



## Measurement report: An assessment of the impact of a nationwide lockdown on air pollution – a remote sensing perspective over India

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**Abstract.** The nationwide lockdown was imposed over India from 25<sup>th</sup> March to 31<sup>st</sup> May 2020 with varied relaxations from phase-I to phase-IV to contain the spread of COVID-19. Thus emissions from industrial and transport sectors were halted during lockdown (LD) which resulted in a significant reduction of anthropogenic pollutants. The first two lockdown phases were strictly followed (phase-I and phase-II) and hence are considered as total lockdown (TLD) in this study. Satellite-based tropospheric columnar nitrogen dioxide (TCN) from the years 2015 to 2020, tropospheric columnar carbon monoxide (TCC) during 2019-2020 and aerosol optical depth (AOD<sub>550</sub>) from the years 2014 to 2020 during phase-I and phase-II LD and pre-LD periods were investigated with observations from Aura/OMI, Sentinel-5P/TROPOMI, and Aqua-Terra/ MODIS satellite sensors. To quantify lockdown induced changes in TCN, TCC, and AOD<sub>550</sub>, detailed statistical analysis was performed on de-trended data using student's paired statistical t-test. Results indicate that mean TCN levels over India showed a dip of 18% compared to the previous year and also against the 5-year mean TCN levels during the phase-I lockdown, which was found statistically significant (p-value <0.05) against the respective period. Furthermore, drastic changes in TCN levels were observed over hotspots namely the eastern region and urban cities. For example, there was a sharp decrease of 62% and 54% in TCN levels as compared to 2019 and against 5-year mean TCN levels over New Delhi with a p-value of 0.0002 (which is statistically significant) during total LD. The TCC levels were high in the North East (NE) region during the phase-I LD period, which is mainly attributed to the active fire counts in this region. However, lower TCC levels are observed in the same region due to the diminished fire counts during phase-II. Further, AOD<sub>550</sub> is reduced over the country by ~16% (Aqua



35 and Terra) from the 6-years (2014-2019) mean AOD<sub>550</sub> levels, with a significant reduction (Aqua/MODIS  
28%) observed over the Indo-Gangetic plains (IGP) region with a p-value of  $\ll 0.05$ . However, an increase in  
AOD<sub>550</sub> levels (25% for Terra/MODIS, 15% for Aqua/MODIS) was also observed over Central India during LD  
compared to the preceding year and found significant with a p-value of 0.03. This study also reports the rate of  
change of TCN levels and AOD<sub>550</sub> along with statistical metrics during the LD period.

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**Keywords:** COVID-19, lockdown, Satellite, TCN, TCC, AOD<sub>550</sub>

## 1 Introduction

Following the outbreak of the novel coronavirus disease (COVID-19) and its declaration as pandemic  
by the World Health Organization (WHO) on 11<sup>th</sup> March 2020, several countries across the globe imposed  
45 national lockdowns to contain the pandemic (Tian et al., 2020). India confirmed its first COVID-19 case on 30<sup>th</sup>  
January 2020 with an exponential increase to 360 cases by 22<sup>nd</sup> March 2020 (<https://www.mohfw.gov.in/>). In an  
attempt to restrict this pandemic, the Indian government called for a ‘Janata Curfew’ on 22<sup>nd</sup> March 2020,  
followed by nationwide lockdown (LD) in phased manner starting from 25<sup>th</sup> March – 14<sup>th</sup> April 2020 (21 days) as  
phase-I, 15<sup>th</sup> April – 3<sup>rd</sup> May 2020 (19 days) as phase-II, 4<sup>th</sup> May – 17<sup>th</sup> May 2020 (14 days) as phase-III and 18<sup>th</sup>  
50 May – 31<sup>st</sup> May in 2020 (14 days) as phase-IV. Under this lockdown, 1.30 billion citizens of India were advised  
to stay in-doors, all the domestic and international flights, transport and industrial production were suspended,  
and only essential services were permitted. However, agriculture farming and its related sectors are permitted  
during phase-II as India is agricultural-dependent country. As indicated above, indoor emissions (cooking) and  
emissions from the emergency services still present in phase-I. For phase-II, crop residue burning is added in  
55 addition to phase-I emissions. Except these, rest of the anthropogenic emissions from above sectors are  
completely shut during phase-I and phase-II. Thus, economic activities were greatly affected and hence there  
was a shortfall in net energy consumption by about 30% (<https://www.ppac.gov.in/>) during strict lockdown  
period (first two lockdown phases).

Air pollution has arisen as an environmental issue which is harmful to human health (Xu et al.,  
60 2020) and extends from local to global scale (Fang et al., 2009). The oxides of nitrogen (NO, NO<sub>2</sub>) play  
important role in tropospheric chemistry and climate change. Exposure to NO<sub>2</sub> has been correlated with an  
increased rate of morbidity and subsequently increased rate of mortality (WHO, 2013). Global emissions of NO<sub>x</sub>  
(NO, NO<sub>2</sub>) are primarily due to anthropogenic activities such as transportation (32% in India), industrial



65 activities (21% in India), thermal power plants (28% in India), biomass burning (19% in India) whereas the natural sources of  $\text{NO}_x$  are soils and lightning (Biswal et al., 2020b). Thus, hotspots region of  $\text{NO}_2$  are thermal power plants, urban cities, and industrial regions. In addition to  $\text{NO}_2$ , carbon monoxide (CO) is also an important trace gas in the troposphere and is the main precursor of secondary pollutant ozone in  $\text{NO}_x$  rich environment. Though CO is not a direct greenhouse gas, it has a global warming potential because of its effects on the lifetime of several greenhouse gases. The natural and anthropogenic sources of CO are forest fire, biofuel  
70 burning, volcanic activities, and incomplete combustion of fossil fuels, oil, coal, woods, natural gas, and oxidation of hydrocarbons. However, significant amount of contribution to CO is from the anthropogenic emission only (Beig et al., 2020). Harmful effects of CO are dizziness, headaches, stomach-ache, confusion, tiredness. CO is tracer of air pollution due to its lifetime of about ~1-2 months (Filonchik et al., 2020).

75 Natural and anthropogenic activities are responsible for aerosols in the atmosphere. Anthropogenic activities over South Asia have caused considerable changes in aerosol composition and loading. Fine mode aerosols ( $\text{PM}_{2.5}$ ) are mainly from gas to particle conversions which are from biogenic and anthropogenic emissions. Coarse mode aerosols (particles with diameter larger than  $10\ \mu\text{m}$ ) arise from natural sources namely deserts, oceans, volcanoes and biosphere with less contribution from anthropogenic activities. Over the ocean  
80 surface, the natural global aerosol mass is controlled by sulphate, sea salt, and dust aerosols (David et al., 2018). Further, Aerosols also affect the earth-atmospheric radiation budget directly in scattering and absorption of incoming solar radiation and indirectly as clouds formation and precipitation (Ramachandran and Kedia, 2013). Thus, aerosols can influence the Indian monsoon (David et al., 2018). Earlier studies indicate that vehicular (Mahalakshmi et al., 2014, 2015) emissions, industrial, and thermal power plant emissions  
85 (Ramachandran et al., 2013) contribute significantly to atmospheric pollution, including gaseous pollutants. The ambient air quality is largely determined by the concentration of trace gases and particulate matter in the atmosphere (Nishanth et al., 2014). Increase in the concentration levels of trace gases and particulate matter has been a challenging environmental issue in urban and industrial areas. Numerous studies have been attempted across the globe to understand the air pollution concentrations during lockdown period and results  
90 indicate varied range of percentage reductions in pollutant concentrations. These studies are based on ground based measurements alone (Mohato and Ghosh, 2020; Mor et al., 2020) or satellite data alone (Biswal et al., 2020a; Xu et al., 2020) or with a combination of ground and satellite (Ratnam et al., 2020; Biswal et al., 2020b; Singh and Chauhan, 2020). Biswal et al. (2020a & 2020b) reported lockdown induced changes in tropospheric  $\text{NO}_2$  variability over the urban and rural regions of Indian sub-continent with marked reduction of 30-50 % over



95 the urban and megacities. This change was mainly attributed to the reduced traffic emissions due to restriction  
on travel. In contrast to the above, increase in levels of air pollutants during lockdown are also noticed at certain  
regions, which are associated with natural emissions (dust storms, forest fires) and prevailing meteorological  
conditions. During India's phase-I of lockdown (25<sup>th</sup> March, 2020 to 7<sup>th</sup> April, 2020), Ratnam et al. (2020)  
100 showed a decrease of AOD<sub>550</sub> over IGP region and a drastic increase over the central India, which were mainly  
due to absence of anthropogenic activities and dominance of natural sources respectively. However the above  
said studies were not performed detailed statistical analysis to indicate the observed changes are significantly  
lower than what could be expected due to inter-annual variability.

Objective of the present study is to understand the air quality quantitatively over the Indian region  
105 under the control measures related to COVID-19 restrictions in the country. Thus, the present study examined  
the spatio-temporal variations of remotely sensed Tropospheric columnar NO<sub>2</sub> (TCN), Tropospheric columnar  
CO (TCC) and Aerosol Optical Depth (AOD<sub>550</sub>) during LD and pre-LD and compared with preceding year  
(2019) and short-term mean (2014-2020). With these three air pollutants, we reported lockdown induced  
changes over the Indian region as a whole, hotspots (usual predominant sources) and urban regions along with  
110 the statistical analysis (using de-trended data). However, no one attempted to study the TCC variability during  
lockdown over the Indian region using satellite measurements. To distinguish natural and anthropogenic  
emissions, we made an attempt to correlate the subsequent changes associated with meteorology, long range  
transport as well as forest fires.

## 2 Data

115 Satellite measured air pollutants data offer reliable, un-interrupted observations with high spatial and  
temporal coverage than ground-based measurements which are point observations. Thus, the TCN observations  
from the Sentinel-5P/Tropospheric Monitoring Instrument (TROPOMI) and Aura/Ozone Monitoring Instrument  
(OMI), TCC data from high spatial resolution TROPOMI, AOD<sub>550</sub> data from Moderate Resolution Imaging  
Spectroradiometer (MODIS) Terra/Aqua sensors are used in the present study. The brief details of these sensors  
120 are given in Table 1. The TROPOMI was launched on 13<sup>th</sup> October 2017 as the single payload on-board the  
Sentinel-5 Precursor (S5P) satellite of the European Space Agency (ESA). TROPOMI is a push-broom imaging  
spectrometer flying in sun-synchronous orbit at 824 km altitude and is designed to retrieve the concentration of  
several atmospheric constituents, which include TCN, TCC, SO<sub>2</sub> etc. It was developed jointly by ESA and Royal  
Netherlands Meteorological Institute (KNMI), which is the most advanced multispectral imaging spectrometer



125 (Martínez et al., 2020). OMI was successfully launched on National Aeronautics and Space Administration's (NASA's) Earth Observing System Aura Satellite which measures NO<sub>2</sub>, SO<sub>2</sub> and aerosol characteristics. The MODIS sensor on-board NASA's the two Earth Observing System Terra and Aqua satellites are providing AOD retrievals.

Parameter	Data source	Resolution	Website
TCN	Aura/OMI Sentinel-5P/TROPOMI	0.25°×0.25° 3.5×7 km <sup>2</sup> (year, 2019) & 3.5×5.5 km <sup>2</sup> (year, 2020)	<a href="https://earthdata.nasa.gov/">https://earthdata.nasa.gov/</a>
TCC	Sentinel-5P/TROPOMI	7×7 km <sup>2</sup> (year, 2019) & 5.5×7km <sup>2</sup> (year, 2020)	<a href="https://earthdata.nasa.gov/">https://earthdata.nasa.gov/</a>
AOD	MOD08_D3 from Terra & MYD08_D3 from Aqua	1°×1°	<a href="https://ladsweb.modaps.eosdis.nasa.gov/">https://ladsweb.modaps.eosdis.nasa.gov/</a>
Fire count	VIIRS	375 m	<a href="https://firms.modaps.eosdis.nasa.gov/download/create.php">https://firms.modaps.eosdis.nasa.gov/download/create.php</a>
Winds and RH	ECMWF-ERA5 reanalysis	0.25°×0.25°	<a href="https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form">https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form</a>

*Reference Period: Jan-July (2014 – 2020); Strict Lockdown Period: 25<sup>th</sup> March – 3<sup>rd</sup> May 2020*

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**Table 1: Data resources**

Daily level 3 TCN data was obtained from Aura/OMI for computing short-term mean of TCN from 2015-2019. However, high spatial resolution TCN and TCC data from TROPOMI is used during LD period of 2020 and equivalent period in 2019. The daily gridded global AOD product (Level 3) from the MODIS sensor on-board Terra (MOD08\_D3\_v6.1) Aerosol Optical Depth at 550 nm, Deep Blue algorithm, Land-only) and Aqua (MYD08\_D3\_v6.1) Aerosol Optical Depth at 550 nm (Deep Blue algorithm, Land-only) satellites were used to investigate the aerosol loading over the Indian region for above said period. Detailed information about OMI sensor on-board Aura and MODIS sensor on-board Aqua/Terra as explained by Li et al. (2020). Over land, the previous studies reported that MODIS derived AOD uncertainty with respect to the Aerosol Network (AERONET) is  $\pm 0.05 \pm 0.20 \times \text{AOD}_{\text{AERONET}}$  (Sayer et al., 2013; Levy et al. 2013). Details of MODIS AOD retrieved algorithm for collection 6.1 and its validation can be found in Hsu et al., (2019) and Sayer et al.,

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(2019) respectively. In addition to the above datasets, fire counts data from Visible Infrared Imaging Radiometer Suite (VIIRS) with confidence >80% were used. To understand the role of meteorology, winds from European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis which gives hourly data at different pressure levels (700 hPa and 850 hPa) was also used in the present study. Similarly, relative humidity from  
145 ECMWF for the respective pressure levels is also used.

### 3. Methods

In the present study we attempted to assess the impact of lockdown on air quality over India by examining remotely sensed daily concentrations of TCN, TCC and AOD<sub>550</sub> for the period of 01<sup>st</sup> January, 2014 to October, 2020. Further, daily concentrations of the above said parameters were de-trended during the study  
150 period to subside the inter-annual variability. Hence, phase wise changes in TCN, TCC levels and AOD<sub>550</sub> could be attributed to LD induced changes. Thus, the present study focused on the air pollution over the Indian region, its individual states, and state capitals during the strict lockdown period (phase-I and phase-II). Analysis of satellite-based observations of TCN from the years 2015 to 2020, TCC during 2019-2020 and AOD<sub>550</sub> from  
155 2014-2020 was carried out for lockdown period (phase-I and phase-II) as well as pre-lockdown period. Short-term climatological means during pre-LD, phase-I, phase-II was computed for TCN from 2015 to 2020 and AOD<sub>550</sub> from 2014 to 2020 to assess the temporal changes of pollutants in the atmosphere. We have focused our analysis for the first two phases of lockdown in which the industrial and transport sectors were brought to a near standstill.

Figure 1 shows the data processing and execution strategy, which was followed in this study. The  
160 detailed methodology used in this study is as follows. Python programming language is used to analyse TCN, TCC and AOD<sub>550</sub> variables during the study period as discussed in Figure 1. The parameters TCN, TCC and AOD<sub>550</sub> are extracted from the respective source files considering quality factors. Swath and mask are calculated for the region of Interest and the data is resampled to the required region of Interest using nearest neighbourhood algorithm. Further, time averaged maps of TCN, TCC and AOD<sub>550</sub> for pre-lockdown, phase-I and  
165 phase-II lockdown were generated for the years 2020 and 2019 along with difference maps. With respect to 2020, if the difference in pollutant concentrations ( $\delta x$ ) is greater than zero indicating an increase effect and vice versa. Short-term climatological means of TCN for the years 2015 - 2020 and AOD for the years 2014-2020 were computed. Thereafter, the regional increase/decrease in pollutant concentrations over the country and individual states were analysed.

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$$\text{If } \begin{cases} b_i > 1\text{SD, positive pixels } (P_p) \\ b_i < -1\text{SD, negative pixels } (N_p) \\ -1\text{SD} \leq b_i \leq 1\text{SD, neglect pixels} \end{cases} \quad (4)$$

Where  $N$  is total number of qualified pixels over the Indian region and  $\mu_b$  is mean bias. At each pixel, weekly bias ( $b$ ) of TCN is estimated from the weekly mean TCN during 2020 lockdown period w.r.t 2019 and 2015-2019 period as shown in equations (1-2). For prominent change detection, additionally 1SD deviation filter was applied on the bias values of TCN and AOD<sub>550</sub>. Therefore, if bias is greater than 1SD then the featuring pixels are classified as positive and if less than -1SD then they are considered as negative pixels. Pixels within  $\pm 1\text{SD}$  are omitted to avoid minimalistic feature changes and for better characterization. Subsequently, we computed the percentage of positive (Increased area) and negative pixels (decreased area) using following equations (5-6).

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$$\% P_p = \frac{\text{count}(P_p)}{N} \times 100 \quad (5)$$

$$\% N_p = \frac{\text{count}(N_p)}{N} \times 100 \quad (6)$$

The same equations were applied on AOD<sub>550</sub> during 2014-2020 study periods. Further to understand LD induced changes in TCN and AOD<sub>550</sub> quantitatively daily mean values are de-trended using yearly data, which accounts for inter-annual variability in TCN and AOD<sub>550</sub> respectively. De-trended values of TCN and AOD<sub>550</sub> are generated by subtracting the linear regression estimated values from the daily means of TCN and AOD<sub>550</sub>. To study the lockdown induced changes with significant levels, a paired t-test (Freedman et al., 2007) was implemented on the de-trended TCN and AOD<sub>550</sub> data during respective study period. The t-test follows a Student's t-distribution under the null hypothesis of  $H_0$  with the means ( $\mu$ ) of two populations are equal ( $\mu_1 = \mu_2$ ) with alternative hypothesis  $H_a: \mu_1 \neq \mu_2$ . To reject or accept the null hypothesis, p-value was used in this study. The hypothesis  $H_0$  is rejected when a p-value is less than 0.05 and accepted if p-value is greater than 0.05 (5 % significance level).

#### 4. Results and Discussion

Present study analysed the satellite based tropospheric columnar NO<sub>2</sub> (TCN), TCC and AOD<sub>550</sub> data to assess the lockdown induced changes over the Indian region.



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#### 4.1 Effect of Lockdown (LD) on TCN

The spatio-temporal variability in TCN concentrations during pre-lockdown and lockdown period (phase-I and phase-II) were analysed for the years 2019 and 2020 using high spatial resolution (Table 1) Sentinel-5P/TROPOMI. Temporally averaged concentrations of TCN during pre-LD (01<sup>st</sup> March to 21<sup>st</sup> March 2020), phase-I and phase-II of lockdown, and the corresponding period of the previous year (2019) are shown in Figures 2a-c, along with the differences in concentration levels between different periods. During pre-LD time of years 2019 and 2020 as shown in Figure 2a, extent of TCN hotspot regions (majorly Eastern and National Capital region) remain same however, a mild reduction of TCN noticed during pre-LD of 2020 compared to 2019. This could be due to inter-annual variability in TCN levels and also the absence of source emissions due to lockdown imposed by neighbouring countries via long-range transport (For example: lockdown imposed in China from 23<sup>rd</sup> Jan, 2020, Italy from 21<sup>st</sup> Feb 2020 and Malaysia from 18<sup>th</sup> March 2020).

The mean TCN over the entire country during phase-I of 2020 and 2019 are  $1.53 \times 10^{15}$  and  $1.86 \times 10^{15}$  molecules  $\text{cm}^{-2}$  respectively. A reduction of about 22 % TCN levels are observed in 2020 compared to 2019 during phase-I, which accounts both inter-annual variability and lockdown-imposed changes. Further to understand the lockdown induced changes in TCN levels, study was focused on TCN hotspots, which includes power plants and metropolitan cities with industrial and transport activities. To contain the spread of COVID-19, about 95 % of the anthropogenic activities were halted (Ratnam et al., 2020) during phase-I LD. However, during phase-I a few anthropogenic emissions are present under essential services (pharma industries, power plants, medical services, vehicles that were carrying daily commodities) and indoor emissions. As a result, the TCN levels and its area of extent as shown in Figure 2b during phase-I of LD in 2020 over the hotspot regions (Eastern region of India) decreased by 22 % when compared to equivalent period of 2019. The eastern region of India has a significant number of major power plants and refineries with associated industries. During phase-I LD in 2020, a reduction of TCN levels is observed over this region, which is due to shutdown of industries and urban activities such as transport and small-scale industries. However, country's high TCN levels are noticed in the eastern region with less spread indicating the active role of power plant industries located in this region. Simultaneously, the National capital region (NCR) shows marked reduction by about ~70 % during phase-I LD. The major source of emissions in the NCR are dominated by heavy traffic, densely located industries, and industries of steel, cement and sugar (Ghude et al., 2008). As mentioned above, India's strict lockdown permitted only essential services therefore remaining all activities were halted during phase-I period. Thus,

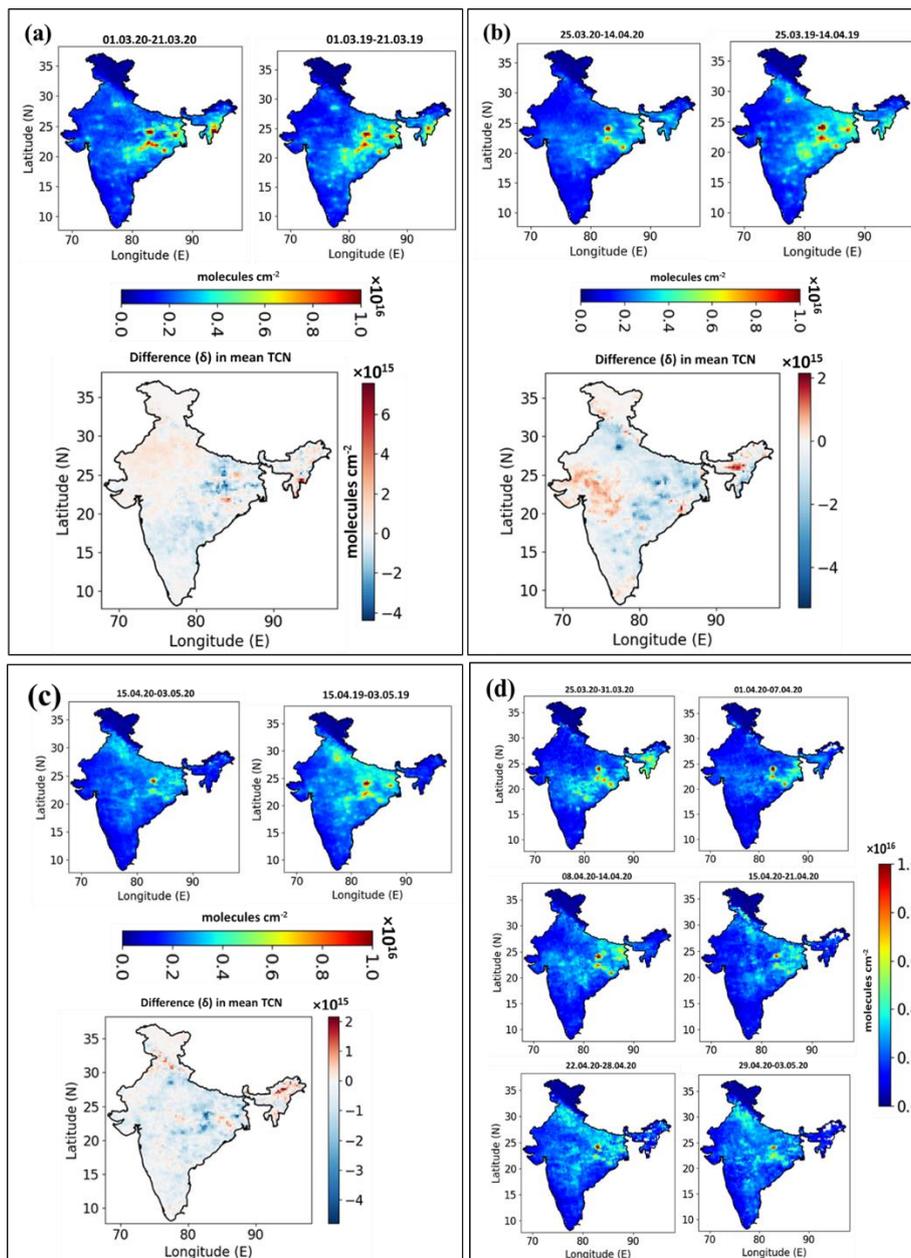


260 resulted in low levels of TCN over the hotspot regions except in eastern region due to continuous operation of power plants (Biswal et al., 2020b).

To sustain the Indian economy, activities namely agricultural practices and associated activities (crop residue burning) are given permission during phase-II along with phase-I restrictions. Figure 2c shows TCN levels and their difference map during phase-II LD. With respect to the same period of phase-II in 2019, the  
265 TCN levels over the country decreased by 13 % with mean TCN of  $1.55 \times 10^{15}$  molecules  $\text{cm}^{-2}$  and  $1.75 \times 10^{15}$  molecules  $\text{cm}^{-2}$  in 2020 and 2019. Thus, continued decrease of TCN levels are recorded over the hotspot regions. However, an increase of TCN also observed over the neighbouring regions of eastern region clearly indicating the dispersion of TCN. In contrast to earlier, an increase in TCN levels over north-east region could be due to seasonal biomass burning in this region. Thus, the mean TCN levels over the entire country is  
270  $1.54 \times 10^{15}$  molecules  $\text{cm}^{-2}$  during total LD (phase-I and phase-II together) with a reduction of 18 % compared to respective period in 2019 as well as with respect to 5 years mean TCN .

Overall, southern part of India reported less TCN values as compared to eastern and NCR regions (hotspot regions) during pre-LD, phase-I and Phase-II. The hotspots over southern part of India are not as dense as in the eastern and northern regions could be one of the reasons for its lower values. The other reason could be  
275 dispersion of TCN values as result of land and sea breeze effect since it is surrounded by Bay of Bengal and Arabian Sea over this region (Ramachandran et al., 2013). Thus, reduced TCN levels over southern part of India irrespective of LD were observed due to above facts. Weekly variations of TCN were also shown in Figure 2d to assess the extent of source emission during the lockdown period. Therefore, present study depicted the possible driving factors of TCN values during pre-LD, phase-I and phase-II using high resolution spatial data from  
280 satellite.

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**Figure 2: Time-averaged TROPOMI TCN concentration and their difference maps between 2020 and 2019 during a) pre-LD b) phase-I lockdown c) phase-II lockdown, d) weekly mean TCN variation starting from 25<sup>th</sup> March to 03<sup>rd</sup> May 2020.**



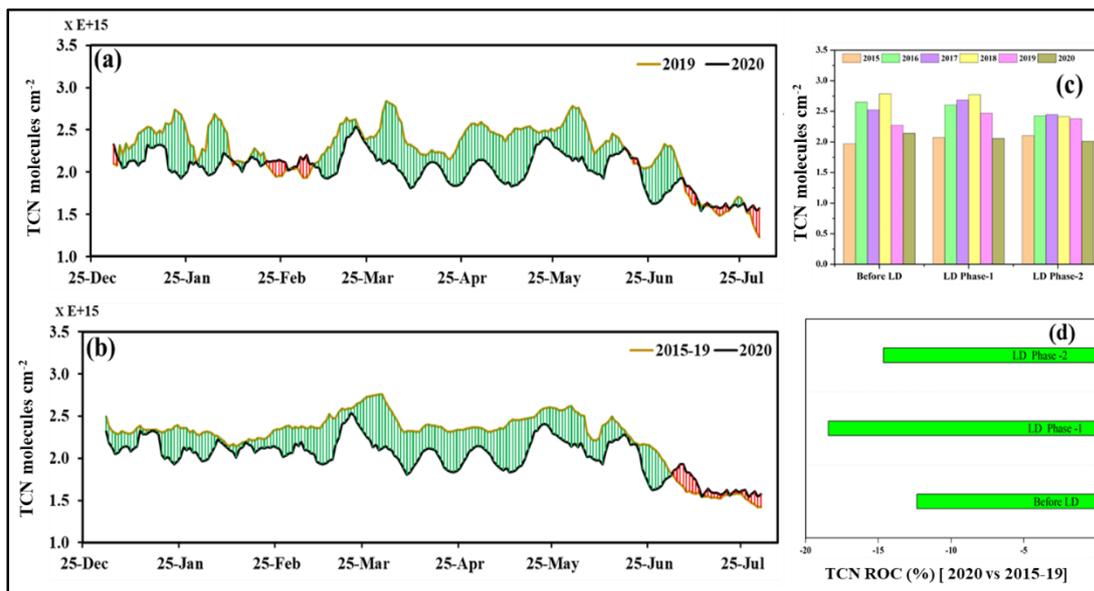
#### 4.1.1 Short-term climatological variations in TCN due to lockdown

295 Time series analysis of TCN was carried out during 2015-2020 for the months of January to July over the entire  
Indian region covering cold and hotspot regions as shown in Figures 3a-d. A smoothing function with span of 7  
days was used for better visualization of patterns/trends in TCN levels as shown in Figures 3a-b, with red (green)  
bars indicating increase (decrease) TCN levels in 2020 relative to 2019 and mean of 2015-2019. The 7-day  
moving average show significant decrease of TCN concentration with 99.99% ( $p$ -value  $\ll 0.05$ ) confidence  
300 interval during total lockdown period. However, it is also noticed that a decrease of TCN during prior and post  
lockdown periods, which is further tested statistically and found insignificant change with a  $p$ -values of 0.08 and  
0.24 respectively. Further statistical significance of TCN variability across hotspot, cold spot regions and also  
over the major cities where TCN dropped ( $\downarrow$ ) drastically (except NE) along their percent drop during total LD  
when compared to 5 years mean TCN levels were summarized in Table 2. It clearly shows the TCN levels over  
305 the IGP (22%  $\downarrow$ ), eastern region (29%  $\downarrow$ ), and major cities (New Delhi 54%  $\downarrow$ ) declined significantly compared to  
preceding 5 years mean TCN levels during the total LD period. Change in TCN during the study period is also  
associated with the inter-annual and seasonal variability besides its dominant anthropogenic sources. Figure 3c  
shows annual means of TCN in pre-LD, phase-I and phase-II LD during 2015-2020 period. It clearly depicts  
inter-annual variability in TCN between the years at each time scale along with the lockdown-imposed changes.  
310 Between the time scales during the study period, a clear seasonality in TCN levels is also observed in Figure 3c.

The horizontal bar plots in Figure 3d show the rate of change (RoC) in TCN levels in 2020 against the  
mean during 2015-2019 indicating the impact of lockdown on TCN concentrations over Indian region. The RoC  
is extremely important in weather and climatological studies because it allows understanding and predicting the  
315 trends/patterns in climatic parameters. RoC is used to describe the percentage change in a parameter over a  
defined time period and it represents the rate of acceleration of the parameter. To compute the RoC in this study,  
we have used de-trended TCN daily values, which accounts inter-annual variability in TCN. Thus, the present  
RoC depicts the TCN variability due to the lockdown-imposed changes alone. There is a clearly observable  
lowering in TCN levels relative to the short-term climatological mean by 12% for the pre-lockdown period as  
320 Lal et al. (2020) also reported similar results. During period from January-April, 2020, authors reported a  
substantial reduction in the level of TCN, TCC, and AOD<sub>550</sub> across the globe during COVID-19 pandemic as  
each country (at different spatial scale) imposed lockdown at different time scales. This could be the reason for  
reduction in concentrations of TCN during pre-LD period in 2020 as compared with 2019 as well as mean



325 picture of 2015-2019. Furthermore, a noteworthy reduction of TCN concentration by 18% and 15% is observed for the phase-I and phase-II lockdowns respectively over the Indian region.



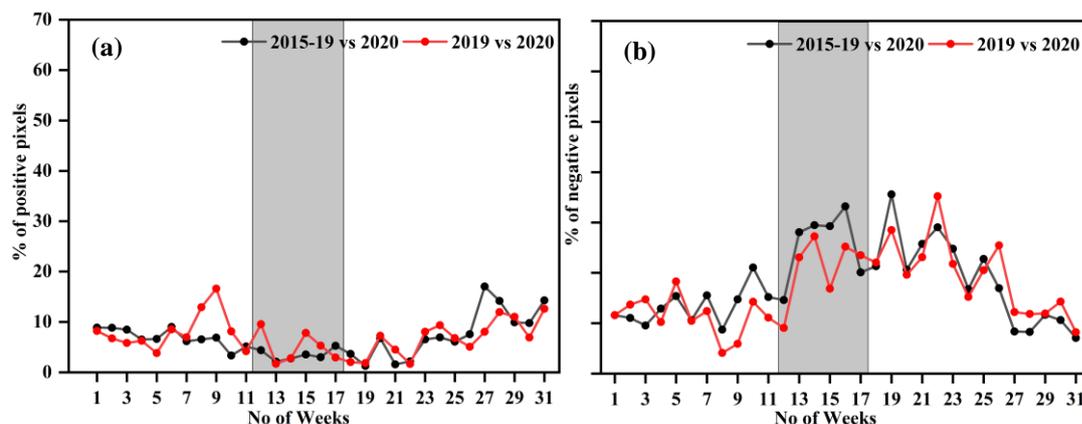
340 **Figure 3: Moving average time series analysis during January-July of TCN during a) 2019 vs. 2020; b) short-term climatological mean of TCN (2015-2019) vs. 2020 c) Annual variations of TCN (2015-2020) during period of before lockdown and different phases of lockdown and d) Rate of change of TCN during 2020 w.r.t. 2015-2019 period.**

Region/City	*Student's Paired t-test p-value (RoC in percent during Total LD)		
	Pre-LD	During total LD	Post LD
IGP	0.03	<< 0.05 (22 % ↓)	0.31
East	0.62	<< 0.05 (29 % ↓)	0.11
NE	0.66	0.19 (3 % ↑)	0.55
New Delhi	0.57	0.0002 (54% ↓)	0.05
Bangalore	0.58	2.62E <sup>-5</sup> (43% ↓)	0.17
Chennai	0.37	0.012 (41% ↓)	<<0.05
Mumbai	0.95	0.011 (35% ↓)	0.17
Hyderabad	0.49	0.0003 (30% ↓)	0.007

\*p-value < 0.05 is significant and vice-versa; (↓, ↑) indicates (decrease, increase)

345

**Table 2: Student's paired t-test for TCN during the lockdown period against 5-year mean (2015-2019)**



360 **Figure4: Aura/OMI measured TCNa) percentage of positive pixels b) percentage of negative pixels during the period 2020 vs (2015-19) and 2020 vs 2019.**

Figures4a-b show statistically computedTCN metrics for number of positive pixels and number ofnegative pixels in percentage during January to July period as number of weeks which starts from 01<sup>st</sup> January. Weekly TCN means for the years 2015-2019, 2019 and 2020 were used to calculate positive and negative pixel count based on methodology stated in section 3.1. Thus, red color line in the Figures 4a-b represent the number of positive/negative pixels for the years 2019vs.2020 and black color line represents the same for the years 2015-2019 vs 2020. The study showed a greaternumber of negative pixels (decreased area) during lockdown weeks and vice-versafor positive pixels which clearly depicts the extent of area affected due to LD and subsequent changes on air pollutants over Indian region.

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#### 4.2 Effect of LD on TCC

The mean TCC levels over Indian region during the pre-lockdown and LD periods were studied to assess the COVID-19 lockdown induced changes in TCC. Figures 5a-c show mean concentrations of TCC over the Indian region during pre-LD, phase-I and phase-II LD periods using TROPOMI data. During the pre-lockdown period (01-21<sup>st</sup> March 2020), TCC levels were higher (mean =  $2.39 \times 10^{18}$  molecules  $\text{cm}^{-2}$ ) as compared to 2019 by ~4.8%, which indicates increasing effect of anthropogenic activitiesand inter-annual variability. As shown in

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Figure 5b difference map, the TCC levels increased in north-eastern (NE) region followed by part of central India (CI) and south of north-west (S-NW) of India as compared to 2019 of phase-I LD period. An observed increase over these regions was evaluated statistically and found insignificant ( $p > 0.05$ ). An increase of TCC in NE region of India is mainly attributed to the active fire counts (Figure 5d) during the phase-I of LD as shown in Figure 5b. During phase-I, other regions of India namely the Indo Gangetic plain (IGP), north and south regions show decreased TCC levels compared to same period of 2019. The decreased TCC levels in these regions during phase-I are attributed to the shutdown of industries (cement, sugar and steel etc.), absence of transportation and restriction on crop residue burning. However, household emissions due to residential cooking are still present during lockdown which is major contribution to CO from rural areas and some parts of urban region (slums). In India, 72 % of the populations live in rural and urban slums and most of them are continued to use household biofuel for cooking under lockdown (Verma et al., 2018; Beig et al., 2020).

However, the mean TCC levels as shown in Figure 5c are higher during the phase-II of lockdown. Over the entire country, the mean TCC value during phase-II is  $2.38 \times 10^{18}$  molecules  $\text{cm}^{-2}$  in comparison to 2019 mean value of  $2.32 \times 10^{18}$  molecules  $\text{cm}^{-2}$ . In phase-II of LD, the TCC levels are decreased in NE region, which is strongly attributed to the reduced active fire activity in this region as shown in Figure 5c. Except in NE region, consistent increase of TCC levels is observed during phase-II. Since agriculture farming industry is exempted in the phase-II LD and observed active fire counts in the central India, thus observed enhancement in the TCC levels during phase-II. An increase or decrease of TCC levels in the atmosphere is mainly dominated significantly by anthropogenic activities compared to natural emissions (Kanchana et al., 2020) as discussed earlier. However, comprehensive reasons for the increase of TCC levels in phase-II are not investigated in this study.

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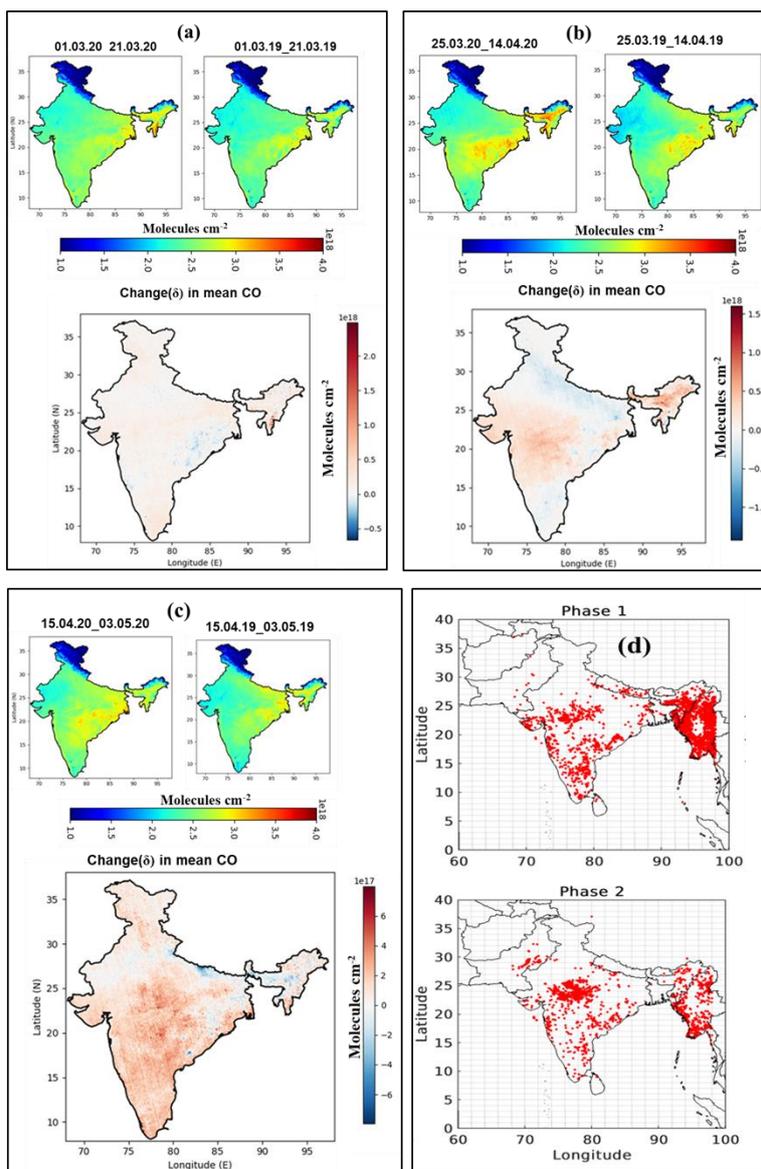
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**Figure 5: Sentinel-5P/TROPOMI derived Time averaged TCC concentration and their difference maps in 2020 and 2019 a) pre-LD b) phase-I lockdown c) phase-II lockdown, d) Fire counts from VIIRS for phase-I, phase-II during 2020.**



#### 440 **4.3 Effect of LD on AOD<sub>550</sub>**

We have used Terra-Aqua/MODIS derived AOD<sub>550</sub> during 2014-2020 for the months of January to July to understand the lockdown-imposed changes. Terra/MODIS AOD<sub>550</sub> represents the footprint for 10:30 and Aqua/MODIS AOD<sub>550</sub> for the 13:30 local time. As we observed similar spatial variation of AOD<sub>550</sub> from both Terra-Aqua/MODIS, only Aqua/MODIS derived AOD<sub>550</sub> is shown here (Figure 6). AOD<sub>550</sub> levels over the Indian region for 2019, 2020 and the difference in AOD<sub>550</sub> for both years for pre-lockdown period is depicted in Figure 6a. During this period, the AOD<sub>550</sub> levels for 2020 over the IGP region (~21% of the Indian Territory landmass) is more compared to rest of the regions of India which is expected throughout the year. This is mainly because of its orographic effect and densely populated (accommodating ~40% of the Indian population). The main anthropogenic sources over IGP region are coal-based power plants and industries, crop residue and forest fires and household cooking which contribute to high AOD in this region. Thus, the IGP is known as first hotspot for anthropogenic aerosol emission in South Asia. During phase-I of LD as shown in Figure 6b, aerosol loading over the IGP region attained its baseline concentration (~45% drop w.r.t. 2019 of the same period) due to the strict implementation of LD. This region is densely populated and congested industrial activities, which were shut down during this period resulted a nearly AOD free atmosphere. This indicates absence of anthropogenic activities due to mobility restrictions. Further, prevailing meteorology over IGP (high wind speed and low relative humidity at 850 hPa and 700 hPa) is also favoured for decrease in AOD<sub>550</sub> during phase-I LD.

Despite the strict LD in the country, unexpected increase in AOD<sub>550</sub> is observed by ~28 % compared to preceding year of the same period over Central India (CI) which is predominantly dominated by dust storms (Ratnam et al., 2020) through long range transport and prevailing meteorology (Pandey et al., 2020). Thus, to understand the prevailing meteorology over CI, phase wise relative humidity and wind speed at pressure levels 850 hPa and 700 hPa respectively were analysed as shown in Figures 7a-b. During phase-I and phase-II, majority of the winds over CI dominated by westerly (calm winds) with high relative humidity. Under this prevailing meteorology, calm winds contribute to slow dispersion and high RH modulates the aerosol chemistry and hygroscopic growth mechanism (Pandey et al., 2020). As a result, the increase of AOD<sub>550</sub> over CI is observed. Further, high AOD<sub>550</sub> over NE regions also observed because of high active forest fire counts (Figure 5d) compared to 2019 LD period. Figure 6c shows AOD<sub>550</sub> during phase-II of India's LD in 2020 against AOD<sub>550</sub> in 2019 of same period. During this phase, an increase in AOD<sub>550</sub> (~3%) over IGP was observed. Over CI, a reduction of AOD<sub>550</sub> (~18%) was observed compared to phase-I of LD and not much change (~1%) when compared to respective period in 2019 which clearly depicts reversal of meteorology in phase-II with respect to



470 phase-I. Causative factors for this decrease over CI w.r.t phase-I are due to low RH and high wind speed at 700  
hPa and 850 hPa over this region.

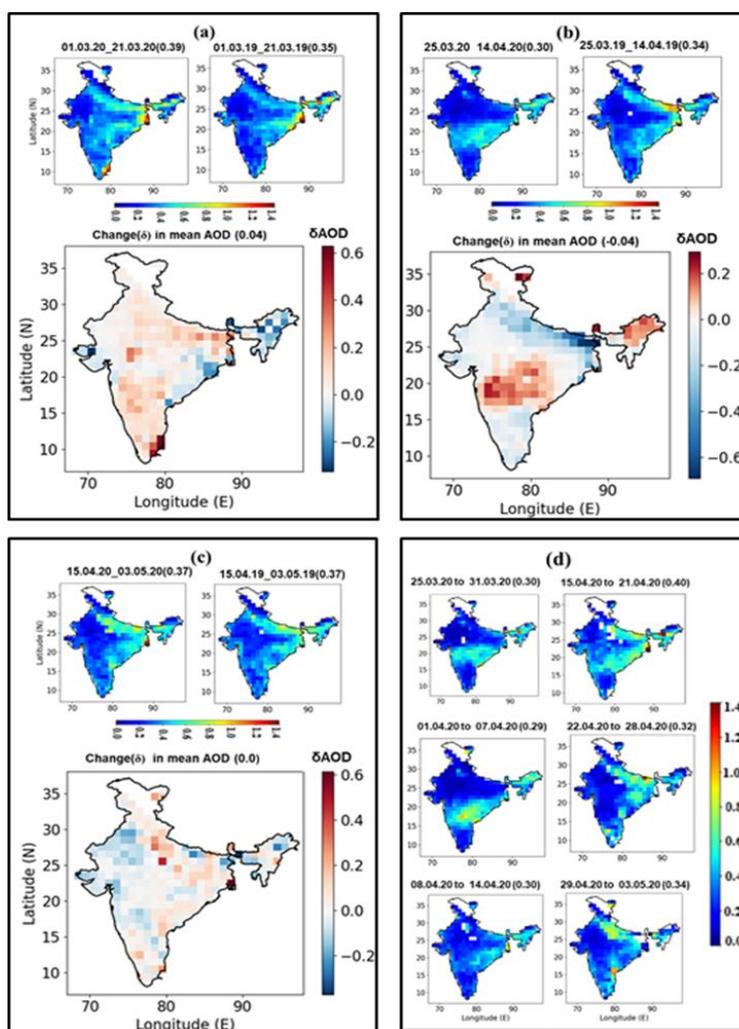
In a Nutshell, this study demonstrates the lockdown induced Terra/MODIS AOD<sub>550</sub> changes over the  
IGP and CI during total LD period shows a significant change with p-value of 0.01 (99 % confidence  
interval)with a decrease of 20 % over IGP and 0.03 (97 % confidence interval)with an increase of 25 % over CI  
475 when compared to equivalent period in 2019.

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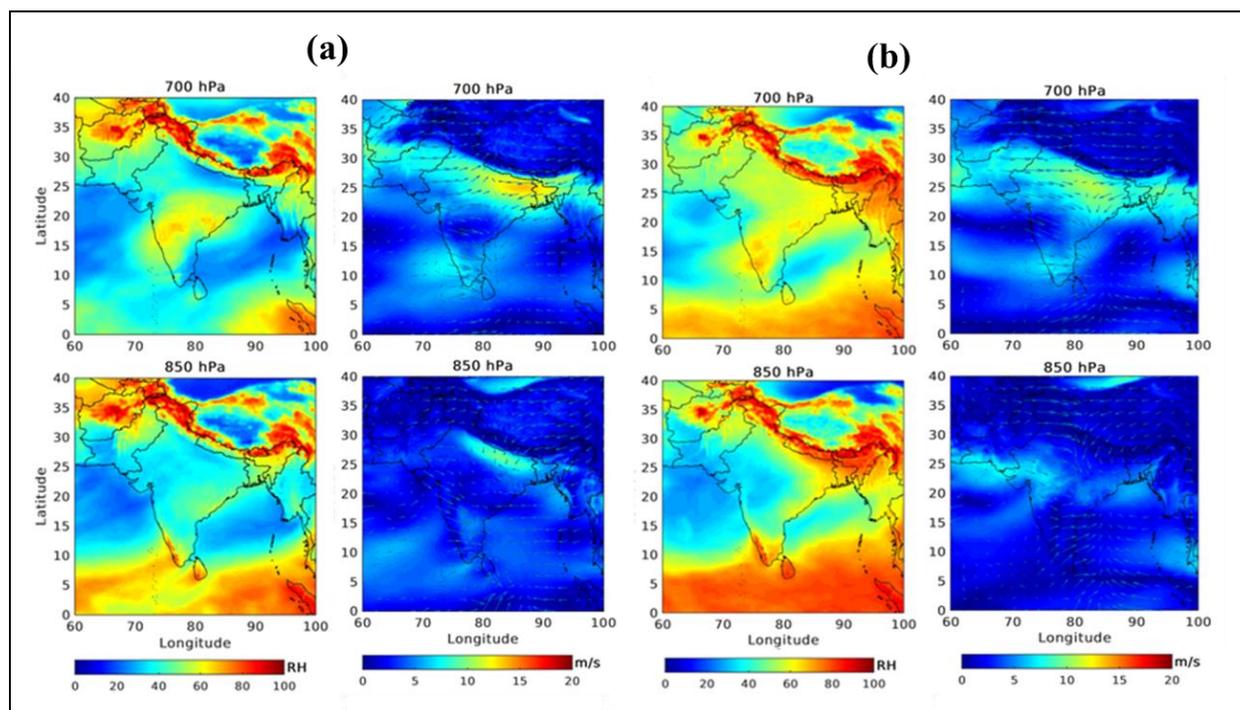
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500 **Figure 6:**Aqua /MODIS derived Time averaged AOD<sub>550</sub> and their difference maps in 2020 and 2019 a)  
pre-LD b) phase-I lockdown c) phase-II lockdown d) weekly variation in total lock period during 2020.



**Figure 7: Mean relative humidity (%) and mean winds ( $\text{ms}^{-1}$ ) observed at 700 hPa and 850 hPa (a) phase-I of lockdown and (b) phase-II of lockdown**

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#### 4.3.1 Short-term climatological variation of $\text{AOD}_{550}$ due to lockdown

Aerosol optical depth is one of the important short-term climatic forcing agents along with long lived greenhouse gases namely carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), water vapor ( $\text{H}_2\text{O}$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ). A 7-day smoothing average filter was applied on  $\text{AOD}_{550}$  time series data as discussed in section 4.1.1. Figures 8a-  
510 d show 7-day moving average time series analysis of  $\text{AOD}_{550}$  levels for MODIS Terra and Aqua from January to July over the Indian region for 2014-2019 mean values, 2019 and 2020.  $\text{AOD}_{550}$  measured by Terra/Aqua-MODIS (Figures 8b & 8d) show a significant change in aerosol loading over the country during the lockdown period in 2020 compared to mean  $\text{AOD}_{550}$  of 2014-2019. Statistical analysis of Student's paired t-test shows a strong significant change in  $\text{AOD}_{550}$  with a p-value of  $\ll 0.05$  for Terra/Aqua-MODIS during the total LD  
515 against 6-year mean (2014-2019). Interestingly the present analysis show a very much significant change of  $\text{AOD}_{550}$  during post LD compared to LD with p-value  $\lll 0.05$  (order of an Integer  $\times 10^{-12}$ ), which attributes to



520 continued effect of lockdown as phase-III and IV and scavenging effect during monsoon season. Due to increase of precipitation in the active summer monsoon (June-July) season, lowering of aerosols is expected (Boucher et al., 2013). Thus, the continued lockdown and active monsoon improved the air quality beyond strict lockdown period as shown in Figures 8a-d.

525 The annual mean  $AOD_{550}$  over the Indian region in each phase is shown as vertical bars in Figures 8e-f, indicating the inter-annual variability of  $AOD_{550}$  across the phases and seasonal modulation between the phases during 2014-2020. Despite inter-annual and seasonal variability of  $AOD_{550}$ , the strict lockdown in 2020 shows a decrease in phase-I and phase-II compared to pre-LD, which could be associated with the reduced anthropogenic sources besides prevailing meteorology as discussed at section 4.3. The RoC in  $AOD_{550}$  was computed (Figures 8e-f) to understand the effect of short-term climatological mean  $AOD_{550}$  over lockdown period in 2020. A positive RoC of +8.8 % (+14%) was observed during pre-LD as measured by Terra/MODIS (Aqua/MODIS) against 6-year mean  $AOD_{550}$ . This increase is tested statistically and found insignificant with p-values of 0.11 and 0.37 for Terra/MODIS and Aqua/MODIS respectively. During phase-I (phase-II) Terra /MODIS showed statistically significant negative RoC with -24 % (-9%) and Aqua/MODIS showed -22 % (-7%) against 6-year mean  $AOD_{550}$  as most of the sectors were turned off except household emissions and essential services. Therefore, this study reports, India's strict lockdown improved the aerosol air quality over the country with markedly changes over the IGP and CI respectively.

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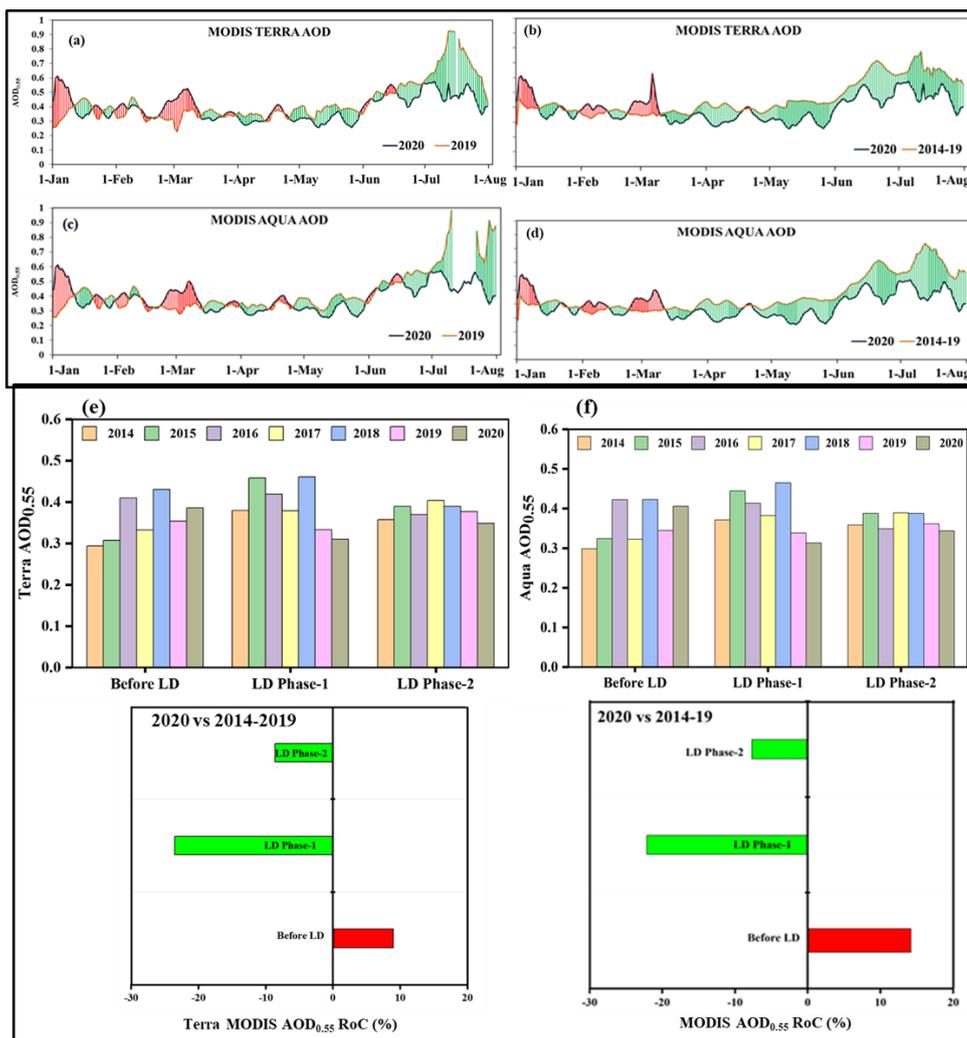
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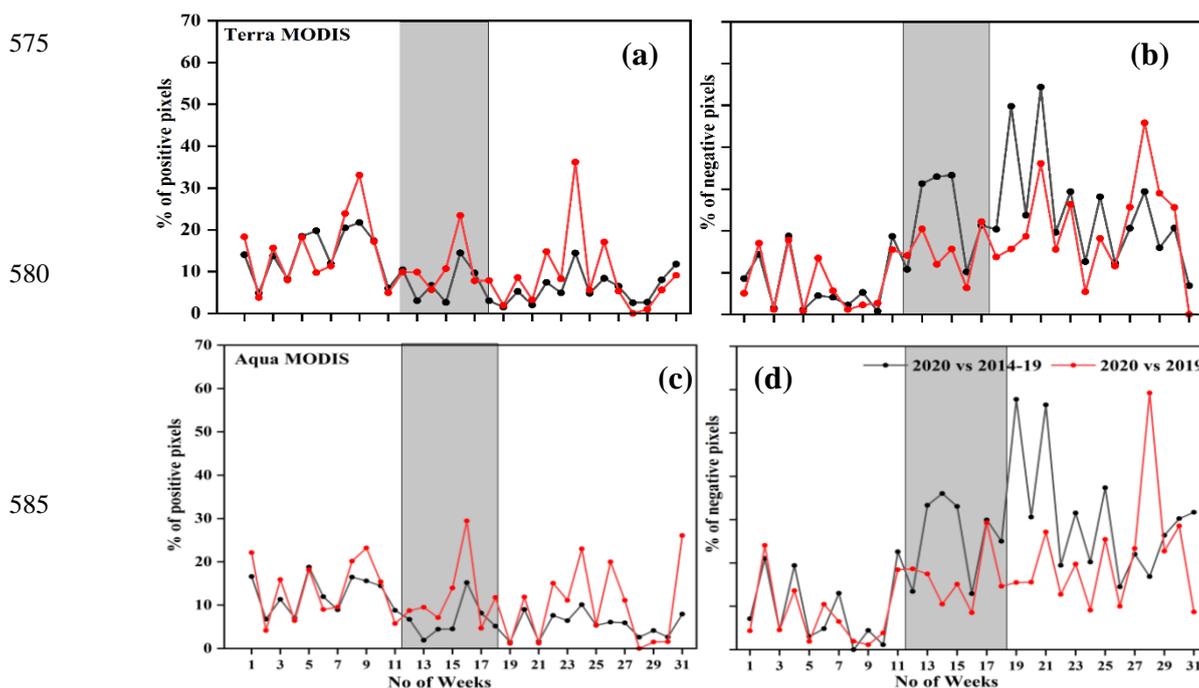
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**Figure 8:** a) Moving average time series analysis of AOD<sub>550</sub> measured by Terra/MODIS during 2019 and 2020; b) Terra/MODIS short-term climatological mean of AOD<sub>550</sub> (2014-2019) vs. 2020; c) time series AOD<sub>550</sub> measured by Aqua/MODIS during 2019 and 2020; d) Aqua/MODIS short-term climatological mean of AOD<sub>550</sub> (2014-2019) vs. 2020; e) Variations of Terra/MODIS measured AOD<sub>550</sub> before Lockdown and different phases of Lockdown and respective RoC; f) Variations of Aqua/MODIS measured AOD<sub>550</sub> before Lockdown and different phases of Lockdown and respective RoC.



570 Figures 9a-d show number of positive and negative AOD<sub>550</sub> pixels in percentage at weekly interval computed from the respective biases during the study period over the Indian region. Figures 9a-b show the percentage of positive and negative pixels of AOD<sub>550</sub> measured by the Terra/MODIS. During the lockdown weeks (shaded in grey color) in 2020, the number of positive pixels were less w.r.t 2019 and short-term climatological mean of AOD. Figure 9b shows more percentage of negative pixel during the same study period indicating the larger area of extent with lower AOD<sub>550</sub> due to strict lockdown in India. This change is even high w.r.t short-term climatological mean of AOD<sub>550</sub>. The Aqua/MODIS derived AOD<sub>550</sub> also shows similar variability and is as shown in Figures 9c-d.



590 **Figure 9:** Terra/MODIS (a) percentage of number of positive pixels (b) percentage of number of negative pixels during the period 2020 vs (2014-19) and 2020 vs 2019. Aqua/MODIS (c) percentage of positive pixels (d) percentage of negative pixels during the period 2020 vs (2014-19) and 2020 vs 2019.

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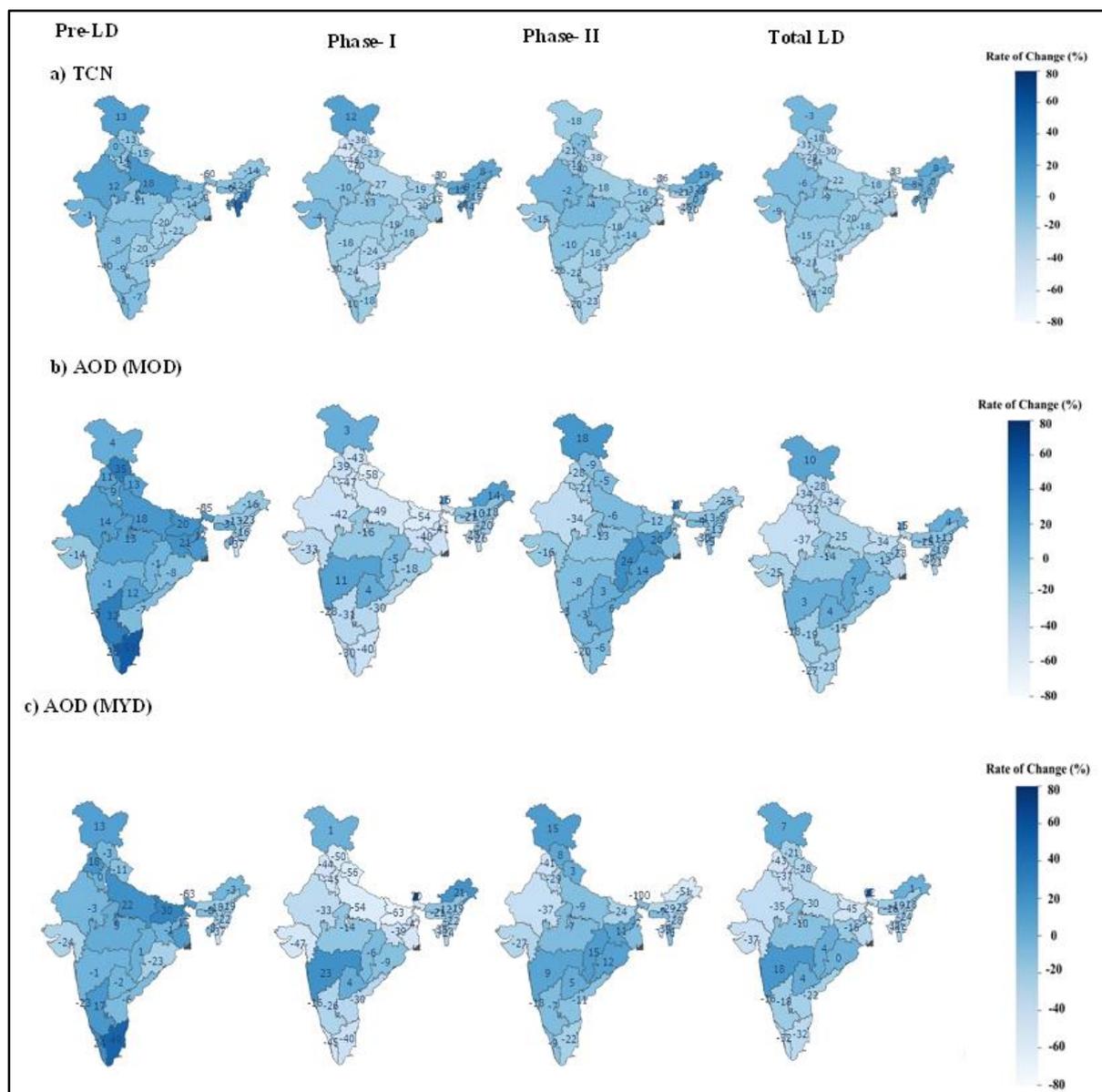


#### 4.4 State wise Rate of Change (RoC) of TCN w.r.t. 2015-2019 and AOD w.r.t. 2014-2019

600 Figures 10a-c show state-wise RoC computed for pre-LD, phase-I, phase II and total LD phases in 2020 with respect to 5 years mean (2015-2019) for TCN and with respect to 6 years mean (2014-2019) for Terra/AOD<sub>550</sub> and Aqua/ AOD<sub>550</sub>. Positive percentage (dark blue above zero) of RoC indicates increase of pollutants for the respective phases shown in the Figure 10 when compared to same phase period of means of TCN for 2015-2019 and means of AOD<sub>550</sub> for 2014-2019. Negative percentage (light blue below zero) of RoC indicates decrease of TCN and AOD<sub>550</sub> w.r.t 2015-2019 and 2014-2019 values respectively for the phases shown in the same Figure 605 10. Results clearly depict the change of pollutants over each state during the lockdown period compared to respective period in 5 years mean for TCN and 6 years mean for both AOD<sub>550</sub>.

During the total lockdown period in 2020 w.r.t the mean of TCN (Top right in Figure 10a) during the same period for 2015-2019, the TCN values are clearly dropped in the hotspot zones namely eastern states (Odisha, Chhatisgarh and Jharkhand) and NCR regions (New Delhi, Ghaziabad, Faridabad, Gurugram and 610 Noida). Thus, the drop in TCN values over these regions are evaluated statistically and found significant change. In similar manner, the AOD<sub>550</sub> measured by the Terra-Aqua/MODIS also shows strong reduction over IGP region during the total LD (top right Figures 10b-c). However, unexpected increasing effect is noticed in the CI states with respect to 6 years mean of respect AOD<sub>550</sub> during phase-I. Similar results are also observed when compared to preceding (2019) year mean AOD<sub>550</sub> which is discussed earlier section in detail manner. Further, it 615 is observed that, the negative RoC of AOD<sub>550</sub> over IGP region during phase-I is more prominent compared to phase-II RoC. It is also noticed further that the RoC of AOD<sub>550</sub> computed from the Terra-Aqua/MODIS showing similar trends during the total lockdown period with small difference in the amplitudes. This difference of amplitude between these two sensors could be due to difference in overpass time, which changes atmospheric dynamics such planetary boundary layer height, solar zenith angle and prevailing meteorology. An average of 620 Terra/Aqua MODIS derived RoC of AOD<sub>550</sub> show strong reduction in the western part of India mainly Rajasthan (-36 %) and Gujarat (-31 %) respectively during the total LD period (Ranjan et al., 2020). Therefore, in a nutshell an analysis of RoC depicts regional variability of air pollutants during the total LD period in 2020 w.r.t to short-term (5-6 years) mean.

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630 **Figure 10: State wise RoC computed for pre-LD, phase-I, phase-II and total LD a) TCN b) Terra/MODIS derived AOD<sub>550</sub> and c) Aqua/MODIS derived AOD<sub>550</sub>**



## 5 Conclusions

635 The present study was carried out an analysis on air pollution in connection with the world's largest lockdown imposed by Government of India to contain the spread of COVID-19. The lockdown was extended as 4 lockdowns with strict lockdown from the phase-I to several relaxations in the phase-IV. However, the lockdown was near total only in phase-I and II, with the total shutdown of industrial and transport sectors. Thus, we have only considered first two phases in the present study as total lockdown. We used satellite-based observations of  
640 tropospheric TCN, TCC and AOD<sub>550</sub> pollutant concentrations analysed during the period of lockdown and prior to LD against the same period of the preceding year (2019) and also against the short-term mean (2014-2019) for about 6 years.

Following are the major findings from the present study

- Due to India's strict LD, the TCN levels are dropped significantly to 18 % across the country compared  
645 to preceding year with a p-value of 0.0007 (confidence interval of 99.93 %).
- Further, analysis is emphasised over the TCN hotspot regions of the Indian sub-continent and observed reduction of (29%) TCN during the total LD period with higher confidence interval.
- The TCN levels with respect to short-term climatological mean are markedly dropped over the urban locations namely New Delhi (-54%), Bangalore (-43 %), Chennai (-41 %), Mumbai (-35 %) and  
650 Hyderabad (-30 %) respectively with high confidence interval about 99.90 %.
- However, during the total LD, an unexpected increase of TCN levels are recorded over NE region, which is directly correlated with the seasonal biomass burning in this region. This increase is also evaluated statistically against 5-year mean TCN and found insignificant with p-value of 0.19.
- The TCC levels are decreased during the phase-I over IGP, north and south regions which could be due  
655 to the absence of transportation and shutdown of industries. Although, variability in the TCC levels werenoticed during the total LD period it was tested statistically and found insignificant. Observed high tropospheric CO levels in the NE region during phase-I LD period, which is mainly attributed to the active fire counts in this region. Also observed low TCC levels in the NE region during phase-II due to the diminished effect of fire counts.
- Since IGP region is densely populated and clustered industries, which were shut down during phase-I  
660 of India's LD, the AOD<sub>550</sub> levels are attained to near baseline in this region (AOD mean value=0.2). This drastic decrease of AOD<sub>550</sub> in the IGP region statistically evaluated and found very significant with a p-value of 0.008 with preceding year (45% decrease) and 50 % reduction against 6-year mean with a p-value <<0.05.



- 665
- Despite the country's LD, the AOD<sub>550</sub> levels are high over the CI, which were predominantly dominated by the transportation of dust storms and prevailing meteorology. Also observed high AOD<sub>550</sub> over NE and is associated with active fire counts. However, this increase is significant in the CI with a p-value 0.03 and insignificant in the NE region with a p-value of 0.33, which indicates insignificant change due to LD.
- 670
- The LD induced changes in AOD<sub>550</sub> measured by the Terra-Aqua/MODIS show a significant change over the Indian region with very high confidence against 6-year short-term climatological mean. This variability helps to improve the regional air quality.
  - Further, an analysis of RoC was carried out to depict the regional variability of air pollutants during the total LD period in 2020 w.r.t to short-term climatological mean.
- 675
- Therefore, this study successfully demonstrates the satellite based TCN, TCC and AOD<sub>550</sub> changes due to the India's lockdown during 2020 and compared against preceding year (2019) and also against the short-term mean picture of 2014-2019.

## 6 Code/Data Availability

- 680
- The satellite and reanalysis data used in the present study are freely available and can be downloaded as summarized in Table 1 with user's credentials.

## 7 Author Contribution

- 685
- Conceptualization and Formal analysis are done by MP,AM, SH, DVM,VKS; Writing – original draft, MP, DVM, ALK; Writing – review & editing DVM, ALK, JS, SSR, MVR and UV

## 8 Conflicts of Interest

The authors declare no conflict of interest.



## 690 Acknowledgement

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## References

- Beig, G., Korhale, N., Rathod, A., Maji, S., Sahu, S. K., Dole, S., Latha, R., and Murthy, B. S.: On Modelling Growing Menace of Household Emissions Under COVID-19 in Indian Metros, *Environ. Pollut.*, <https://doi.org/10.1016/j.envpol.2020.115993>, 2020.
- 705 Biswal, A., Singh, T., Singh, V., Ravindra, K., and Mor, S.: COVID-19 lockdown and its impact on tropospheric NO<sub>2</sub> concentrations over India using satellite-based data, *Heliyon*, 6(9), e04764. doi: 10.1016/j.heliyon.2020.e04764, 2020a.
- 710 Biswal, A., Singh, V., Singh, S., Kesarkar, A. P., Ravindra, K., Sokhi, R. S., Chipperfield, M. P., Dhomse, S. S., Pope, R. J., Singh, T., and Mor, S.: COVID-19 lockdown induced changes in NO<sub>2</sub> levels across India observed by multi-satellite and surface observations, *Atmos. Chem. Phys. Discuss.* [preprint], <https://doi.org/10.5194/acp-2020-1023>, in review, 2020b.
- 715 Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Rasch, P.: Clouds and aerosols. *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change.* K., Tignor, M.; Allen, S.K., Boschung, J., Nauels, A.; Xia, Y.; Bex, V.; and Midgley, P.M., Cambridge University Press, Cambridge, UK and New York, NY, USA, <https://www.ipcc.ch/report/ar5/> (last access: 5<sup>th</sup> October 2017), 2013.
- 720 David, L.M., Ravishankara, A.R., Kodros, J.K., Venkataraman, C., Sadavarte, P., Pierce, J.R., Chaliyakunnel S., and Millet, D.B.: Aerosol optical depth over India, *J. Geophys. Res. Atmos.*, 123(7), 3688– 3703, <https://doi.org/10.1002/2017JD027719>, 2018.
- 725



- Fang, M., Chan, C.K., and Yao, X.: Managing air quality in a rapidly developing nation: China, *Atmos. Environ.*, 43(1), 79–86, doi:10.1016/j.atmosenv.2008.09.064, 2009.
- 730 Freedman, D. A., Pisani, R. and Purves, R. *Statistics* 93–110 (W. W. Norton & Co Inc, New York, 2007).
- Filonchyk, M., Hurynovich, V., Yan, H., Gusev, A., and Shpilevskaya, N.: Impact Assessment of COVID-19 on Variations of SO<sub>2</sub>, NO<sub>2</sub>, CO and AOD over East China, *Aerosol Air Qual Res.*, 20(7), 1530–1540, <https://doi.org/10.4209/aaqr.2020.05.0226>, 2020.
- 735 Ghude, S. D., Fadnavis, S., Beig, G., Polade, S. D., and Van Der A, R. J.: Detection of surface emission hot spots, trends, and seasonal cycle from satellite-retrieved NO<sub>2</sub> over India, *J. Geophys. Res. Atmos.*, 113(D20), <https://doi.org/10.1029/2007JD009615>, 2008.
- 740 Hsu, N. C., Lee, J., Sayer, A. M., Kim, W., Bettenhausen, C., and Tsay, S. -C.: VIIRS Deep Blue Aerosol Products Over Land: Extending the EOS long- Term Aerosol Data Records. *J. Geophys. Res. Atmos.*, 124(7), 4026–4053, <https://doi.org/10.1029/2018JD029688>, 2019.
- 745 Kanchana, A. L., Sagar, V. K., Pathakoti, M., Mahalakshmi, D. V., Mallikarjun, K., and Gharai, B.: Ozone variability: Influence by its precursors and meteorological parameters-an investigation. *J. Atmos. Sol.-Terr. Phys.*, 211, 105468, <https://doi.org/10.1016/j.jastp.2020.105468>, 2020.
- Lal, P., Kumar, A., Kumar, S., Kumari, S., Saikia, P., Dayanandan, A., Adhikari, D., and Khan, M.L.: The dark cloud with a silver lining: Assessing the impact of the SARS COVID-19 pandemic on the global environment, *Sci. Total Environ.*, 732, 139297, <https://doi.org/10.1016/j.scitotenv.2020.139297>, 2020.
- 750 Levy, R.C., Mattoo, S., Munchak, L.A., Remer, L.A., Sayer, A.M., Patadia, F. and Hsu, N.C.: The Collection 6 MODIS aerosol products over land and ocean. *Atmos. Meas. Tech.* 6: 2989–3034, doi:10.5194/amt-6-2989-2013, 2013.
- 755 Li, R., Mei, X., Chen, L., Wang, L., Wang, Z., and Jing, Y.: Long-Term (2005–2017) View of Atmospheric Pollutants in Central China Using Multiple Satellite Observations, *Remote Sens.*, 12(6), 1041, <https://doi.org/10.3390/rs12061041>, 2020.
- 760 Mahato, S., Pal, S., and Ghosh, K. G.: Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India, *Sci. Total Environ.*, 730, <https://doi.org/10.1016/j.scitotenv.2020.139086>, 2020.
- Mahalakshmi, D.V., Sujatha, P., Naidu, C.V., and Chowdary, V. M.: Contribution of vehicular emissions on urban air quality: results from public strike in Hyderabad, *Indian J. Radio Space Phys.* 43, 340–348, 2014.
- 765 Mahalakshmi, D. V., Sujatha, P., Naidu, C. V., and Chowdary, V. M.: Response of vehicular emissions to air pollution and radiation-A case study during public strike in Hyderabad, India. *Sustain. Environ. Res.*, 25(4), 227–234, 2015.
- 770 Alono, S.M., Deeter, M., Worden, H., Borsdorff, T., Aben, I., Commane, R., Daube, B., Francis, G., George, M., Landgraf, J., Mao, D., McKain, K., and Wofsy, S.: 1.5 years of TROPOMI CO measurements: comparisons to MOPITT and Atom, *Atmos. Meas. Tech.*, 13, 4841–4864, <https://doi.org/10.5194/amt-13-4841-2020>, 2020.



- 775 Mor, S., Kumar, S., Singh, T., Dogra, S., Pandey, V., and Ravindra, K.: Impact of COVID-19 lockdown on air quality in Chandigarh, India: Understanding the emission sources during controlled anthropogenic activities, *Chemosphere*, 263, <https://doi.org/10.1016/j.chemosphere.2020.127978>, 2020.
- 780 Nishanth, T., Praseed, K., Kumar, M.K.S., and Valsaraj, K.T.: Observational study of surface O<sub>3</sub>, NO<sub>x</sub>, CH<sub>4</sub> and total NMHCs at Kannur, India. *Aerosol Air Qual. Res.*, 14(3), 1074-1088, doi: 10.4209/aaqr.2012.11.0323, 2014.
- Pandey, SK, and Vinoj, V: Surprising increase in aerosol amid widespread decline in pollution over India during the COVID19 Lockdown, *eartharxiv.org*, <https://doi.org/10.31223/osf.io/5kxm2>, 2020.
- 785 Ramachandran, S., and Kedia, S: Aerosol-precipitation interactions over India: review and future perspectives, *Adv Meteorol*, <https://doi.org/10.1155/2013/649156>, 2013.
- 790 Ramachandran, A., Jain, N. K., Sharma, S. A., and Pallipad, J.: Recent trends in tropospheric NO<sub>2</sub> over India observed by SCIAMACHY: Identification of hot spots. *Atmos. Pollut. Res.*, 4(4), 354-361. <https://doi.org/10.5094/APR.2013.040>, 2013.
- 795 Ranjan, A.K, Patra, A.K, and Gorai, A.K.: Effect of lockdown due to SARS COVID-19 on aerosol optical depth (AOD) over urban and mining regions in India. *Sci. Total Environ.*, 745, 141024. <https://doi.org/10.1016/j.scitotenv.2020.141024>, 2020.
- Ratnam, M.V., Prasad, P., Raj, S. T. A., and Hoteit, I.: Effect of Lockdown due to COVID-19 on the Aerosol and Trace Gases Spatial Distribution over India and Adjoining Regions, *Aerosol Air Qual Res.*, 21(2). <https://doi.org/10.4209/aaqr.2020.07.0397>, 2021.
- 800 Sayer, A. M., Hsu, N. C., Bettenhausen, C., and Jeong, M. -J.: Validation and uncertainty estimates for MODIS Collection 6 “Deep Blue” aerosol data, *J. Geophys. Res. Atmos.*, 118(14), 7864-7872, <https://doi.org/10.1002/jgrd.50600>, 2013.
- 805 Sayer, A. M., Hsu, N. C., Lee, J., Kim, W. V., and Dutcher, S. T.: Validation, Stability, and Consistency of MODIS Collection 6.1 and VIIRS Version 1 Deep Blue aerosol data over land. *J. Geophys. Res. Atmos.*, 124(8), 4658-4688, <https://doi.org/10.1029/2018JD029598>, 2019.
- Singh, R.P., and Chauhan, A.: Impact of lockdown on air quality in India during COVID-19 pandemic. *Air Qual Atmos Health.*, 13, 921–928, <https://doi.org/10.1007/s11869-020-00863-1>, 2020.
- 810 Tian, H., Liu, Y., Li, Y., Wu, C., Chen, B., Kraemer, M., Li, B., Cai, J., Xu, B., Yang, Q., Wang, B., Yang, P., Cui, Y., Song, Y., Zheng, P., Wang, Q., Bjornstad, O., Yang, R., Grenfell, B., Pybus, O., Dye, C.: An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China, *Science*, 368(6491), 638-642. doi: 10.1126/science.abb6105, 2020.
- 815



- Verma, M., Pervez, S., Deb, M. K., and Majumdar, D.: Domestic use of cooking fuel in India: a review on emission characteristics and associated health concerns. *Asian J. Chem.*, 30(2), 235-245, <https://doi.org/10.14233/ajchem.2018.21006>, 2018.
- 820 World Health Organization (WHO): Review of evidence on health aspects of air pollution–REVIHAAP project: final technical report. Bonn: WHO European Centre for Environment and Health, 2013.
- Xu, K., Cui, K., Young, L., Hsieh, Y., Wang, Y., Zhang, J., and Wan, S.: Impact of the COVID-19 Event on Air Quality in Central China, *Aerosol Air Qual Res.*, 20(5), 915-929. doi: 10.4209/aaqr.2020.04.0150, 2020.