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Impact of COVID-19 lockdown on the atmospheric boundary layer and instability process over Indian region

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HIGHLIGHTS

• The abrupt reduction in anthropogenic activities increased the surface temperature results in a decrease in relative humidity and increase in wind speed.
• Elevated ABL height is observed in the same regions where higher surface temperatures are noticed.
• The changes associated with these parameters are strongly reflected in instability parameters also.
• The decrease in CAPE is depicted in the places of higher surface temperature, wind speed, and higher ABL height.

ABSTRACT

The abrupt reduction in human activities during the first lockdown of the COVID-19 pandemic created unprecedented changes in the background atmospheric conditions. Several studies reported the anthropogenic and air quality changes observed during the lockdown. However, no attempts are made to investigate the lockdown effects on the Atmospheric Boundary Layer (ABL) and background instability processes. In this study, we assess the lockdown impacts on the ABL altitude and instability parameters (Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CINE)) using WRF model simulations. Results showed a unique footprint of COVID-19 lockdown in all these parameters. Increase in the visibility, surface temperature and wind speed and decrease in relative humidity during the lockdown is noticed. However, these responses are not uniform throughout India and are significant in the inland compared to the coastal regions. The spatial variation of temperature (wind speed) and relative humidity shows an increase and decrease over the Indo Gangetic Plain (IGP) and central parts of India by 20% (100%) and 40%, respectively. Increase (80%) in the ABL altitude is larger over the IGP and central parts of India during lockdown of 2020 compared to similar time period in 2015–2019. This increase is attributed to the stronger insolation due to absence of anthropogenic activity and other background conditions. At the same time, CAPE decreased by 98% in the IGP and central parts of India, where it shows an increase in other parts of India. A prominent strengthening of CINE in the IGP and a weakening elsewhere is also noticed. These changes in CAPE and CINE are mainly attributed to the
1. Introduction

The outbreak of novel coronavirus disease 2019 (COVID-19) in early 2020 resulted in lockdowns all over the world. The lockdown measures implemented to control the spread of COVID-19 resulted in disruption to many sectors, such as transportation, commerce, and cultural activities. In India, the first case of COVID-19 was reported on January 30, 2020. Facing the great challenge of the fast-spreading virus, the Government of India has enforced a nationwide lockdown from 25 March 2020 to 14 April 2020. Further, the lockdown was extended from 15 April to 3 May and then from 4 May to 14 May to reduce the number of COVID cases. During this lockdown, a series of containment measures were taken to control the fast spread of the disease, which included travel bans of all types of services, closure of domestic and international terminals, quarantine of residential areas, restrictions on social gatherings (including religious activities), and the closure of industries, shopping centres, worship places, schools, and other educational institutions.

Lockdown and containment measures implemented on human and industrial activities worldwide have resulted in significant reductions in air pollution at various locations (Berman and Ebisu, 2020; Kanniah et al., 2020; Wang, 2020; Xu et al., 2020; Garcia-Dalmau et al., 2021). The Ozone Monitoring Instrument (OMI) onboard the Aura satellite (NASA) and the TROPOspheric Monitoring Instrument (TROPOMI) onboard the Sentinel-5P (ESA) satellite measurements at various locations (e.g., China, USA, France, Italy, and over India) revealed a reduction in NO2 emissions of 20–30% (Shakil et al., 2020; Wang, 2020; Ratnam et al., 2021). Over India, an exponential decrease in the emission of greenhouse gases (GHGs), air quality (a 50% drop in the air quality index), noise, and water pollution is observed having a positive impact on the environment in a short period of time. Several studies have reported a sharp reduction in the pollution levels over India at different places (Jain and Tanya., 2020; Kumar et al., 2020; Mahato et al., 2020; Navinya et al., 2020; Sharma et al., 2020; Shehzad et al., 2020; Singh et al., 2020; Jain et al., 2021). One of the major changes is reported by Mahato et al. (2020) over megacity Delhi, where the pollution levels in PM10 and PM2.5, NO2, and CO significantly dropped as high as about 60%, 39%, 52.68%, and 30.35%, respectively.

Most of the studies focused on pollutant variability before and during the lockdown and the impact of temperature, humidity on mortality rates in many regions (Babu et al., 2020; Berman and Ebisu, 2020; Vinoj et al., 2020; Ratnam et al., 2021a, 2021b). These changes are expected to reflect on the boundary layer processes including the thermo-dynamical changes and in turn can provide feedback to the observed changes in the pollution concentrations as they are inter-linked. To the best of our knowledge, no study has focused on the lockdown impact on surface meteorological parameters linked to the atmospheric boundary layer (ABL) and instability parameters (Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CINE)) over India. Therefore, this work aims to evaluate the incidence of COVID-19 lockdown impacts on surface meteorological parameters (visibility, temperature, relative humidity, and wind speed), ABL altitude, and the instability parameters by using WRF model simulations over India. The origin of the different data sets used in the present study is reported in Section 2. Section 3 focuses on the variability of surface meteorological parameters, ABL altitude, and instability parameters obtained from various sources, and the conclusions are summarized in Section 4.

2. Data and methods

Since the observational network is limited to understand the ABL and instability processes, we used WRF model simulations for covering entire Indian region and for better understanding the underlying processes. Before using these model simulations, they are compared with the surface and upper air measurements and the details mentioned in the following subsections.

2.1. WRF model outputs

The downscaled simulations utilized in this study are performed with the Advanced Research Weather Research and Forecasting (WRF-ARW) model. This model (WRF) is one of proven regional climate modelling (RCM) tools for simulating localized features via downscaling of global reanalysis fields (Lo et al., 2008; Caldwell et al., 2009; Viswanadhapalli et al., 2017; Viswanadhapalli et al., 2019). The model is configured into an 18-km grid covering from 10°S to 40° N and 40° E to 110° E with 62 vertical levels with the model top as 30 hPa. The model physics parameterizations configured in this study are chosen based on several past studies (Srinivas et al., 2013, 2018; Madala et al., 2016; Attada et al., 2018; Vijaya et al., 2018) over the India region. These physical parameterization schemes include Thompson et al. (2008) for cloud microphysical process, RRTMG both for long-wave and shortwave radiation processes (Iacono et al., 2018), YSU non-local scheme (Hong et al., 1996; Hong et al., 2004) for planetary boundary layer turbulence, Betts–Miller–Janjic (BMJ) for cumulus convection (Janjic, 1994), and the NOAH MP scheme for land surface processes (Niu et al., 2011). As the objective is to study the features of weather parameters precisely, we have adopted the approach of the consecutive re-initialization method by initializing the model on a daily basis (Lo et al., 2008; Viswanadhapalli et al., 2017; Viswanadhapalli et al., 2019). i.e., the WRF model is initialized at 1200 UTC on every day with NCEP Final Analysis (FNL) data integrated for 36 h during the study period (8 March–14 April 2020). In all daily simulations, we discard the first 12-hours of model simulation by considering it as a spin time, and the remaining 24-hour model products merged to get a continuous data record for the entire study period. The hourly products are extracted at different vertical pressure levels from 1000 hPa to 100 hPa with 25 hPa resolution.

To characterize the temporal and spatial variation of surface parameters, ABL height, and instability parameters during the COVID-19 lockdown, we split the whole study period into two stages:

1. Prior to the lockdown (i.e., the pre-lockdown (PLD) period from 8 to 21 March), most activities were at normal levels.
2. During the lockdown (DLD) period (25 March – 14 April), when the public is required to stay at home, traffic emissions and industrial activities are significantly reduced.

We have considered PLD and DLD during the 2015–2019 and 2020 years to understand the mean and relative differences in various atmospheric parameters. The relative difference (RD) is estimated as: \( RD = \left( \frac{\text{DLD-PLD}}{\text{PLD}} \right) \times 100 \).

2.2. Surface meteorological parameters

The ground station data for visibility, surface temperature, relative humidity, and wind speed over the Indian region at 12 stations (Fig. 1) are obtained from the National Climate Data Centre (https://www.ncdc.noaa.gov/cdo-web/datasets) during the years 2015–2020. The quality control procedure is applied and subjected to a variety of internal consistency, frequent-value, outlier, and spatial consistency
In this study, we have computed daily mean values by making use of the hourly observations.

2.3. Radiosonde data

To validate the model simulations, we have utilized the radiosonde observations obtained from the Integrated Global Radiosonde Archive version 2 (IGRAv2) in the present study. This data provides information on the vertical structure of the atmosphere. Several quality control checks were applied to improve data quality before archiving the data. The quality control document along with background information can be obtained from https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00975. The radiosonde data was interpolated to 100 m to remove the outliers (Basha and Ratnam, 2009). To study the COVID-19 impact over different geographical regions across India, we have selected 12 stations, out of which 6 are inland stations and the remaining 6 stations are coastal from the years 2015 to 2020. During the COVID-19 period, radiosondes are launched only at 00 GMT. The number of sondes available during the pre-lockdown (PLD) and during lockdown (DLD) periods for each station is shown in Fig. S1. From radiosonde pressure, temperature, and water vapor data, we have estimated the refractivity. The ABL height was computed from refractivity observations using the wavelet covariance transform technique (Ratnam and Basha, 2010; Basha et al., 2018). We used similar procedure for calculating ABL height from model simulations.

The Convective Available Potential Energy (CAPE) is a measure of the vertically integrated buoyant energy of an air parcel between its level of free convection (LFC) and equilibrium level (EL) (Chakraborty et al., 2018, 2019, 2021). The Convective Inhibition Energy (CINE) is an important parameter in determining the stability of the atmosphere to moist convection. The CINE is a measure of the energy required by a rising air parcel to reach its LFC, which is the activation energy for the system. In this work, we have considered 00 GMT profiles for estimating the ABL height, CAPE, and CINE where most of the radiosonde observations are available. The detailed procedure for estimating the CAPE, and CINE is given in Chakraborty et al. (2018, 2019).

3. Results and discussion

3.1. Evaluation of the model simulations

Before using the model outputs, it is essential to evaluate them with the standard measurements. The evaluation of surface (temperature, RH and wind speed), ABL height and instability parameters (CAPE and CINE) is depicted in Figs. S2 & S3 and in Tables S1-S6 with mean and standard deviation, correlation and RMSE between the observed and model data. A very good correlation is observed in all the parameters between observed and model simulations. Typical profiles of the temperature, relative humidity, and wind speed for 31 March 2019 and 2020 from radiosonde and model simulations over New Delhi (top panel) and Chennai (bottom panel) are shown in Fig. S2. The radiosonde data is illustrated with the blue line, and the red line corresponds to the modelled simulation data. The vertical profiles of temperature, RH, and wind speed of the model data sets compared very well with the radiosonde data sets. Further, we calculated the mean difference, correlation coefficient, and RMSE between the radiosonde and model data collected during March and April 2015–2019, 2020. The mean difference between radiosonde and model data is in the range of 0.6 ± 0.75 K for temperature, 9.0 ± 8% for RH, and 1.4 ± 1.6 m/s for the wind speed. A good correlation is also observed between the two data sets in all the parameters (Fig. S3). This suggests that model data sets simulated the changes very well with respect to the observations, which can be used for further analysis. Results are compared qualitatively and quantitatively obtained from model data with both surface meteorological and radiosonde observations.

3.2. Changes in the surface parameters during the lockdown

Fig. 2 demonstrates the changes associated with surface meteorological parameters, i.e., visibility, temperature, relative humidity, and wind speed over New Delhi (inland station) and Chennai (coastal station) during PLD and DLD of the 2015–2019 and 2020 years. The increase in visibility is clearly evident during DLD compared to PLD in 2015–2019 and 2020. The increase in visibility is about ~200 m (~500 m) during the 2015–2019 (2020) years when DLD is subtracted from PLD days over New Delhi. Similarly, over Chennai, the increase of about ~100 m (~150 m) during the 2015–2019 (2020) years. The relative change in visibility during 2020 is four times high compared to 2015–2019 year. The increase in visibility is high over inland stations compared to coastal stations. However, the relative change in DLD days of 2020 and 2015–2019 shows a clear increase in visibility over Thiruvananthapuram, Chennai, Visakhapatnam, and Bhubaneshwar compared to other stations (Fig. 3a). The percentage increase in visibility is very low over Goa compared to other stations. Apart from the lockdown, the visibility differences between inland (New Delhi) and coastal stations probably arise due to the presence of land-sea breeze phenomena during this season, which strongly controls the dispersion of pollutants and visibility with high humidity levels.

The temperature increased significantly in DLD days compared to the PLD over New Delhi and Chennai stations, as depicted in Fig. 2b and f during the 2015–2019 and 2020 years, respectively. The temperature difference between DLD and PLD during 2015–2019 (2020) is about ~1.9 °C (~4.87 °C) over New Delhi, whereas it is 1.5 °C (~2.28 °C) over Chennai. The relative change reveals an increase in temperature in all the stations during 2020 compared to 2015–2019 (Fig. 3b). The temperature changes are large over inland stations compared to the coastal stations. The relative change between the DLD days of 2020 and 2015–2019 shows an increase in temperature which can be attributed to the decrease in pollution levels and less scattering effect of aerosols at surface levels, which results in an increase in direct solar radiation reaching the Earth's surface.

In the case of RH, a drastic reduction during DLD compared to PLD during 2020 over New Delhi. The decrease in humidity is about ~9% and 18% during 2015–2019 and 2020. The Chennai stations do not show any significant changes in humidity (Fig. 2g). Inland stations represent a large decrease in RH compared to coastal stations (Fig. 3c). The relative change in
RH represents a significant decrease during 2020 compared to 2015–2019. This reduction in RH can be associated with the fact that surface temperatures are increasing while the moisture content has remained unchanged, thereby leading to a reduction in the relative saturation levels during the lockdown period.

Further, moderate increase in wind speed over New Delhi by ~0.3 m/s (0.6 m/s) is observed in the mean difference between DLD and PLD periods during the 2015–2019 (2020) years. Similarly, over Chennai, the wind speed represents an increase by 0.6 m/s (0.9 m/s) during the 2015–2019 (2020) years. Wind speed shows a clear increase in the DLD period in 2020 compared to the 2015–2019 year. All the stations show an increase in wind speed during DLD days in the 2020 year compared to 2015–2019. The increase in the temperatures might have led to the changes in surface pressures and enhanced winds. In turn, due to the lack of a land/sea breeze effect, this intensification of winds can be regarded as a major factor responsible for the dispersal of pollutants and an increase in surface temperature and visibility, particularly in the inland stations.

Subsequently, we also examined the spatial distribution, mean difference between DLD and PLD days of 2015–2019 and 2020 in the temperature, relative humidity, and wind speed obtained using WRF model simulations as shown in Figs. S4, S5 and S6. An increase in the temperature by ~6 °C during the DLD in both the years in Northwest India and Central India is visible. The southern part of India shows little change in temperature compared to other parts of India (Fig. S4). Fig. 4(a, b, & c) depicts the relative change in temperature between DLD and PLD during the 2015–2019 and 2020 years, as well as DLD changes during the 2015–2019 and 2020 years. Increase in temperature is observed in DLD over most of India, except the southern part (Fig. 4a & b). Significant increase in temperature is noticed over the central and western parts of India. The changes in temperature clearly suggest the impact of lockdown seems to be high in the north compared to the southern parts of India.

The decrease in humidity is clearly observed in the DLD days throughout the India in 2020 except western Himalayan region (Fig. S5f). The relative change in humidity shows a 40% decrease during 2015–2019 and 2020 as shown in Fig. 4d & e. In 2015–2019, an increase in humidity is noticed over the west coast and northeast of India, whereas in 2020, humidity decreases drastically all over India, with a larger decrease in the IGP region during the DLD period. Similarly, the relative change in the DLD periods of 2020 and 2015–2019 represents decrease in humidity over IGP region and increase in humidity over interior peninsula India (Fig. 4f).

The difference in simulated wind speeds indicates clearly an increase in surface winds over the IGP region during 2020 and the central part of India in 2015–2019 (Figs. S6f, 4g & h). Moreover, the changes in the wind speed show a 100% increase in the wind speed over the IGP region during the 2020 DLD period.

The increase in temperature, wind speed, and decrease in relative humidity may be closely related to the increase in solar radiation due to the reduction of primary emissions during the COVID-19 lockdown. In other words, the inland regions experience significant reduction in amounts of aerosol emissions both from anthropogenic and natural sources in the form of dust, sulphate and carbonaceous aerosols. As a result, a decrease in aerosol and cloud albedo from the first two sources inadvertently resulted in higher surface heating, drier weather, and stronger winds in these regions during lockdown compared to previous years. The significant alternation in surface meteorological parameters due to COVID-19 lockdown could also modify the boundary layer properties drastically, which will be discussed in the next section.

3.3. Changes in the Atmospheric Boundary-Layer (ABL) height during the lockdown

The layer adjacent to the surface in which vertical mixing is particularly important is termed ABL, which is directly influenced by the presence of the earth’s surface. Solar heating causes thermal plumes to rise, transporting moisture, heat, and aerosols. All these thermals redistribute heat, moisture, and the drag on the wind within the boundary layer, as well as pollutants and other constituents of the atmosphere. In doing so, it plays a crucial
role in modulating the weather (temperature, humidity, wind strength, air quality, etc.) as we experience it, living on the surface. Therefore, we have investigated the ABL variability during the DLD and PLD of the 2015–2019 and 2020 years. Increase in ABL height is clearly seen in DLD compared to PLD days in both years and at both New Delhi and Chennai stations (Fig. S7). However, increase in the ABL height is large during 2020 DLD days when compared to 2015–2019 DLD days. Over New Delhi, increase in ABL is about ~180 m in 2015–2019 whereas it is 700 m in 2020, however, over Chennai station, decrease in ABL height is observed during 2015–2019 DLD period whereas it increased by 700 m in 2020. The relative change in ABL height reveals an increase in 2020 compared to 2015–2019 in all the stations (Fig. 5a). Inland stations exhibit a maximum increase in ABL height compared to coastal stations. During 2015–2019 in both PLD and DLD days similar variation in ABL height is observed. Conversely, the increase in ABL height in DLD days is large in major parts of India compared to PLD of 2020 (Fig. S8). The mean difference clearly represents the increase in ABL height (by 800 m) during 2020 compared to 2019 in DLD days in central part of India (Fig. S8). However, the relative change in ABL height showed an increase of 80% during 2020 compared to 2015–2019 lockdown days (Fig. 5b & c). Further, we have plotted the relative change between the DLD days of 2020 and 2015–2019 years (Fig. 5d). This clearly shows the increase in ABL height that is quite apparent over the northeast, IGP, and central parts of India by ~80% and reduced over the south east India by 10%.

A prominent elevation in ABL height hints towards stronger vertical mixing due to higher surface temperature in DLD of 2020. This is attributed to the absence of radiatively active aerosols, which disturb the lapse rate profiles by creating inversions. Further, reduced RH and stronger heating due to higher temperature in these places further lead to an adiabatic ascent of air, hence causing a jump in the convective boundary layers in these regions (Zhang et al., 2013), as observed in the spatial patterns during the lockdown. This entire process can lead to changes in the stability parameters which is discussed in next sub-section.

3.4. Changes in the instability indices during the lockdown

Talukdar et al. (2019) showed the relation between aerosol concentrations and CAPE. Increase in aerosols concentration (particularly the black carbon) decreases the CAPE. Several studies reported the decrease/increase in aerosol concentration over India in DLD period (for ex. Ratnam et al., 2021a, 2021b). Therefore, in this section, we present the changes observed in CAPE/CINE from radiosonde and model simulations over India in PLD and DLD days during 2015–2019 and 2020. Fig. S9 shows the variability in CAPE over New Delhi and Chennai during PLD and DLD of 2015–2019 and 2020. Large variability in CAPE is observed over Chennai compared to New Delhi. The difference between CAPE values observed between DLD and PLD of 2015–2019 (2020) is 380 J/Kg (~350 J/Kg) over New Delhi, whereas over Chennai it is 1965 J/Kg (548 J/Kg) as depicted in Fig. S9. These observations clearly reveal that decrease in CAPE is clearly noticed over New Delhi and Chennai stations in the DLD days of 2020 compared to 2015–2019. The relative change in CAPE shows a drastic decrease over New Delhi (99%) followed by Nagpur (97%), and Raipur (80%) compared to other stations (Fig. 6a). Coastal stations (Chennai, Visakhapatnam, and Bhubaneswar) show an increase in DLD of 2020. The radiosonde observations clearly demonstrated the decrease in CAPE in DLD of 2020 compared to 2015–2019 (green colour bars in Fig. 6a). The spatial averaged CAPE during PLD, DLD days of 2015–2019, 2020 and mean difference between DLD and PLD is shown in Fig. S10. During 2015–2019, in DLD days, the CAPE values are high expect few parts of India and in 2020, the CAPE values reduced. The mean difference between DLD and PLD days shows a sharp decrease in CAPE throughout the IGP region in the model simulations. The relative change in the spatial variation of CAPE (%) during 2015–2019 and 2020 is illustrated in Fig. 6b & c. During 2019, CAPE shows an increase throughout India except for a small portion, whereas in 2020 a sharp decrease is noticed throughout the IGP region (east-central part of India by 100%). This increase in CAPE seems to be high along the coastal (both east and west coast of India) regions, and it is probably due to the presence of high humidity levels (Basha and Ratnam, 2009; Chakraborty et al., 2021). The relative change in CAPE during 2020 and 2015–2019 DLD days exhibits a decrease throughout India (Fig. 6d). In 2020, the CAPE decreased by ~80% in India compared to 2019 in DLD days. The spatial distribution of CAPE reveals that weak instability exists during the DLD days of 2020 compared to 2015–2019.

To explain the disparity in CAPE across India, it needs to be considered that, normally, as the pre-monsoon season advances from PLD to DLD, land heating plays a prominent role in inducing small-scale extreme convective weather events. However, in the IGP during the lockdown period of 2020, a drastic reduction in RH was observed despite strong intensification in surface temperatures and wind speed. It may be noted that though surface heating can promote surface buoyancy, in the absence of moisture abundance, it is difficult for air plumes to maintain a steep pseudoadiabatic profile compared to the environment. In addition, stronger horizontal winds further cancel the inherent buoyancy, generating a differential wind shear that is not conducive to convective genesis. Hence, CAPE decreases there. From another viewpoint, CAPE decreases despite elevated ABL in some of these regions because boundary layer dynamics can initiate convective plumes, but they cannot develop into a mature convective cumulus cloud unless they get ample moisture ingress. Hence, reduced RH and stronger winds have always led to reduced CAPE, particularly in the polluted IGP regions where the effect of increased temperature and reduced RH is most prominent owing to the typical abundance of aerosol cooling effects in all other years in those locations.
The CINE is an important parameter for determining the stability of the moist convection as it provides the basic inhibiting negative force to the plumes as they try to blow across the ABL. In consecutive figures, it may be noted that the CINE values are always negative in sign, hence an apparent reduction in its value actually signifies the strengthening of the same. A gradual intensification is observed over New Delhi compared to Chennai during DLD days, as revealed by Fig. S11. Nevertheless, CINE shows a prominent intensification in all the radiosonde stations (Fig. 7a), which is also supported by weakening of CAPE in those regions. Spatial mean difference reveals opposite features in CINE compared to CAPE in 2015–2019 and 2020 (Fig. S12). Lower values of CINE during 2020, particularly in the DLD, as compared to 2015–2019, is also seen from Fig. 7c and d. The CINE values decreased during 2020 compared to 2015–2019 during the DLD period (Fig. 7d). To explain the reason behind these trends, it has to be remembered that CINE acts as the inhibitory force opposing CAPE; hence, reduced buoyancy and CAPE will automatically lead to a stronger inhibition of CINE and vice-versa. Coming to spatial plots in normal years, CINE shows a relative weakening, as also supported by an increased CAPE in DLD with respect to PLD, hence CAPE increases and CINE reduces. In 2020, the same also holds true for the entire Indian region, except for the southern and eastern IGP, where CINE strengthens. This phenomenon can now be primarily attributed to a weaker CAPE, as also explained by the decrease in RH and increase in wind speed there. But from another point of view, studies such as Talukdar et al. (2019) have already discussed the interdependence of aerosol (black carbon) and CAPE over a tropical station like Gadanki. Regardless of all of this, it can be inferred that during lockdown, the presence of dry convection and low humidity levels (moist convection) and less cloud liquid formation leads to lower values of CAPE, and thus increased CINE, particularly in polluted inland regions, as previously demonstrated in this study.

4. Summary and conclusions

In this work, we have estimated the effects of the COVID-19 lockdown on the ABL height, and instability parameters from observations (surface and upper air radiosonde) and model simulations over India. We use surface observations, radiosondes, and model simulations to investigate the changes. Since it is quite common to expect changes in all these parameters during the lockdown days (DLD) compared to the pre-lockdown days (PLD) (as the transition from the late winter to early summer season is taking place), we compared these parameters with respect to the DLD and PLD days of the 2015–2019 and 2020 years. The main findings are summarized below.

1. The increase in visibility (by 15%) is clearly evident in all stations during the DLD period of 2020 compared to 2015–2019. However, this change is not same throughout India. The increase in visibility is high over inland stations compared to coastal stations, which can be attributed to the reduction of pollutants, particularly over inland stations (Ratnam et al., 2021a). Further, the visibility difference between inland and coastal stations is caused by the presence of land-sea breeze phenomena during March and April, which strongly controls the dispersion of pollutants and visibility with high humidity levels.

2. The surface temperature showed an increase in the DLD period of 2020 in all the stations by 17%. The spatial distribution of temperature shows an increase by ~3–4 °C over the central and western parts of India (Fig. S4). The abrupt reduction in anthropogenic emissions due to the COVID-19 lockdown resulted in an increase in surface air temperature over India. The simulated surface temperature is slightly higher than the observed one.
3. A decrease in RH is observed in all the stations by 16%. The inland stations showed a drastic decrease during the 2020 DLD days compared to the coastal stations. The RH decreased by 10–40% across India during the 2020 DLD days in terms of spatial variation. This reduction in RH can be associated with the fact that surface temperatures are increasing while the moisture content has remained unchanged, thereby leading to a reduction in the relative saturation levels during the lockdown period.

4. Wind speeds increased by 3 m/s throughout India in the DLD period of 2020. In terms of spatial variation, the wind speed drastically increased by ~100% over central India and the IGP region during 2020 compared to 2015–2019 DLD. The increase in temperatures might have led to the changes in surface pressures and enhanced winds. In turn, due to the lack of a land/sea breeze effect, this intensification of winds can be regarded as a major factor responsible for the dispersal of pollutants and an increase in surface temperature and visibility, particularly in the inland stations.

5. A prominent elevation in ABL height in DLD 2020 is observed in all the stations and from spatial variability over central India and the IGP region compared to the DLD 2015–2019 period. This increase in ABL height is mainly due to strong vertical mixing caused by the higher surface temperature. Further, this is attributed to the absence of radiatively active aerosols, which disturb the lapse rate profiles by creating inversions. This increase in ABL height, particularly in norther and eastern parts of India, might fuelled in reducing the pollution concentrations (through stronger vertical mixing) that are well reported in addition to the decrease in the anthropogenic activities.

Fig. 5. (a) The relative change (%) in the ABL height at different stations between DLD and PLD of 2015–2019 and 2020 obtained from the radiosonde observations. (b) & (c) Spatial relative change (%) in ABL height during 2015–2019 and 2020 between DLD and PLD days obtained using WRF model simulations. (d) Spatial relative change (%) in ABL height between DLD of 2020 and 2015–2019 years.
6. The CAPE increases intensely over coastal stations while it decreases over inland stations (New Delhi, Nagpur, and Raipur) due to dry convection and a decrease in humidity levels. Quite different changes are observed in the CAPE spatially, with a significant decrease in the IGP and central part by 100%. Concurrently, other regions show an increase in CAPE during the DLD days of 2020. When compared to 2015–2019, a decrease in CAPE is observed throughout India during the DLD of 2020. Spatial variability of CINE shows a net intensification in some parts of the IGP, central India, and the southern part of India by 50%, while other parts show an increase of 50–75%. These changes in CAPE

![Graph and images showing relative change in CAPE between DLD and PLD days in 2015-2019 and 2020, and spatial differences in various regions.](image-url)

Fig. 6. (a) The relative change (%) in CAPE at different station between DLD and PLD of 2015–2019 and 2020 obtained from the radiosonde observations. (b) & (c) Spatial relative change (%) in CAPE during 2015–2019 and 2020 between DLD and PLD days obtained suing WRF model simulations. (d) Spatial relative change (%) in CAPE between DLD of 2020 and 2015–2019 years.
and CINE can be mainly attributed to the dearth of saturation in lower troposphere levels, which prevented the development of strong pseudo-adiabats and instabilities above the cloud base during DLD.

Due to the COVID-19 lockdown, the surface air temperature started to warm up due to the reduced emissions over India. The increased temperature results in a decrease in relative humidity and an increase in wind speed. Elevated ABL height is observed in the same regions where higher surface temperatures are noticed. The changes associated with these parameters are strongly reflected in instability parameters also. The decrease in CAPE is depicted in the places of higher surface temperature, wind speed, and higher ABL height. Our study illuminates the changes associated with COVID-19 lockdown on different meteorological parameters over India, in turn on the ABL height and on the instability parameters. The background atmosphere thus responded differently across India with respect to geographical locations and associated dynamics (particularly the impact on the inland and coastal regions). Major conclusion drawn from this study is that one need to consider changes in the background
