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The impact of improved air-quality due to COVID-19 lockdown on surface meteorological parameters and planetary boundary layer over Gadanki, a tropical rural site in India

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ABSTRACT

The nation-wide lockdowns imposed in India during March–May 2020 (in four phases) to curb the spread of the novel Corona virus, greatly enhanced the near-surface air-quality due to lowering of industrial, transport and human activities. The present study focuses on the changes in the vertical structure of aerosol concentration and how those changes impacted radiation balance, the planetary boundary layer (PBL) height and surface meteorological parameters. Instrumented tower and Ceilometer measurements made at Gadanki (13.45°N, 79.18°E), located in a rural environment, coupled with satellite-derived Aerosol Optical Depth (AOD) data have been used to understand the changes in lockdown period. Significant reduction in backscatter density during the lockdown compared to 2019 indicates that aerosol reduction during the lockdown is not only limited to the surface, rather observed in the entire PBL. Except for the fourth phase of lockdown during which several relaxations have been given for vehicular movement and other anthropogenic activities, the reduction in backscatter density is seen in all phases of lockdown. However, the reduction is prominently seen in the second and third phases. The AOD also reduced by 40% around Gadanki, comparable to that of in urban regions. Due to the reduction in aerosols during the lockdown period, the insolation increases by 60 Wm⁻², which is expected to increase the temperature. However, the increased loss of long-wave radiation (due to reduction in trapping gases) and more rain events during the lockdown period decreased the temperature by ~1 °C. Measurements also suggest that the most of net radiation is partitioned into the latent heat flux increasing the humidity and lowering the PBL height (due to reduced strength of thermals and sensible heat flux).

1. Introduction

The Severe Acute Respiratory Syndrome – Corona Virus Disease – 2019 (SARS-COVID-19), also recognized as SARS-CoV-2, has substantially impacted the health of billions of people and slowed down the economy of almost all countries. In an effort to control the spread of COVID-19 and its impact on the public health, several countries had imposed nationwide lockdowns (Vian et al., 2020). Though the first COVID case in India is reported on 30 January 2020, the cases increased exponentially to 519 cases by 24 March 2020 (please visit https://covid19.who.int/region/searo/country/in for real time statistics). Considering the health emergency and so as to contain the virus spread, Indian government imposed a series of lockdowns in the form of a voluntary “Janata Curbew” during 07:00–21:00 IST (Indian Standard Time = Coordinated Universal Time, UTC + 05:30 h) on 22 March 2020, followed by a 68 day-lockdown in 4 phases, Phase 1: March 25 – April 14 (21 days); Phase 2: April 15 – May 03 (14 days); Phase 3: May 04–17(14 days); and Phase 4: May 18–31 (14 days). Except for essential activities like food and medical needs, the lockdown (LD) period constrained about 1.3 billion Indians to in-doors, which had considerably suspended the economic activities affecting the transport, industrial production, power usage, etc. (Le et al., 2020; Sharma et al., 2020; Singh et al., 2020). Further, the execution of LD policy resulted in drastic decrease in the anthropogenic emissions (Mahato et al., 2020; Sharma et al., 2020; Singh et al., 2020; Chaitanya Jain et al., 2021), and aerosol loading into the planetary boundary layer (PBL).

Recent studies over different countries/cities/regions across the globe have reported significant changes in concentrations of particulate matter (PM) and trace gases, primarily significant reductions in PM₂.₅, PM₁₀, NO₂ and CO and increase in O₃ (Bauwens et al., 2020; Le et al.,...
present study focuses on understanding the impact of reduced emissions none of the studies mentioned above addressed this issue. Therefore, the period. 

atmospheric constituents, such limited data may not provide realistic climatological reference. In the present study, the present study, on the other hand, examines the changes in the vertical structure of aerosol backscatter in the PBL. Also, to understand the impact of LD, the anthropogenic parameters are compared against reference data sets, which in most of the earlier studies have been taken from 1 or 2 years of observations. Given the large year-to-year variability of atmospheric constituents, such limited data may not provide realistic climatological reference. In the present study, a meaningful reference data set is obtained by averaging 10 years of observations. The global radiation budget is highly influenced by the aerosols through scattering and absorption of incoming solar radiation. Whereas, the long-wave radiation balance is primarily controlled by the Earth’s surface properties (temperature, type of soil, etc.) and abundance of trace gases. Significant observed reductions in aerosol and trace gas compositions during the LD can alter the entire PBL. Unfortunately, none of the studies mentioned above addressed this issue. Therefore, the present study focuses on understanding the impact of reduced emissions on the vertical column of aerosols and its response on radiation balance, meteorological parameters and PBL height during the COVID-19 LD period.

2. Experimental setup and methodology

Detailed analysis has been carried out to assess how the LD has influenced the meteorological parameters over Gadanki (13.45°N, 79.18°E), a rural site in south India. Gadanki is surrounded by a diverse nativity of scattered ecosystems such as small villages, agricultural lands, forest areas and hillocks ranging as high as 600 m. More details of the location, topography, and background climatology are given in Sandeep et al. (2014) and Satheesh Kumar et al. (2015). The location of the study region and topography around the region. It is to reiterate that COVID-19 LDs have been imposed in phased manner with gradual relaxations in 3rd and 4th phases, particularly for vehicular and human movements. To better understand the impact of LDs, we have considered the data between 14 February and 31 May, covering a month time before the LD to the end of fourth phase of LD.

Fig. 1. (a) Location of Gadanki (13.45°N, 79.18°E) in southern India shown by pink circle and (b) the complex topography surrounding the study site, NARL (black asterisk). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Hourly measurements of temperature, wind speed, short wave irradiance (SWR↓) and net long wave radiation (ΔLWR = LWR↑−LWR↓) made by instrumented towers during (February–May) 2010–2020 are considered for analysing the variations near the Earth’s surface (Refer to Sandeep et al., 2014 for details about the type/make of instruments, resolution and accuracies). The symbols ↓ and ↑ represent incoming and outgoing radiations, respectively. These measurements are averaged after quality controlling (removing the data corresponding to cloud and rain) to obtain clear-sky climatological hourly means.

Vertical profile of backscattered density of aerosols (BSD) (during clear-sky conditions) and PBL height are obtained continuously from ceilometer observations (during February to May 2019 and 2020). Vaisala Ceilometer (model - CL51), operated with a 910 nm infrared Indium Gallium Arsenide (InGaAs) diode laser beam, returns the backscattered signals at 16 s temporal resolution and 10 m height resolution. It is being operated continuously at NARL from January 2019. Though several methods exist in the literature for deriving the PBL height using lidar measurements (Seibert et al., 2000; Su et al., 2017; Vishnu et al., 2017), the methodology adopted in the present study follows Münkel and Räsänen (2004). The method considers the largest gradient in BSD profile as PBL height. However, there are other factors that produce enhanced backscatter and large gradients in BSD, like clouds and aerosols layers. We have removed the data corresponding to clouds in the
present study (procedure will be discussed later in this section). Remaining outliers, if at all present, are removed while averaging the high-resolution data of 16 s to 30 min. PBL height by removing 2σ values, where σ is the standard deviation.

Additionally, the Aerosol Optical Depth (AOD) data (from https://ladsweb.modaps.eosdis.nasa.gov) measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on-board the Terra satellite are also considered to assess the change in the columnar AOD during the LD. The MODIS aerosol product (MOD08_D3) monitors the ambient AODs over oceans and continents with a spatial resolution of 1° x 1° resolution, but for the present study, the Level-3 daily averaged AOD data over southern peninsular India, including Gadanki region, during the period February to May in the years 2010 to 2020 have been considered.

It is ensured that the data used in the present analysis is thoroughly checked by applying various quality flags. The outliers or the spurious peaks, if any, creeping into the data are removed by applying the 2σ condition (σ is the standard deviation) where the data points are treated as outliers if they lie beyond the mean ± 2σ. The surface and upper-air measurements during disturbed weather conditions, i.e., particularly during dense clouds and rain, differ considerably from their climatological patterns/values and therefore can bias the climatological means. Also, techniques for the estimation of PBL height may fail in the presence of low-level dense clouds, because these clouds produce large gradients in the backscatter profile at their boundaries. The data corresponding to those days/periods need to be removed from the present analysis to obtain realistic background mean values. To identify these periods/days, both SWR1 and ΔLWR measurements have been used and these thresholds are evaluated by comparing the results with ceilometer-identified cloud patches. A typical example is demonstrated in Fig. 2, wherein simultaneous measurements of ceilometer-derived BSDs and surface radiation parameters (ΔLWR and SWR1) observed on 22 April 2019 are shown. It is clearly evident from Fig. 2 that clouds and drizzle occurred over the site at several times between 04 and 18 UTC, as evidenced by enhanced BSDs (at times seen only as a narrow layer and also in the vertical column). These timings coincide well with an increase in ΔLWR (during the night-time) (Fig. 2b) and decrease in SWR1 (during the day) (Fig. 2c). It is, therefore, possible to identify clouds/rain by monitoring the SWR1 and ΔLWR and the same philosophy is adopted in the present study to remove them. The BSDs above dense clouds are also affected by the presence of clouds (because of strong attenuation). Therefore the data inside and above the clouds are omitted from the present analysis. Also, as the rain scavenging reduces aerosol concentration, the data during and 24 h after the rain are not considered for obtaining mean profiles of BSD. Altogether 90 out of ~1000 observational days (i.e., during 14 February to 31 May from the years 2010 to 2020) are removed based on the above criteria.

3. Results

3.1. Variation in vertical profiles of aerosol backscatter density

Influence of series of LDs on the aerosol backscatter density is assessed by segregating the ceilometer derived data during 2019 and 2020 into before LD and during LD episodes (referred to as bef-LD and dur-LD, respectively). The PBL undergoes significant diurnal variation, so does the aerosol concentration within the PBL. The 24 h average of BSD will have a peak at a lower height (~500 m) due to the lowering of PBL height and compressed high-density aerosol column during the night. Therefore, the analysis is carried out separately by grouping BSD data corresponding to turbulent hours (06–12 UTC = 11:30–15:30 IST, Indian Standard Time) (hereafter referred to as BSD-turb) and calm hours (18–24 UTC = 23:30–05:30 IST) (referred to as BSD-calm). During noon to evening, the atmosphere is highly turbulent and aerosols are carried to greater heights (up to top of the PBL) by thermals, and thus the surface aerosol levels reduce due to the vertical diffusion of aerosols. The transported aerosol layers do occur over the study site, but mostly above the PBL. This can be easily identified as a layer of enhanced BSDs in the backdrop of low BSDs and the corresponding data are removed from the present analysis.

Time-height variation of the mean BSDs for turbulent hours and calm hours during 14 February–31 May are shown in Fig. 3, separately for 2019 and 2020. Means are taken over turbulent hours and calm hours separately every day. During 2019, the BSD-turb values are generally moderate and are of the order of 103 in the entire PBL. Not much variation is seen in BSDs with time, except that there is a gradual increase in the height of moderate BSD values, due to increased strength of thermals as the summer progresses. The BSD-calm values are relatively large (~104), but mostly confined to 500–700 m during the entire study period, except for few days in the latter half of the study period (peak of the summer). During 2020, the BSD values are almost comparable to that of 2019 before LD, however during LD, a clear reduction in BSD values can be seen in the entire PBL. The reduction is more significant in calm hours above the nocturnal PBL height (500–600 m as given by Ceilometer). In some of the LD phases, the BSD values are smaller than those seen before LD. Chaitanya Jain et al. (2021) found that the surface trace gases (NO, NO2, CO, O3, SO2, CO2, and CH4) and PM over Gadanki varied significantly during the LD period when compared to that of in 2019. For instance, they noted that the surface PM (1, 2.5 and 10 μm) reductions are in the range of 40–50% during the LD. Present study clearly reveals that the reduction in aerosols (in terms of BSDs) is not only at the surface, but is also observed in the entire PBL.

We now discuss the factors responsible for the reduction in aerosols concentrations. Zhang et al. (2020) studied the association between aerosol concentration and wind shear. A similar analysis has been performed using ERA5 (5th generation of atmospheric reanalysis) data (Hersbach et al., 2020), over Gadanki location. Wind shear is estimated between 975 hPa and 850 hPa and between 850 hPa and 700 hPa before and during the LD using the data of 2010–2019 (representing the climatological value) and 2020 (LD year). Wind shear values of climatology and 2020 are nearly equal before LD. Also climatological shear values corresponding to LD period are smaller than that of before LD, but are nearly equal to that observed during LD of 2020 (not shown here). Nearly equal wind shear values of climatology and 2020 before as well as during LD indicate that the wind shear is not responsible for the observed reduction in aerosol (BSD) concentration. The number of rain events during LD is also large compared to 2019. It could also impact the aerosols through wet scavenging. However, these events are highly localized and mostly convective in nature in this season (Saikranthi et al., 2014). Moreover, BSD values immediately after the rain events are found to be moderate, but do not show any significant large reductions,
indicating that the wet scavenging may not be the main factor for the observed reduction in aerosols. But, the rain (and increased soil moisture) did affect the vertical diffusion of aerosols by reducing the sensible heat flux (will be discussed later). The reduction in anthropogenic activities could be the major factor for the reduction in observed aerosols, as also noted at other urban sites in India and elsewhere.

The BSD observations are further analyzed by segregating into various regimes, viz., before LD Vs various LD phases; and during turbulent Vs calm hours. Fig. 4 (a–d) illustrates the intra- and inter annual differences in the mean vertical distribution of BSDs during the turbulent and calm hours of 2019 and 2020. The LD started in the beginning of the summer and continued till the end of summer. Generally, the BSDs are higher during the summer due to increased levels of dust because of dryness in the Earth’s surface and increased road traffic (due to mango business and increased pilgrimage as summer is the main pilgrimage season for this region). Indeed, mean BSD profiles for turbulent hours in 2019 are larger throughout the summer; however, they are relatively smaller during the first 3 LDs. The BSDs in the 4th LD are nearly comparable to that of in 2019. Fig. 4(b) shows the positive BSD anomaly in the entire PBL before- and during first 3 LD periods (2019 minus 2020) in turbulent hours. However, BSD reduction is more prominent in 1st and 3rd phases ($200 \times 10^9 - 400 \times 10^9$ m$^{-1}$ sr$^{-1}$). The BSD vertical profile does not vary much in years 2019 and 2020 and the anomaly of BSD is close to zero. Fig. 4(d) illustrates BSD anomaly profiles for calm hours, which clearly show negative (positive) anomaly below (above) a typical 500 m height, respectively, before and during first and fourth LD phases. Interestingly, a positive BSD anomaly is seen at all heights during second and third LD phases. The maximum decrease of aerosols during the third LD phase over this rural environment is also reported by Chaitanya Jain et al. (2021). Several relaxations have been given for the third and fourth LDs, and the road traffic and human activity increased to a great extent and therefore adding additional aerosols, which resulted in the increase of BSDs near normal during the 4th LD phase.

Fig. 4. The vertical distribution of mean BSD in (a) turbulent hours and (c) calm hours of 2019 (dash lines) and 2020 (solid lines) before and during the four LD phases that are indicated by grey, black, magenta, blue and red colours, respectively. (b) and (d) shows the BSD anomalies in various LD epochs of 2019 and 2020 during turbulent and calm hours, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
3.2. Satellite observations of AOD in southern peninsular India

As mentioned earlier, the variations in the backscatter density profiles are studied using Ceilometer measurements over a single site spanning 2 years. To substantiate the results, multi-year (2010–2020) AOD derived from MODIS/Terra over southern peninsular India, covering Gadanki region, has been analyzed. The climatological AOD is obtained by averaging data over 10 years period (2010–2019). Again the averages have been made by segregating the data into two groups: climatological data before LD refers to the average AOD taken over the period 14 February - 23 March and climatological data during LD refers to the average AOD taken over the period 24 March – 31 May. The average AODs, climatological and in 2020 before and during the LD are shown in Fig. 5 a & d and b & e, respectively. Spatial distribution of AOD anomalies (in %) before and during LD for 2020, calculated using \( \left( \frac{AOD_{2020} - \text{mean (2010–19)}}{\text{mean (2010–19)}} \right) \times 100 \), are shown in Fig. 5 c and f, respectively. Statistically significant anomalies (at 95% confidence level) are only shown here. The figures clearly reveal positive anomalies as high as 30% before the LD and negative anomalies up to ~40% during the LD period. Though the above anomalies are seen most part of the south-eastern parts of India, they are strikingly apparent over Gadanki region. The significant decrease of anthropogenic emissions during the LD period can also have the meteorological relevance.

3.3. Impact of lockdown on the radiation and surface meteorological parameters

This section focuses on how the reduced aerosol concentration, as shown above, impacts the radiation and surface meteorological parameters. The comportment of surface energetics during the LD has been assessed by in-situ tower measurements (temperature, humidity, surface winds, SWR↓ and ∆LWR) during 2010–2020. However, as LD effect is insignificant during the fourth phase, as seen in previous section, the present analysis is restricted up to third LD phase. The results showed a remarkable change in surface state variables during the LD period. The mean and standard error, SE (= standard deviation/√n, where n is number of data points) have been represented through independent measurements. There is a general consensus that the population density and hence the anthropogenic activity could significantly dictate the PM concentrations and the reduction during LD is primarily due to the reduction in anthropogenic activity (Ravindra et al., 2019a, 2019b, 2020; Sarfraz et al., 2020; Selvam et al., 2020; Singh et al., 2020). The present study shows that the reduction is not only limited to urban regions, rather is seen even in rural regions. One reason could be due to the reduced vehicular and human activity on the national highway (NH-71) bordering the northern territory of the study site. Nevertheless, the reduction on the PM/BSD during the LD period can also have the meteorological relevance.

Fig. 5. The spatial variation of AOD in Peninsular India (a and b) before and (d and e) during the LD periods of 2010 to 2020. AOD anomalies before and during LD epochs are also shown. The magenta circle represents the location of the study site, Gadanki. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
LD period compared to climatological means throughout the day, with relatively larger differences during the evening transition (around 12 UTC). Absolute humidity is lower than the climatological mean before the LD, but an opposite feature is seen during the LD. The humidity is higher during LD by $0.2 - 0.4 \text{ g m}^{-3}$ (10–20% higher) than the climatological humidity throughout the day. Higher increase could be due to increased latent heat flux as several rain events occurred during the LD increasing the soil moisture. Winds are weaker during 2020 before and after the LD than climatological means. Nevertheless, the magnitude and duration of reduced wind speeds are higher during the LD than before. Even, Su et al. (2020) have reported identical meteorological variations over Beijing and attributed to the dynamical processes happened during

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**Fig. 6.** The diurnal variation of SWR↓ and ΔLWR (a and d) before and (b and e) during the LD. The red curves and red shaded regions represent the mean and standard deviation in SWR↓/ΔLWR before the lockdown and the blue colour represent the statistics of SWR↓/ΔLWR during lockdown period. The anomalies calculated in (c) SWR↓ and (f) ΔLWR before and during the LDs are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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**Fig. 7.** The diurnal variation of air temperature, wind speed and absolute humidity (a, d and g) before and (b, e and h) during the lockdown. While red curves and red shaded regions represent the mean and standard deviation in the air temperature/wind speed/absolute humidity before the LD, blue colour represents the statistics during the LD. The anomalies calculated in (c) temperature, (f) wind speed and (i) absolute humidity before and during the LDs are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
the LD period. Therefore, it would be intriguing to note that almost all the state variables have shown an anomalous variation over the study site. Altogether, the variations in the vertical distribution of aerosol concentrations, surface variables (temperature, wind speed, ∆LWR and SWR) and PBL height have inter-dependency and all parameters are highly influenced by the variation of anthropogenic activities that happened during the LD period. The nexus between these parameters are discussed at length in the next section.

3.4. Impact of the lockdown on the planetary boundary layer height

The distributions of Ceilometer-derived maximum PBL height, estimated on every day, before and during LD for 2019 and 2020 are shown as box plots in Fig. 8. Two features are strikingly apparent from the Fig. 8: (1) The variability in PBL height is quite high during 2019 before and after 24 March and (2) The PBL height is lower in 2020 than in 2019 before and after the LD. The variability in PBL height within the period, before or after the LD, can be seen from the box plot (both in 50% of distribution, i.e., width of the box, and in 95% of distribution, i.e., values between horizontal lines). The variability is relatively less in 2020, but the lowest variability is seen during the LD period in 2020. Also, the mean PBL height in 2020 is nearly 120 m (4.5%) lower than that observed in 2019. This abnormal shallow behavior of PBL is also reported elsewhere (Su et al., 2020; Chaitanya Jain et al., 2021). Su et al. (2020) observed that the PBL height had reduced by 45% over northern China, triggering the strong aerosol-PBL interactions, while Chaitanya Jain et al. (2021) used Era 5 data to observe a decrease of PBL height by 4.9%. During 2020, the number of rain events is larger than that of in 2019 (can be seen from white patches in Fig. 3) and they increase the soil moisture. The increased soil moisture increases the latent heat flux, but reduces the sensible heat flux and thereby the PBL height (Pan and Mabrt, 1987; Sandeep et al., 2014; Guo et al., 2019; Xu et al., 2021). The addition of more moisture through latent heat flux can be seen in the increase in humidity during LD in 2020 (Fig. 7).

4. Discussion

The measurements have shown several interesting observations, we, however, focus our discussion on two aspects: (1) There is a substantial change in aerosol concentration (in terms of BSDs and AOD) in the entire boundary layer and in the PBL height during the LD compared to the same period in earlier years; (2) Impact of reduction in anthropogenic activities on surface parameters.

Several studies reported a reduction in aerosol concentration, particularly PM levels, during the LD primarily due to the reduction in transportation, industrial production and power usage (Chaitanya Jain et al., 2021; Le et al., 2020; Sharma et al., 2020; Singh et al., 2020). Surprisingly few studies reported enhancement in aerosols and attributed it to lowering of PBL height (Su et al., 2020; Chaitanya Jain et al., 2021). All these studies are based on surface aerosol measurements. Our observations clearly reveal two interesting facts, (1) Reduction of aerosols not only confined to the surface, but also observed in the entire column of PBL and (2) In spite of observed lower PBL (Fig. 8), the aerosols (both BSDs and AOD) reduced considerably (Figs. 3 and 5). These results clearly indicate that the reduction is not due to mere change in vertical dispersion (or change in PBL height), rather due to the reduction from other sources, like transportation and agricultural works (note that even though the study site is in a rural environment surrounded by mango and sugarcane fields but lies just besides a national highway connecting Tirupati and Bangalore).

The day to day variability in SWR at the surface depends on several aspects related to sun, like solar cycle, season and solar zenith angle and atmospheric factors, like the presence of clouds, rain and different types of aerosols (absorbing and scattering). The solar cycle 25 started in 2019 and therefore one would expect smaller SWR, given the close association between the solar cycle and SWR. However, the observed SWR is much higher than the climatological SWR (peak variation is ~200 W m⁻²). Data corresponding to other influential factors like presence of clouds and rain are removed to obtain unbiased estimates. However, the AOD (Fig. 5) and BSDs within the boundary layer (Fig. 4) during the LD period reduced considerably over Gadanki. Independent aerosol observations at Gadanki have shown a reduction of ~40–50% in PM₂.₅ and 20% in BC during the LD period in comparison with the same period in 2019 (Chaitanya Jain et al., 2021). The increased SWR, therefore, is primarily due to the reduction in scattering aerosols and also by the reduction in absorbing BC. Increased SWR certainly increases the temperature of Earth’s surface (assuming no change in albedo) and also LWR. Measurements also show substantial reduction of short-lived greenhouse gases during the LD period (Singh et al., 2020; Chaitanya Jain et al., 2021), which indicates a considerable reduction in long-wave trapping and LWR. The net LWR clearly show more loss of long-wave energy during the day and night compared to earlier years and also to pre-lockdown period. Further, the higher occurrence of rain events during LD compared to 2019 and associated increase in soil moisture will certainly change the surface parameters. Higher amount of soil moisture increases the latent heat flux and reduces the sensible heat flux. The increase in moisture seen in Fig. 7 could be due to increased addition of moisture through latent heat flux. Due to the loss of more LWR and reduced sensible heat flux, the air temperature (at 2 m) is also found to be lower than the climatological value. The reduction is more prominent during the night time. The observed shallow PBL height (compared to 2019) is also due to reduced sensible heat flux. Lower temperature and PBL height compared to their climatological values indicate weaker turbulence and associated sensible heat flux (not shown). Weaker surface winds during the LD could be due to weakened downward transport of momentum due to turbulence.

Comparison of observations with climate and Earth System Model (ESM) simulations reveals agreement in variation of some parameters and disagreements in others. Both simulations and observations show an increase in SWR due to the reduction in anthropogenic aerosol contribution (Gettelman et al., 2021). In response, ESM simulations suggest an increase of 0.3 K (at regional level) and 0.03 K (at global scale) in surface temperature (Gettelman et al., 2021) and climate model simulations show a surface warming of 0.04–0.07 K in South Asia, both are in contrast to the observed lower temperature (than climatological value) at Gadanki (Yang et al., 2020; Gettelman et al., 2021). The increase in temperature by these simulations considers the effects of clouds (scattering/trapping of SWR/LWR and also indirect effects due to aerosol-cloud interaction). However, in the present study, data corresponding to clouds are removed.

5. Summary and conclusions

Stringent ban on human, industrial and vehicular activity was imposed in India in phased manner (with more relaxations in later phases) to contain the spread of COVID-19 from 24 March to 31 May.
2020. The lockdown period has created a natural ideal reference weather condition to study the variations not only at surface levels but also at the higher altitudes. Suite of ground-based remote sensing and in-situ instruments has been utilized to understand the impact of COVID-19 lockdown on the surface energetics and the boundary layer variables in a tropical atmosphere. Overall observations and measurements show significant anomalies during second and third LD phases. However, the effect faded in the fourth phase due to rainfall events and more relaxations in LDs. Some of the important conclusions are as follows –

1) Backscatter densities representing the aerosol concentrations have remarkably reduced during the LD in the entire PBL, due to the reduction in anthropogenic activities. The reduction (relative to 2019) is more prominent in 2nd and 3rd phases, while it is negligible in the 4th phase. The minimal reduction in the 4th phase is primarily due to increased influence of rain and more relaxations during that phase.

2) Satellite-based AOD observations over Gadanki region have again shown an AOD reduction of ~40% and this reduction percentage is comparable to those reported in most of the urban and sub-urban areas in India and elsewhere.

3) The changes in aerosol concentration affected the natural radiation balance. A significant increase in SWR↓ is observed due to the reduction in scattering aerosols and absorbing BC, both affect the surface SWR↑. The increase in SWR↓ is expected to increase the temperature (Gettelman et al., 2021), but a decrease is observed. The temperature reduction and absolute humidity increase are attributed to higher partitioning of net radiation into latent heat flux. More rain events are observed during the LD in 2020 compared to 2019, which would have enhanced the soil moisture and latent heat flux during the LD. More loss of LWR could also contribute to the reduction of net radiation at the surface and temperature change.

4) The maximum PBL height has lowered by 4.5% (~120 m) during the LD and is attributed mainly to more rain events and lower sensible heat flux and weak PBL thermais.

The lockdown has significantly influenced the diurnal variation of different meteorological parameters from the surface to PBL heights. The significant impact of lockdown on the rural atmosphere, as deduced in the present work, would serve as a laboratory weather reference in assessing the contemporary problems such as increase in air pollution and global climate change due to increased human intervention in the natural habitat.

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. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Jain, Chaiti, D., Madhavan, B.L., Singh, Vikas, Prasad, S., Kanti, N., Ravindra, K., 2020. Backscatter densities representing the aerosol concentrations have remarkably reduced during the LD in the entire PBL, due to the reduction in anthropogenic activities. The reduction (relative to 2019) is more prominent in 2nd and 3rd phases, while it is negligible in the 4th phase. The minimal reduction in the 4th phase is primarily due to increased influence of rain and more relaxations during that phase.

Satellite-based AOD observations over Gadanki region have again shown an AOD reduction of ~40% and this reduction percentage is comparable to those reported in most of the urban and sub-urban areas in India and elsewhere.

The changes in aerosol concentration affected the natural radiation balance. A significant increase in SWR↓ is observed due to the reduction in scattering aerosols and absorbing BC, both affect the surface SWR↑. The increase in SWR↓ is expected to increase the temperature (Gettelman et al., 2021), but a decrease is observed. The temperature reduction and absolute humidity increase are attributed to higher partitioning of net radiation into latent heat flux. More rain events are observed during the LD in 2020 compared to 2019, which would have enhanced the soil moisture and latent heat flux during the LD. More loss of LWR could also contribute to the reduction of net radiation at the surface and temperature change.

The maximum PBL height has lowered by 4.5% (~120 m) during the LD and is attributed mainly to more rain events and lower sensible heat flux and weak PBL thermais.

The lockdown has significantly influenced the diurnal variation of different meteorological parameters from the surface to PBL heights. The significant impact of lockdown on the rural atmosphere, as deduced in the present work, would serve as a laboratory weather reference in assessing the contemporary problems such as increase in air pollution and global climate change due to increased human intervention in the natural habitat.

Declaration of Competing Interest

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