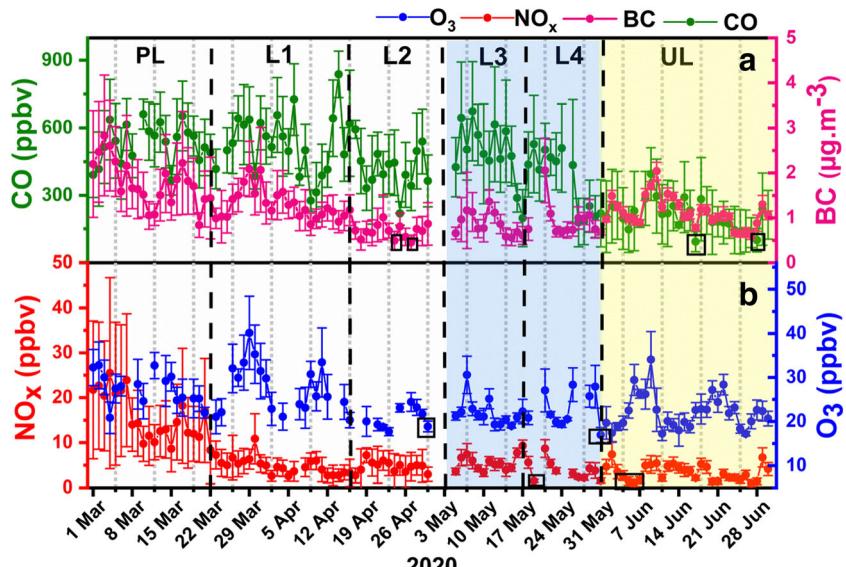
($1.01 \pm 0.34 \mu\text{g m}^{-3}$) concentration during weekend is due to the imposition of weekends curfew.

During the study period, there was a transport of air masses exclusively from the marine region (Fig. S2). It has been reported that pollutants like CO and BC are also evinced over the Indian Ocean due to the coastal anthropogenic activities (Girach et al. 2020; Venkataraman et al. 2005). Hence, there is a chance of regional transport of CO and BC to the study site through the marine air masses in regions between the coast and the southern site of the measurement location (Fig. S2). These regions include residential areas within Bhubaneswar city as well as slums and villages on the outskirts of the city all the way up to the coast. All these regions will have some activities related to CO emissions like biomass and garbage burning, brick kilns, and ancillary activities. Assuming an

average wind speed of 10 m/s, an air parcel would take about 16 h to reach from Puri (or the coast) to Bhubaneswar, covering a distance of 60 km. This travel time is much lower than the lifetime of NO_x ($\tau < 2$ days), BC ($\tau < 7$ days), as well as longer lived O₃ and CO. Thus, despite being southerly in direction, the winds can still carry the impact of continental emissions to the vicinity of Bhubaneswar. However, the study site witnessed several rain events over the region for the entire L2 phase (Fig. S1), which could have resulted in wet scavenging of pollutants like O₃ and BC, and hence the reduction in pollutant concentration was quite prominent during the L2 phase.

A *t* test shows an insignificant overall increment of $\sim 3\%$ ($p > 0.2$) for O₃ in low NO_x conditions during L1 as compared to PL (Fig. 4). The mean O₃ value was 27.45 ± 3.64 ppbv during

Fig. 5 Temporal variation of **a** CO and BC **b** NO_x and O₃ during pre-lockdown, lockdown 1.0, lockdown 2.0, lockdown 3.0, lockdown 4.0, and unlock-1 (March–June 2020) at Bhubaneswar. The blue-coloured background portion represents imposition of night curfew between 7 PM and 7 AM while the yellow-coloured background portion represents imposition of night curfew between 9 PM and 5 AM. The small boxes represent minimum concentration gases observed during the study period



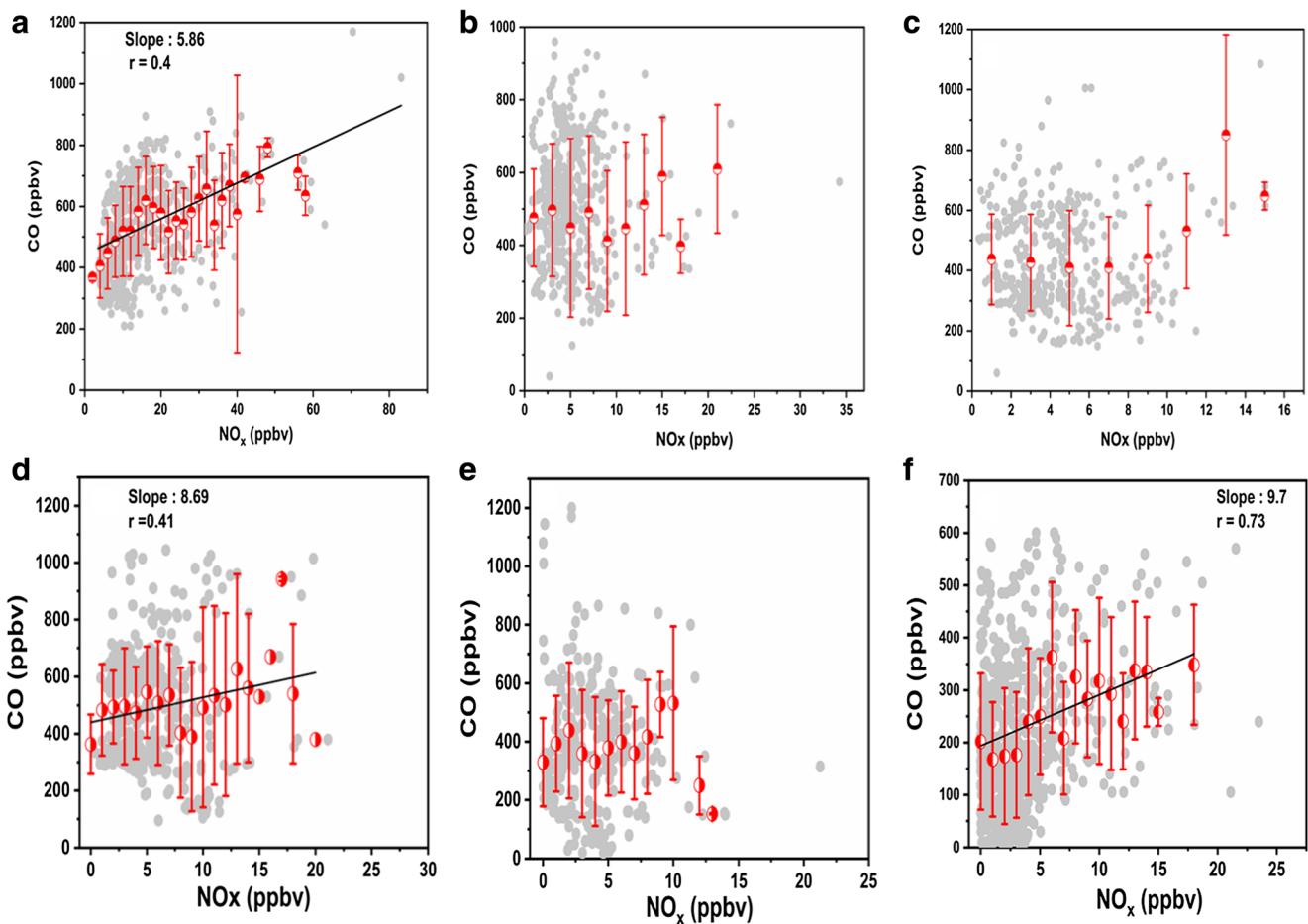


Fig. 6 Relationship of CO and NO_x over Bhubaneswar during **a** pre-lockdown, **b** lockdown 1.0, **c** lockdown 2.0, **d** lockdown 3.0, **e** lockdown 4.0, and **f** unlock-1

PL, which rises to 28.33 ± 5.63 ppbv during L1. An enhancement in the O_3 level during L1 with favourable meteorological conditions was also observed in other parts of eastern India (Sharma et al. 2020b) along with Barcelona, Spain (Tobias et al. 2020), and China (Huang et al. 2020). Similarly, O_3 concentration was found to be higher during lockdown (25 March–17 May 2020) as compared to before lockdown (10–20 March 2020) in five major cities of Rajasthan (Sharma et al. 2020a). However, apart from L1, the concentration of O_3 is lower than the PL concentration. Likewise, Sharma et al. (2020b) reported diminution of O_3 concentration in the western, northern, and southern regions of India during the lockdown phases.

The photochemical chain reaction which produces O_3 is controlled by complex non-linear chemistry (Seinfeld and Pandis 1998; Tiwari et al. 2015) as represented in equations (1) to (3):



Henceforth, it is evident from the above equations that NO_x concentrations significantly control O_3 photochemistry. Several previous studies over the Indian subcontinent revealed that vehicular emissions are the major source of NO_x (Aggarwal and Jain 2015; Jain et al. 2016). Recently, Singh and Chauhan (2020) also reported a significant reduction in tropospheric NO_2 over eastern India during lockdown as compared to the same period of 2019. Similarly, Xu et al. (2020) reported a significant reduction in primary pollutants due to lockdown in Hubei Province, Wuhan, Jigmen, and Enshi in Central India. Hence, a prominent reduction of $\sim 65\%$ in NO_x during L1 compared to PL over the study site facilitates O_3 accumulation in the urban atmosphere. However, a lack of precursor transport mediated by cleaner marine air masses and cloudy sky due to frequent rain events during L2, L3, L4, and UL reduced O_3 production over the study site. Fig. S4 shows the daytime relationship between O_3 and NO_x during the six different lockdown phases. An anti-correlation ($r = -0.75$) between O_3 and NO_x during PL (Fig. S4a) is attributed to an increase in O_3 concentration during daytime due to

Table 2 Comparison of Inter-annual BC, CO and O₃ concentration for the period of April and May at Bhubaneswar

Pollutant	CO (ppbv)			8 h O ₃ (ppbv)			BC ($\mu\text{g m}^{-3}$)		
	2014	2020	% change	2014	2020	% change	2015	2020	% change
Years/period of observation									
April	553.10 ± 187.68	474 ± 154.91	(-) 14.3	42.7 ± 9.2	23.4 ± 5.47	(-) 45.18	1.94 ± 0.57	0.95 ± 0.29	(-) 51.03
May	407.40 ± 116.96	439.7 ± 196.94	(+) 7.9	34.7 ± 10.49	22.2 ± 2.11	(-) 36.15	1.91 ± 0.41	0.87 ± 0.31	(-) 54.45

photochemical production and decrease in NO_x due to photochemical decomposition as well as boundary layer dilution (Lal et al. 2014; Ghosh and Sarkar 2016). The titration of O₃ at higher NO_x levels during PL was not observed during the lockdown periods (Fig. S4 b & c). Nonetheless, a lack of correlation between O₃ and NO_x during lockdown (Fig. S4 b, c, d & e) indicates O₃ chemistry is complex, and its production does not simply increase with NO_x reduction. During L1, the enhancement in O₃ concentration in low NO_x emission might be due to a change in volatile organic carbon (VOC) and NO_x ratio. However, in the absence of concomitant measurements of VOC, it is not possible to estimate the exact production potential of O₃.

We also made an attempt to compare the complete lockdown period (April–May 2020) pollution scenario with the available data for the same period of previous years. The mean and sigma of CO, O₃, and BC for different periods of observation are presented in Table 2. Immediate previous years (2016–2019) for all the pollutants were not available, so we compared the measurements during 2014–2015, when these measurements are available for O₃, CO, and BC. There was a more than 40% reduction in O₃ and 50% reduction in BC concentration of the current period (2020) in comparison to the same period of the previous years of observation. The 1-sigma standard deviations of these gases during the lockdown period are much less compared to the year-to-year variation (Table 2). This supports the fact that apart from local/regional meteorology, the various lockdown phases had a significant effect in bringing about a reduction in the concentration of various primary as well as secondary pollutants. The overall reduction in O₃ can be attributed to lower precursor levels, also impacted by the lower amount of transported precursors as well as inhibiting meteorological conditions like rain events and cloud cover. Interestingly, we did not observe as much reduction in CO as it is emitted through both anthropogenic and biogenic sources, and its lifetime is intrinsically related to the chemical processing in the atmosphere. Even during the complete lockdown phase during April–May 2020, biofuel emissions could be significantly active for cooking purposes (in the city slums as well as in the surrounding villages). Furthermore, OH radical, the

main chemical scavenger of CO, is mostly well buffered in NO_x ranges encountered during the study period (Mallik et al. 2018).

Conclusion

The extent of change in air quality is studied over Bhubaneswar, an urban city in eastern India, during an unprecedented nationwide lockdown scenario. A significant reduction of primary pollutants, like NO_x (~ 67%) and BC (~ 47%) reveals that a reduced traffic pollution and essential anthropogenic activities led to better air quality during lockdown periods. There was a more than 40% reduction in O₃ and a 50% reduction in BC concentration of the current period (2020) in comparison to the same period of the previous years. This supports the fact that apart from local/regional meteorology, the various lockdown phases had a significant effect in bringing about a reduction in the concentration of various primary as well as secondary pollutants. The overall reduction in O₃ was attributed to lower precursor levels, as well as inhibiting meteorological conditions like rain events and cloud cover. Among CO, NO_x, BC, and O₃, CO was the least impacted from the lockdown due to lower contribution of fossil fuels to CO sources and a much longer atmospheric lifetime mediated by natural chemical processing in the atmosphere. The nationwide lockdown has provided a unique opportunity for the researchers and policymakers to take a closer look at the impact of emission reductions on air quality and develop balanced mitigation strategies for controlling multiple pollutants.

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Authors' contributions Subhasmita Panda: original draft, methodology, data analyses, review and editing. Chinmay Mallik: methodology, data analyses, investigation, review and editing. Jyotishree Nath: methodology, data curation. Trupti Das: writing, investigation, review and editing,

supervision, funding acquisition. Boopathy Ramasamy: review and editing, visualization, investigation, funding acquisition.

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Compliance with ethical standards

Competing interests The authors declare that they have no known competing interests.

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