Transformation of Air Quality over a Coastal Tropical Station Chennai during COVID-19 Lockdown in India

Special Issue:

Special Issue on COVID-19 Aerosol Drivers, Impacts and Mitigation (XII)

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ABSTRACT

To prevent the spread of COVID-19, Government of India imposed strict lockdown in the country from 24 March–31 May 2020, which allows the environment to revive with reduced emissions. The present work analyses the PM_{2.5}, NO₂, O₃, CO and SO₂ along with meteorological parameters (humidity, temperature and wind speed) at a tropical coastal station Chennai for March–May 2019 and 2020 at five locations: Alandur Bus depot, Velachery, Manali, Teynampet and U.S. Embassy Chennai. Chennai is a megacity of southern India and the state capital of Tamil Nadu, one of the worst affected states due to COVID-19. Though overall PM_{2.5} values decreased for the lockdown (ranging from ~32–187%), weekly analysis shows the variation in reduction/increase. SO₂ and O₃ values were found increasing for two sites: Teynampet (~40% in SO₂ and ~48% in O₃) and Velachery (~42% in SO₂ and ~5% in O₃), but decreasing for Alandur (~30% in SO₂ and ~50% in O₃) and Manali (~247% in SO₂). NO_x and CO were reduced during the lockdown (~47–125%) for all the sites. The source regions examined by concentration weighted trajectory analysis were found to change for transporting pollution to the site. The analysis shows there are local scale variations in the air pollution for the city during COVID-19 lockdown.

Keywords: COVID-19, CWT analysis, Particulate matter, Nitrogen dioxide, Sulphur dioxide

OPEN ACCESS

Received: May 15, 2020

Revised: June 6, 2020

Accepted: December 25, 2020

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Publisher:

Taiwan Association for Aerosol Research

ISSN: 1680-8584 print

ISSN: 2071-1409 online

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1 INTRODUCTION

Novel Coronavirus or COVID-19, the greatest pandemic of the century (WHO, 2020) poses unprecedented situations for human survival in the world. Since its declaration to a pandemic and public health emergency of international concern by World Health Organisation (WHO) on January 30, 2020 (WHO, 2020); several countries put strict restrictions on the movement of people to stop spreading of COVID-19 (e.g., Bao and Zheng, 2020; Collivignarelli *et al.*, 2020; Dantas *et al.*, 2020; Navinya *et al.*, 2020). On March 24, 2020, Government of India announced its first lockdown, which was followed by various stages till May 31, 2020, countrywide (<https://www.mygov.in/covid-19>). The lockdown affects human life in multiple ways, though the environment receives mostly positive improvements (Arora *et al.*, 2020; Bherwani *et al.*, 2020).

Several studies reported the change in the environment during COVID-19 and spread of COVID-19 correlation with meteorology and pollution (e.g., Ahmadi *et al.*, 2020; Arora *et al.*, 2020; Bashir *et al.*, 2020; Nakada and Urban, 2020; Sicard *et al.*, 2020), and on the future planning of restrictions to keep the better environment (Paital, 2020). Muhammed *et al.* (2020) reported a decrease of 20–30% in NO₂ concentrations over China, Europe, Italy, France, Spain and USA during COVID-19 period using Aura and Sentinel-5P datasets. Though some studies reported the definite relation between meteorology and COVID-19 (Ahmadi *et al.*, 2020; Sahin *et al.*, 2020), these relations were not uniformly valid. Shahzad *et al.* (2020) pointed out that the spread of the virus may be influenced by various other factors and hence not explicitly showing any clear

correlation with weather parameters in general. It has also been argued that the more polluted regions had higher risks of spreading of COVID-19 (Bontempi, 2020; Conticini *et al.*, 2020; Fattorini and Regoli, 2020).

In such a situation, understanding the emission patterns of a megacity is far more important for better planning to reduce the future emissions. India has a high population density in megacities, and has reported significant modelling studies for control/projected emissions (e.g., Ghude *et al.*, 2013; Sahu *et al.*, 2017; Guttikunda and Jawahar, 2018). For the present study, we have studied the air pollution variation during COVID-19 lockdown for Chennai, a coastal Indian megacity. Few reported studies dealing with multicity analysis, are highlighting the reduction in pollution during the lockdown period of COVID-19 over Chennai. Kumar *et al.* (2020) studied fine particulate matter using satellite derived Aerosol Optical Depths (AOD) and in-situ observed hourly data by U.S. Embassy over five megacities of India (Delhi, Kolkata, Mumbai, Chennai and Hyderabad) during COVID-19 lockdown. They found that aerosol loading decreased 29% over Chennai with considerable improvements in premature deaths. Jain and Sharma (2020) also took five megacities (Delhi, Kolkata, Mumbai, Chennai and Bangalore), but using the in-situ observations. They take more than one station at each of the city, and Chennai had four reporting stations. The study reported a 14% reduction in $PM_{2.5}$ and 30% reduction in NO_2 , a 25% reduction in CO and a 3% rise in O_3 during the lockdown phase. Arshad *et al.* (2020) attempted AOD and NO_2 variations during COVID-19 lockdown phase using satellite datasets over major cities of India and Pakistan. The study reported a reduction of 32–42% in NO_2 and ~45% reduction in AOD over the entire Indo-Pak region.

Sharma *et al.* (2020) focused on pollutants variation of twenty big cities of India including Chennai for analysis pre and during lockdown phases of COVID-19 and the results were supporting the earlier findings of reduced $PM_{2.5}$, PM_{10} , CO and NO_2 , and increased O_3 concentration during lockdown period. Navinya *et al.* (2020) reported a reduction of 30.2% in $PM_{2.5}$, 69.2% in SO_2 , 36.30% reduction in NO_2 , 23.7% reduction in CO during lockdown phase over Chennai. Laxmipriya and Narayanan (2020) measured $PM_{2.5}$ and PM_{10} at five sites in Chennai using the indigenous instrument, and supported the findings of massive reductions by other researchers. Arumugam and Rajathi (2020) used $PM_{2.5}$, PM_{10} , CO, NO_2 , SO_2 and O_3 over Chennai gave a descriptive statistical analysis of reductions in these pollutants with ANOVA fitting to variations.

Though various studies reported a reduction in pollutants and increase in O_3 during COVID-19 lockdown, the detail about site to site variations have not been reported in these studies. The microscale feature may impact the local pollution values and the variation reported as an average values (including all the sites) may miss out the detail of an individual site variation. The present study will attempt to analyse the pollution change of five criterion pollutants (i.e., $PM_{2.5}$, NO_x , O_3 , CO and SO_2) during the COVID-19 lockdown at five different sites in the city: Teynampet, Alandi, Velachery, Manali and U.S. Embassy. To find the difference in values, the previous year data (2019) will be compared with the 2020 data. The changing pollution levels may also be associated with changing source patterns, and hence the present study also analysed the change in source pattern for pollution during COVID-19 lockdown using Concentration weighted trajectory (CWT) method based on back-trajectories obtained by lagrangian model HYSPLIT. The study attempts to understand the nature of variation of reduced/changed levels of pollutants during COVID-19 lockdown. The study is also crucial to understand the baseline emissions, as Chennai is the Indian megacity with lower pollution levels, and the state capital of Tamil Nadu, one of the worst COVID-19 hit regions in India.

1.1 Study Sites, Data Used and Methodology

The study region is Chennai, a tropical coastal station situated at the coast of Bay of Bengal. Chennai is the state capital of Tamil Nadu and one of the densely populated megacities of India with a population of 4,646,732 (Census, 2011). The sites in Chennai are: Teynampet, U.S. Embassy, Alandur bus depot, Manali and Velachery. The five sites are covering main populated areas of Chennai and are ~23 km away spatially from north to south. The locations of all five sites are depicted on Google earth imagery in Fig. 1. Teynampet is the monitoring station of world air quality index (WAQI) project (<https://aqicn.org/products/gaia/>), located in the commercial localities in the city of Chennai. U.S. Embassy is also located in the Teynampet area, though is < 1 km spatial distance from the WAQI station. The CPCB monitoring stations are: Velachery, a

Fig. 1. Site locations for the present study using Google earth imagery. The location of Chennai on the map of India is denoted by a black star in the inset.

residential cum commercial area in South Chennai; Alandur, an urbanised zone of Chennai corporation, in Guindy division and Manali, an Industrial cum residential area.

The data for the present study has been adopted from different sources. The data has been adopted for the pre-lockdown (1–23 March 2020), lockdown period (24 March–31 May 2020) and same period of 2019. The air quality data at Teynampet (13.05°N, 80.25°E) has been taken from world air quality index (<https://waqi.info/aqicn.org>), for daily average values of fine Particulate Matter (PM_{2.5}), Nitrogen di oxide (NO₂), surface ozone (O₃), Sulfur dioxide (SO₂) and Carbon Monoxide (CO) concentrations and meteorological parameters (humidity, temperature and wind speed). For PM_{2.5}, NO_x, O₃, SO₂ and CO; we have also taken data from the Central Pollution Control Board (CPCB) at Alandur bus depot, Velachery and Manali. At Manali, O₃ observations were absent for the period of our analysis (<https://cpcb.nic.in>). We have also obtained PM_{2.5} data at Consulate General of the United States, Chennai (13.03°N, 80.15°E) from AirNow website (www.airnow.gov). The units for PM_{2.5} are $\mu\text{g m}^{-3}$ and parts per billion volume (ppbv) for NO_x, O₃, SO₂ and CO. The spatial distance between Teynampet and Consulate General of the United States, Chennai is < 1 km, though the pollution statistics and population density differ at both the places, hence will allow understanding microscale differences. Details about COVID-19 lockdown dates are obtained from the Government of India website (<http://www.mygov.in>).

Before starting the analysis, all the datasets have been quality checked by these two criterions: (a) removal of all zero, negative and invalid data points by the manual inspection of the dataset, (b) outlier detection to clean the obtained dataset (Kumar *et al.*, 2020). The data has been analysed to understand the lockdown effect on pollution and compared with the same period of 2019. To get the percentage variation in various pollutants, we calculated the percentage change in values of 2020 from that of 2019 as

$$\text{Percentage Change of Pollutant in 2020} = \frac{(\text{Values in 2020} - \text{Value in 2019})}{\text{Value in 2019}} \times 100 \quad (1)$$

The change in pollution parameters for the lockdown period of 2020 and similar period of 2019 has been analysed with 1%–99% data limit, 25, 50 and 75% quartiles and mean values of the data. For understanding the weekly progression of pollution change, we have also calculated weekly variations in percentage change from 1 March–31 May 2020 for Teynampet and U.S. Embassy sites.

We employed back trajectory analysis using National Oceanic and Atmospheric Administration's Lagrangian model: HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectories). The HYSPLIT

derived two days (48 h) isentropic back trajectories at every three hours using GDAS (Global Data Assimilation System) $1^\circ \times 1^\circ$ data sets (Draxler and Hess, 1998) has been used for the present work. Concentration weighted trajectory (CWT) analysis has been employed based on two-day back trajectories. The CWT method allows understanding the geographical overview of emission source areas, contributing the transported pollutants to study region, i.e., Chennai in the present case. The method calculates the weighted concentration of each grid cell, combined with measured average concentrations of the pollutant at the site and corresponding trajectories crossing each grid cell. The details of CWT methodology can be adopted from Dimitriou (2015). The figures used in the present work have been prepared using originlab (www.originlab.com) and Matlab (www.mathworks.com) software, respectively.

2 RESULTS

2.1 Variation of Meteorological Parameters

The daily average air temperature, relative humidity (RH) and wind speed data at Teynampet, Chennai has been analysed for lockdown period (24 March–31 May 2020) and the similar period of 2019, presented in Fig. 2. The RH values of 2020 were $\sim 10\%$ higher to 2019, till 10 May 2020, after which both years values are fluctuating and coming to a similar range (Fig. 2(a)). The air temperatures were low during the lockdown phase (Fig. 2(b)), with $\sim 2^\circ\text{C}$ difference until 10 May 2020. As the temperature and RH variations at the surface are correlated (Sahu *et al.*, 2019), the increase in humidity and decrease in air temperature in the present case is justifying their nature of correlation. Though wind speed is fluctuating, there is a clear increase in 2020 wind speed throughout the lockdown period compare to the previous year's value (Fig. 2(c)). The high wind speed can reduce the pollution load over any area by transporting it to longer distances (Oke *et al.*, 2017).

The results are displaying that basic meteorological variables were not behaving the same as that of the previous year during the lockdown period, and this can impact the pollution dispersion over the region. Though one cannot relate one to one the difference of the meteorological variables to changed pollution during the lockdown period, it is to keep in to account that not only imposing restrictions on vehicular and industrial emissions, natural forcings were also different for transportation and dispersion of pollutants over the region during 24 March–31 May 2020.

2.2 Change in Air Pollutants during COVID-19 Lockdown

Pollution change during lockdown is widely reported globally, with reduced values in various

Fig. 2. Variation of meteorological parameters (a) Relative Humidity (%), (b) Air Temperature (in $^\circ\text{C}$) and (c) Wind Speed (m s^{-1}) during lockdown period of 2020, and similar period of 2019.

components (Bherwani *et al.*, 2020; Bontempi, 2020). Over Chennai also, there are various reported studies of reduced pollution during lockdown period and some of them are documented in Table 1 with sites, type of data used for analysis and key findings. Though all of these studies are having a prime focus on aerosols, some of them also reported NO₂, CO, SO₂ reduction and surface ozone increase during the lockdown period. However, as most of them were taking Chennai as one of the many sites, the results were calculated for the overall period as a single value by either subtracting from the previous year or from the pre-lockdown phase. Table 2 suggests that the variations are different by various studies due to different sampling sites, the difference in the period to compare, different sampling instruments/methods and different satellite data acquisitions. The reductions reported for PM_{2.5} are in the range 5.4–97%, 29–45% for AOD, 18–42% for NO₂, 25.96–69.2% for SO₂, 18–25% for CO and increase of 3–47% for O₃. Though as these values are based on average of different sites, the variations for different sites may show a different picture compare to overall average values of Chennai.

The present study attempts to see the change in pollutants during COVID-19 lockdown (from baseline of 2019), to understand the environmental change with lockdown restrictions. Fig. 3 shows the differences in values of pollutants during the lockdown period of 2020 and the same period of 2019. The figure plots 1–99% data limit; 25, 50 and 75% quartiles and mean values of the total period. For SO₂ (Fig. 3(a)), the values during COVID-19 lockdown are higher to the previous year at Teynampet and Velachery, however, the Alandur and Manali are showing reduction during the lockdown period. For NO_x (Fig. 3(b)) and PM_{2.5} (Fig. 3(c)), the values during the lockdown are less than the previous year for all the sites. As reported by various studies, there is an increase

Table 1. Change in various atmospheric pollutants during the COVID-19 lockdown over Chennai as reported by various researchers.

S. No.	Study	Study Site(s) [type of data]	Key Findings
1	Kumar <i>et al.</i> (2020)	U.S. Embassy [in-situ and satellite]	32% reduction in PM _{2.5} and 29% reduction in AOD loading
2	Jain and Sharma (2020)	Alandur Bus depot, Manali, Manali village, Velachery residential area [in-situ]	14% reduction in PM _{2.5} , 30 % reduction in NO ₂ , 25 % reduction in CO and a 3% rise in O ₃
3	Arshad <i>et al.</i> (2020)	Total Indo-Pak region [satellite]	32–42% in NO ₂ and ~45% reduction in AOD
4	Sharma <i>et al.</i> (2020)	CPCB stations (name not mentioned) [in-situ]	31, 10, and 18% reduction in PM _{2.5} , CO, and NO ₂ in general over all stations
5	Navinya <i>et al.</i> (2020)	Manali [in-situ]	30.2% reduction in PM _{2.5} , 69.2% reduction in SO ₂ , 36.30% reduction in NO ₂ , 23.7% reduction in CO
6	Laxmipriya and Narayanan (2020)	Ambattur, Maduravayol, Porur, Valasaravakkam, Koyembedu and Annanagar [in-situ]	80–97% reduction in PM _{2.5} and PM ₁₀
7	Zhang <i>et al.</i> (2020)	Chennai [satellite]	30.62% reduction in NO ₂ , 38.19% reduction in PM _{2.5} , 25.96% reduction in SO ₂ and 47.13% increase in O ₃
8	Singh and Chauhan (2020)	U.S. Embassy [in-situ and satellite]	5.4% reduction in PM _{2.5} and reduced values of NO ₂
9	Siddiqui <i>et al.</i> (2020)	Chennai [satellite]	33% reduction in NO ₂

Table 2. Percentage change in various pollutants for the total lockdown period (24 March–31 May) for 2020 compare to 2019 for the present study.

Parameter	Teynampet	Velachery	Alandur	Manali	U.S. Embassy
NO _x	–47.53	–33.92	–55.66	–41.63	–
SO ₂	40.47	71.69	–94.36	–71.23	–
O ₃	48.01	5.16	–33.37	–	–
CO	–90.72	–5.60	–61.36	–9.40	–
PM _{2.5}	–39.73	–65.24	–40.37	–42.14	–24.23

NO₂ value.

Fig. 3. Box-Whisker diagram for the (a) SO_2 , (b) NO_x , (c) $\text{PM}_{2.5}$ and (d) O_3 . The diagram is indicating the 1% data limit (lower X), 99 % data limit (upper X), 25, 50 and 75% quartiles with lower upper extreme in the box, and mean values (square) of the total lockdown period. The legend indicates the station name and year, i.e., T: Teynampet; V: Valechery; A: Alandur; M: Manali and USE: U.S. Embassy with 19: 2019 and 20: 2020, respectively.

in O_3 values at Teynampet and Velachery; however, Alandur shows a reduction in O_3 during the lockdown period. We don't have data for O_3 at Manali, and only $\text{PM}_{2.5}$ observations were available at U.S. Embassy. Though NO_x and CO were reduced during the lockdown at Alandur, the reduced O_3 values may be a result of transported O_3 reduction at Alandur; compare to previous year. It is reported at various sites in India that transported O_3 are able to maintain higher concentrations at a site even with less local production locally (Sinha *et al.*, 2016). However, the microscale analysis was not made for the present study due to unavailability of such observations, and we may not be able to confirm the exact reasons of reduced O_3 during the lockdown period.

To quantify the exact differences between the lockdown period and previous year values, we have computed the percentage change (given in Table 2). The values are in the range of previously reported studies (Table 1), though it is clear that at each site, the variation differs. The highest reduction in $\text{PM}_{2.5}$ occurs at Velachery (65.24%), whereas the lowest reduction happened at the U.S. Embassy (24.23%). Velachery also showed the highest increase in SO_2 values (71.69%) and the least increase in CO (5.60%). Alandur, on the other hand, showed reduced values of all the pollutants, including O_3 also. Teynampet also showed increased SO_2 values (40.47%) during the lockdown. The O_3 values increased by 48.01% at Teynampet during the lockdown. Though the O_3 values were not available at Manali, other pollutants reduced significantly at Manali during the lockdown. The difference in concentrations can be attributed to local emission patterns mainly, as the sites are nearby in the spatial distance, but have a different population density, locality and architectural planning and emission patterns.

To further understand the day to day variations of pollutants during the lockdown period and comparative period from previous year, we have analysed the daily values at Teynampet, as it is the commercial area and is centrally located among the chosen five sites in Chennai for the present study. Fig. 4 represents the daily variation of $\text{PM}_{2.5}$ and SO_2 from 1 March–31 May 2020 and 2019 at Teynampet. While analyzing $\text{PM}_{2.5}$ variation, we can see that though the levels of

Fig. 4. Variation in $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$) and SO_2 (ppmv) for 1 March–31 May of 2020 and 2019. The top row shows variation in $\text{PM}_{2.5}$ ((a) and (b)), and the bottom row shows variations in SO_2 ((c) and (d)). The left column is representing 2019 and the right column is 2020.

pollution are generally in the range of $60\text{--}100 \mu\text{g m}^{-3}$ for most of the days, there were some episodic events observed in 2019 (Fig. 4(a)) as well as in 2020 (Fig. 4(b)), where the values were reaching up to $\geq 400 \mu\text{g m}^{-3}$ in a daily average. Such high pollution events were observed frequently in 2020 during pre-lockdown (i.e., 1–23 March), however, during lockdown period, such cases were comparatively less than 2019. The observation articulates that episodic pollutions events were active even during the lockdown period, changing the average of weekly/monthly data quickly with high values.

As the lockdown imposed strict regulations of non-movement of vehicles (except emergency services) and shutdown of industries, these higher values of $\text{PM}_{2.5}$ are not results from vehicular or industrial emissions. However, thermal power plants burning coal may not be ruled out for such events. There are more than seven major thermal power plants in the state of Tamilnadu with North Chennai thermal power station of 1830 MW capacity running right at Chennai (<http://www.tangedco.gov.in/linkpdf/tncnctps.pdf>), which is utilizing coal for power generation. The episodic events may be results of changed dispersion due to meteorological conditions on a particular day. The SO_2 variations are showing that during March 2019 (Fig. 4(c)), the values were on the higher side ($\sim 25\text{--}35$ ppmv), which substantially reduces to lower values till 31 May. However, during the lockdown period, the higher values of SO_2 are observed for few days (Fig. 2(d)) compare to 2019, which again may be a result of change emission pattern and related to thermal power plants emissions. Other reason for such increase may be related to higher use of fossil fuels (coal and wood) in residential areas, producing high values (Sahu *et al.*, 2008). However, overall changes are in the pollution limits specified by the Government of India (CPCB, 2015).

Fig. 5 represents the change in surface O_3 , NO_2 and CO during 1 March–31 May 2019 and 2020 at Teynampet. O_3 has substantially increased during 2020, especially during the lockdown period (Fig. 5(b)). The values are almost double of 2019 (Fig. 5(a)) for the same period. Though air temperature reduces in 2020 (Fig. 2(b)), this increase in O_3 is a result of a decrease in NO_2 and CO (Figs. 5(d) and 5(f)) during the lockdown period. The reduced vehicular and industrial emissions show a direct decrease in NO_2 and CO, resulting in a hike in O_3 values, which was not the case in 2019 (Figs. 5(a), 5(c) and 5(e)).

The percentage change (based on Eq. (1)) for the weekly changes of all the pollutants observed at Teynampet (designated as site 1) and also the $\text{PM}_{2.5}$ values at Consulate General of the United States (designated as site 2) are given in Table 3. The reduced values (negative sign) are marked

Fig. 5. Variation in O₃ (ppbv), NO₂ (ppbv) and CO (ppmv) for 1 March–31 May of 2020 and 2019. The top row shows variation in O₃ ((a) and (b)), middle row shows variation in NO₂ ((c) and (d)) and the bottom row shows variations in CO ((e) and (f)). The left column is representing 2019 and the right column is 2020.

Table 3. Percentage change in various pollutants on a weekly basis for 2020 compare to 2019. Site 1 is Teynampet and Site 2 is Consulate General of the United States, Chennai.

	Week of the study	Site 1: PM _{2.5}	Site 2: PM _{2.5}	Site 1: SO ₂	Site 1: O ₃	Site 1: NO _x	Site 1: CO
Lockdown Period	W1 (1–7 March)	–49.81	51.84	–43.06	–0.95	–61.58	1.99
	W2 (8–14 March)	–35.48	–8.53	–31.24	32.63	–76.09	15.82
	W3 (15–21 March)	19.92	–25.57	–27.66	246.84	–65.07	40.07
	W4 (22–28 March)	–29.40	–1.43	–54.26	97.56	–49.53	–45.33
	W5 (29 March–4 April)	–42.15	34.50	0.89	129.21	–15.24	–55.21
	W6 (5–11 April)	–42.50	26.26	247.28	324.55	–19.74	–58.10
	W7 (12–18 April)	12.31	22.05	182.78	241.92	16.72	–41.93
	W8 (19–25 April)	–37.90	–127.20	24.56	200.51	–19.09	–50.25
	W9 (26 April–2 May)	–4.42	–136.99	35.03	218.93	0.56	–53.38
	W10 (3–9 May)	7.46	–252.54	93.00	137.62	–50.24	–57.23
	W11 (10–16 May)	–15.66	–129.13	–4.91	69.56	–77.76	–29.37
	W12 (17–23 May)	–17.33	21.47	121.57	18.64	44.19	–33.75
	W13 (24–31 May)	–52.97	–33.17	107.24	–2.49	–29.21	–35.16

with a blue colour for visual understanding. Both sites 1 and 2 are < 1 km spatial distance to each other; however, the range of PM_{2.5} they are recording is different. The difference may result due to various reasons including population density, traffic, and instrument use at two sites. However, not commenting on the nature and reason of differences in values, we want to highlight here the difference in percentage change for these two sites, representing the local impacts on measurements. For the first three weeks, during the pre-lockdown period, Site 1 is showing mostly reduced value of PM_{2.5}, while Site 2 PM_{2.5} values have increased. During the lockdown period, Except W7 and W10, Site 1 values of PM_{2.5} are always showing a reduction in 2020. Though, Site 2 experience higher PM_{2.5} in W5, W6, W7 and W12 and the level of PM_{2.5} was higher than previous year values. This difference may be explained with the fact that though most of the public transportation and

other emissions were reduced during the lockdown, the embassy area was not that affected due to nature of work in various consulates located in that area. Increase in value signifies that emissions are constantly increasing over the Consulate area. The SO_2 variations raised unexpectedly in 2020, especially during the lockdown period. Though the values of SO_2 over the study area is well within threshold limits, the results are indicating residential burning of coal and wood might have increased during the lockdown period, significantly contributing to the increase (Sahu *et al.*, 2008) producing increased values in 2020. The O_3 values increase markedly in all the weeks of study during the lockdown, which is associated with reduced values of NO_2 and CO due to restrictions on vehicular and industrial emissions.

The changed values of various pollutants during the COVID-19 lockdown period are supporting the findings of reported values from literature (Table 1). The values are not exactly matching with previous studies, due to difference in period to compare with and the averaging methods. The other reason for difference may be due to the reason that earlier studies only showed the average picture of variation for the whole period (either by taking average of in-situ observations at several sites or by satellite data), the present work is able to show the difference in location wise pollution change. Teynampet (commercial site) and U.S. Embassy (government office area) are able to show difference in the pollution reduction, though both are close by spatial distance. The other sites, which are north or south to these sites, are also able to bring the local scale differences in pollutants reduction during COVID-19 lockdown.

2.3 Identifying Changes in Source Regions with Changed Pollution Levels

Two days isentropic back trajectories at every three hourly intervals have been computed for 24 March–31 May 2019 and 2020 using HYSPLIT model. The back trajectories are not showing any significant differences in their number concentrations to any particular region during the lockdown period. As the pollution levels have been changed during the lockdown period, one can expect a change in the source regions as well. Identifying the source pattern will be even more challenging during the lockdown period, as the reduced pollution is not only present at the study site but also to source regions transporting pollution to study site. We have performed CWT analysis using the back trajectories and hourly $\text{PM}_{2.5}$ data obtained at site 2 (US Consulate). The reason for choosing $\text{PM}_{2.5}$ at site 2 is its hourly availability, providing more data points for CWT, and also the higher variability in $\text{PM}_{2.5}$ data during the lockdown.

Fig. 6 is showing CWT analysis for 2019 (Fig. 6(a)) and 2020 (Fig. 6(b)) for 24 March–31 May. As we can see, the source regions for transported pollution reaching to study site for 2019 are widely spread (Fig. 6(a)) and reach to the site by crossing states of Andhra Pradesh, Telangana, Karnataka and Maharashtra. The megacity Mumbai and Pune in Maharashtra are also appearing as source region to the study area. The oceanic transport and its relative contribution to the site in 2019 are insignificant in 2019. During the COVID-19 lockdown (Fig. 6(b)), the pollution source-apportionment pattern changed. The regions of Andhra Pradesh and Karnataka are prime source areas contributing to transported pollution. Highly populated and polluted cities of Maharashtra

Fig. 6. Concentration weighted trajectory plot for $\text{PM}_{2.5}$ using two day three hourly isentropic back trajectories for (a) 2019 and (b) 2020. Site location is depicted by a black star in both the figures.

and Telangana are not significantly transporting pollution to the site during the lockdown. The source apportionment results are also suggesting that the local contribution to PM_{2.5} is relatively small in the observed values. Another crucial finding of CWT is redistribution of oceanic component contribution. During the lockdown, oceanic transportation increases, suggesting that sea salt sprays are also significant contributing regions to Chennai pollution. As the prospect changed due to COVID-19, so as the source regions and their relative contribution to transported pollution over Chennai.

3 SUMMARY

The present study investigated daily pollution change during COVID-19 lockdown over Chennai. The work can be summarised in the following points:

- There is an increase in RH (~10%), decrease in air temperature (~2°C) and increase in wind speed (~2 m s⁻¹) during COVID-19 lockdown over Chennai.
- The SO₂ values increased at Teynampet and Velachery (40.47 and 70.69%) but there is a reduction at Alandur and Manali (94.26 and 71.23%).
- PM_{2.5} values showed significant reduction at all five sites during the COVID-19 lockdown. The values reduced in a range of 24.23–65.24%, respectively. Though the weekly analysis showed that the decrease is not at constant rate and there are weeks with higher values as well. The reason may be attributed to operational coal-powered thermal power plants in nearby regions and higher use of fossil fuel during the lockdown. There is an evident decrease in NO_x and CO at all the sites of present study (41.63–55.66% for NO_x and 5.60–90.72% for CO). The increase in O₃ during the lockdown period is observed at Teynampet (48.01%) and Velachery (5.16%), but the Alandur site reported a decrease in O₃ values (33.37%) during the lockdown period.
- The CWT analysis reveals the change in source regions during lockdown for the transported pollution reaching to Chennai.

The present study supported the findings of previously published works on air pollution change during COVID-19 over Chennai, however, observe the variation separately for the different sites in the city. The study could able to find following crucial observations apart from previously reported work over Chennai: Higher SO₂ values at Teynampet and Velachery with reduced O₃ at Alandur and change in source region pattern during the lockdown period. Though the results are preliminary in nature and require further analysis to characterize the site specific variation over the region, it is evident that the average reduced values of air pollutants may not be able to satisfy the individual localities of a region during the COVID-19 lockdown.

ADDITIONAL INFORMATION

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.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

ACKNOWLEDGEMENTS

Authors want to acknowledge the Central Pollution Control Board (<https://cpcb.nic.in>), AirNow group (www.airnow.gov) and world air quality index (<https://waqi.info/aqicn.org>) for providing the datasets. We want to thank HYSPLIT development team for providing the model and National Center for Environmental Prediction (NCEP) for the GDAS data. We are thankful to the Editor, Prof. Rajasekhar Balasubraman and two anonymous reviewers for their constructive suggestions to improve the quality of this manuscript.

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