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Changes in Air Quality, Meteorology and Energy Consumption during the COVID-19 Lockdown and Unlock Periods in India

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Abstract: The increasing population and its associated amenities demand innovative devices, infrastructure, methods, plans and policies. Regional climate has a great role in deciding the air quality and energy demand, and therefore, weather and climate have an indisputable role in its consumption and storage. Here, we present the changes in trace gases and associated regional weather in India during lockdown and unlock periods of COVID-19. We observe a reduction of about 30% in sulphur dioxide (SO_2) and 10–20% in aerosols in the Indo-Gangetic Plain (IGP), large cities, industrial sites, mining areas and thermal power plants during lockdown as compared to the same period in the previous year and with respect to its climatology. However, a considerable increase in aerosols is found, particularly over IGP during Unlock 1.0 (1–30 June 2020), because of the relaxation of lockdown restrictions. The analyses also show a decrease in temperature by 1–3 °C during lockdown compared to its climatology for the same period, mainly in IGP and Central India, possibly due to the significant reduction in absorbing aerosols such as black carbon and decrease in humidity during the period. The west coast, northwest and central India show reduced wind speed when compared to its previous year and climatological values, suggesting that there was a change in regional weather due to the lockdown. Energy demand in India decreased by about 25–30% during the first phase of lockdown and about 20% during the complete lockdown period. This study thus suggests that the reduction of pollution could also modify local weather, and these results would be useful for drafting policy decisions on air pollution reduction, urban development, the energy sector, agriculture and water resources.

Keywords: lockdown; trace gas; temperature; winds; energy; regional climate

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1. Introduction

Air pollution has become a serious concern, particularly in developing countries such as India, due to its severe impact on the environment, climate and human health [1–3]. In a recent estimate from the World Health Organization (WHO) [4], about 91% of the world population is exposed to poor air quality. India has also been facing the issue of poor air quality in most of its big cities for the past several years [5–7]. Power generation, transportation, industries, construction, residential and commercial activities are the major anthropogenic sources of air pollution in India [8]. All these aforementioned activities have also increased significantly over the past decades.

The world came to a halt as a result of the COVID-19 outbreak, with practically all human activity, including industries and vehicular mobility, being severely curtailed. The first COVID-19 case was reported in India on 30 January 2020, and it gradually spread to other parts of the country. To manage the spread of COVID-19 infection, a nationwide strict lockdown was implemented from 24 March to 31 May 2020. Lockdown refers to the complete prohibition of leaving the house except in an emergency. During this period, the government paused all transportation modes, except for essential goods and services across the country. Furthermore, construction, industrial activities, educational institutions and other anthropogenic activities were strictly prohibited.

Several studies have been conducted to analyse the spatial and temporal distribution of air pollutants during lockdown across the globe, focusing primarily on metropolitan cities [9–12]. Studies have also shown improvement in air quality in different Indian cities [13–15] and in the cities of the Indo-Gangetic Plain (IGP), such as Delhi [16,17]. In addition, satellite measurements have shown that aerosol amounts in India were at the lowest in the past 20 years during the lockdown period in 2020 [18]. Similarly, the particulate matter ($PM_{2.5}$) concentration decreased by about 42% over India during lockdown as compared to that in the same period of the previous year [19].

The exceptional decline in air pollution across India during lockdown could affect local weather. For instance, aerosols as cloud condensation nuclei (CCN) play a decisive role in cloud formation [20]. It may affect the climate and weather in various ways through mechanisms associated with scattering and absorption of light. Aerosols such as black carbon (BC) can absorb incoming solar radiation and thus can alter the atmospheric stability and convection process [21]. For example, soot particles can heat the atmosphere, which can cause an increase in the static stability that inhibits cloud formation by reducing evaporation from the surface [22]. There is a significant reduction in $PM_{2.5}$ and trace gases such as NO_2 and NH_3, which help in the formation of secondary aerosols and led to a notable drop in CCN concentration during lockdown in 2020 [23].

Weather conditions play a key role in energy demand; for instance, hot and humid summer conditions require more power for fans, air conditioners, irrigation and pumping of water [24–26]. A decline in the energy demand globally during the lockdown period of 2020 can be identified with the drop in worldwide financial activities and subsequent reduced use of energy sources such as petroleum products [27]. The electricity consumption of India dropped by approximately 19% on 3 April 2020, and there was a reduction in power production from coal by 26% in the first two weeks of lockdown [28], but the electricity demand increased during the unlock period [29]. The share of renewables increased in energy generation, while base-load operations decreased. The renewables thus had precedence in energy production during lockdown, as they could not be closed down completely to adjust their output to match the call, henceforth shielding them from the impacts of unforeseen situations such as the COVID-19 pandemic [30].

Manmade activities have led to severe air pollution problems across the globe. India also faces several issues regarding public health, ecosystem damage and climate change, owing to the reduction in air quality. In this context, temporary restrictions imposed due to the COVID-19 pandemic have given opportunity for the environment to heal itself from the continuous damage caused by anthropogenic activities. Most studies mentioned above are focused on the changes in air pollution levels during lockdown. The impact of lockdown on weather is least explored for the Indian region. Therefore, we examine the changes in SO_2, AOD, BC and dust ($PM_{2.5}$) distributions during the pre-lockdown, lockdown and unlock periods in India. Furthermore, the impacts of lockdown on regional weather in terms of temperature (T), relative humidity (RH), precipitation (P), ultraviolet (UV) radiation, total cloud cover (TCC), and winds are analysed. Finally, we also investigate the changes in energy demand during the lockdown and unlock periods in India. We use satellite and reanalysis data together with daily energy demand information from Power System Operation Corporation Limited, Government of India, for this assessment. This is the first study that discusses the impact of lockdown on air quality, meteorology and energy demand together for India.

2. Data and Methods

The government of India (GOI) declared a lockdown to contain the rapid spread of COVID-19 from 25 March to 31 May 2020 in India. Following this, the unlock period began in June 2020, with the GOI naming it Unlock 1.0 (1–30 June 2020), Unlock 2.0 (1–31 July 2020), Unlock 3.0 (1–31 August 2020) and Unlock 4.0 (1–30 September 2020), with restrictions eased in each phase of the unlock period, as illustrated in Figure 1. In addition to this pan-India analysis, we also assess the pollution and weather anomalies in specific regions such as central India (CI), IGP, northeast (NE), northwest (NW), peninsular India (PI) and hilly regions separately, as shown in Figure 1. It is impossible to cover the entire regions in India using ground-based measurements because the stations are mostly located in urban areas. Therefore, we use satellite and reanalysis datasets to examine the changes in atmospheric trace gases, particulates and meteorology throughout the lockdown (April–May), pre-lockdown (March 2020), and unlock periods (June–September), as these data have better spatial and temporal coverage. Due to the restriction in anthropogenic and industrial activities, the energy demand has decreased worldwide. Therefore, we also assess the energy demand during the lockdown and unlock periods in India.

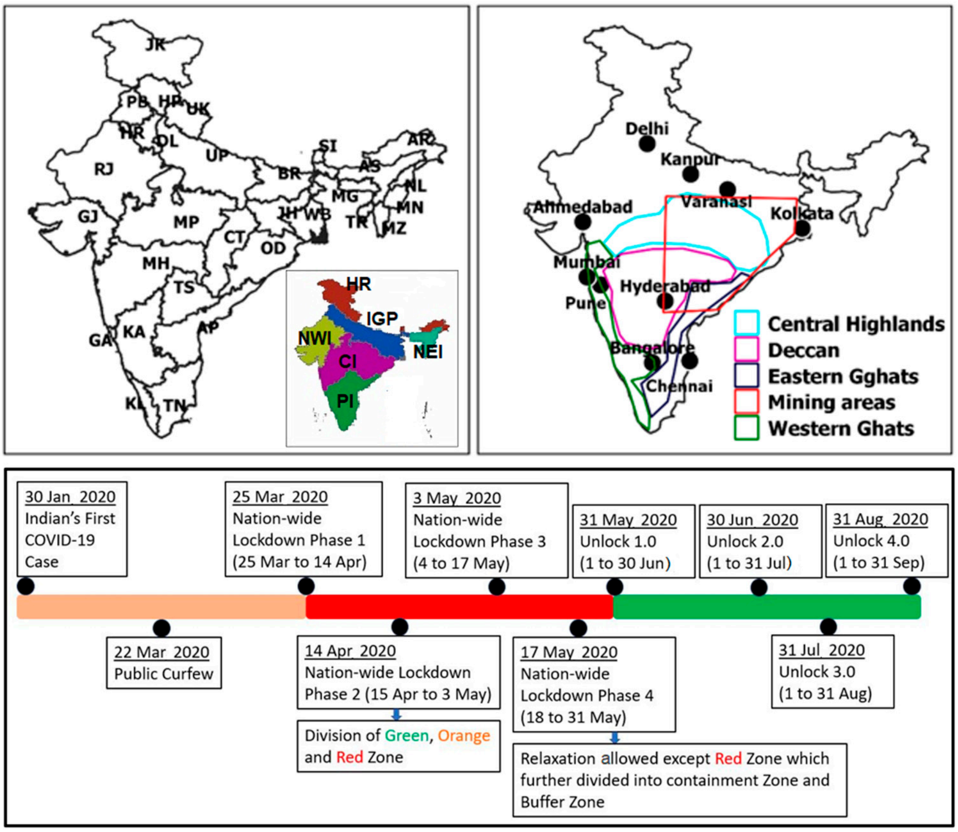

Figure 1. Geographical location of states (name of the states are given in Table S1 with abbreviation), major cities and different regions in India. The regions shown in the inset are central India (CI), Indo-Gangetic Plain (IGP), northeast India (NE), northwest India (NW), Peninsular India (PI) and hilly regions (HR). Bottom panel is the timeline of the COVID-19 situation and lockdown restriction in India (Sources: Ministry of Home Affairs, Government of India).

To investigate the impact of lockdown on the atmospheric concentration of trace gases, SO_2 data from TROPOMI (Tropospheric Monitoring Instrument) on board the Sentinel-5 Precursor (S5P) were used [31]. This satellite was put into orbit in October 2017 by the European Space Agency to monitor air pollution. Clean regions and areas with low SO_2 values are often retrieved with negative vertical columns, but were advised to keep, except for the outliers that are smaller than -0.001 mol. m^{-2}, TROPOMI with 3.5×7 km^2 spatial resolution and the revisit time of one day, while also scanning the Earth surface in very fine swaths that help in the detection of much smaller SO_2 plumes. The following criteria for QA value were met for the SO_2 data before running the harp convert tool: air mass factor polluted > 0.1, snow ice < 0.5, QA value > 0.5, total vertical column > -0.001, solar zenith angle < 60° and cloud fraction < 0.3. The SO_2 band was considered only when the solar zenith angle was smaller than 70° [32–34]. Apart from that, we used OMI (Ozone Monitoring Instrument) to calculate the climatology of SO_2 from its measurement record. OMI on Aura provides long-term SO_2 data at a spatial resolution of 0.25° × 0.25°.

The AOD, BC and dust data were taken from Modern-Era Retrospective Analysis for Research and Applications (MERRA) v2 for the same periods. This is an atmospheric reanalysis developed by the Global Modeling and Assimilation Office (GMAO) and has a spatial resolution of 0.50° × 0.625° [35,36]. The reanalysis incorporates observations that were not previously available in MERRA. It also includes changes to the Goddard Earth Observing System model and analysis method. However, MERRA-2 has undergone significant changes, including the incorporation of aerosol observations. It offers 3 h global gridded data of both aerosol diagnostic and parameters that are not easily observed, with specific applications ranging from air quality to climate change.

Precipitation, temperature, RH, TCC, zonal (U) and meridional (V) components of wind at 10 m, and UV (ultra-violet) data for the pre-lockdown, lockdown and unlock periods were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5 (ERA 5). This is the most recent ECMWF reanalysis, offering hourly, daily and monthly data on several atmospheric, sea-state, and land-surface parameters from 1979 onwards at a spatial resolution of 0.25° × 0.25° [37]. It was developed using 4D-Var data assimilation in the ECMWF Forecast System with 137 vertical levels from 1000 to 0.01 hPa.

We also compared the trace gases and particulates with respect to their climatology made from the past 20 years (2000–2019) of data for the corresponding lockdown period of 2020. Atmospheric pollution has a great influence on meteorological processes, including cloud and precipitation processes, humidity, and incoming solar radiation. Therefore, we also examined meteorology during the lockdown and unlock periods. In the case of wind, wind speed and direction were evaluated using the U (zonal) and V (meridional) components.

We computed the percentage change in all parameters for the lockdown period with respect to their climatology (2000–2019) for same period. Similarly, changes during lockdown were also computed with respect to the pre-lockdown period and the previous year (2019). In addition, changes during the unlock period, 2018 (April–May), and 2019 (April–May) were also estimated with respect to its climatology. The following equation was used for the computation:

$$\%\ Y_{lockdown/unlock} = \frac{Y_{lockdown/unlock} - Y_{climatology\ (2000-2019)}}{Y_{climatology\ (2000-2019)}} \times 100$$

where Y indicates the different atmospheric and meteorological parameters, e.g., AOD, BC, dust, T, P, RH and winds.

We also performed a correlation analysis to better understand the relationship between air pollutants and weather indicators or parameters. In addition, a one-way analysis of variance (ANOVA) was carried out to find the influence of BC and AOD on meteorological parameters. Statistical significance was tested at 95% confidence interval.

3. Results and Discussion

3.1. Changes in Air Quality: SO_2, AOD, BC and Dust

Figure 2 shows the pre- and post-lockdown SO_2 over India. In the mining regions of eastern India, there was about 30% reduction in SO_2 during lockdown as compared to the pre-lockdown period in 2020 (Figure 2 bottom panel). This decline was mainly due to the drop in vehicular emissions and coal mining activities during lockdown [38]. The reduction in SO_2 over Chennai was very small, which implies that lockdown was not very effective there [39]. As lockdown restrictions were relaxed in different phases of unlock, the emissions from vehicles and other anthropogenic activities (e.g., industrial activities) increased throughout India. However, SO_2 during the unlock period was found to be lower than that in the lockdown period of 2020 (Figure 2 middle panel). This reduction in SO_2

was due to its removal from the atmosphere by precipitation (wet deposition) during the unlock period (Figure S1 bottom panel).

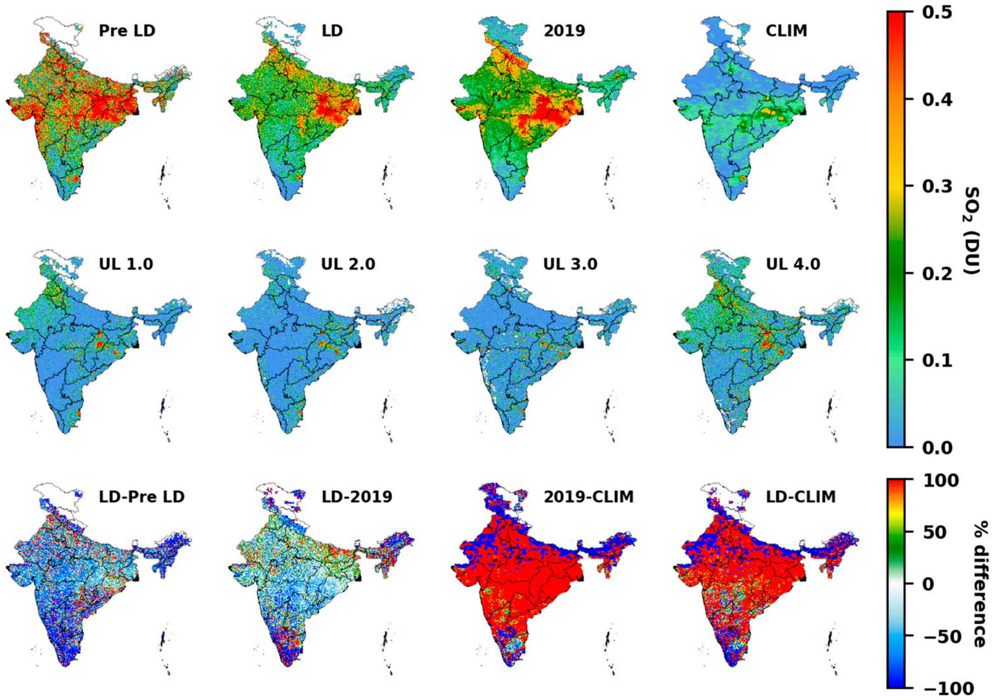

Figure 2. The average SO_2 distribution in India during different periods: pre-lockdown (pre LD), lockdown (LD), corresponding lockdown period of 2019 (2019), climatology for the lockdown (CLIM) and unlock (UL 1.0, 2.0, 3.0 and 4.0) periods. The difference between SO_2 concentrations during lockdown and pre-lockdown (LD—Pre LD), 2019 (LD—2019) and climatology (LD—CLIM), and the difference in SO_2 concentration between 2019 and climatology (2019—CLIM) are shown in the bottom panel.

In addition to a decrease of about 10–20% AOD in IGP, PI and NEI during lockdown relative to pre-lockdown in 2020, we also observe a decrease of about 10% in AOD over India, except in some parts of hilly, NWI and PI regions as compared to its climatology for the same period (Figure 3 bottom panel). The decrease in aerosols in IGP and other regions of India was also found in other studies [40]. The reasons for the decrease in atmospheric particulates were the reduction in transport, industrial production and urban activities. In contrast, some regions in NW and CI exhibited higher AOD in lockdown as compared to its climatology and previous year, indicating that there were still aerosol sources during lockdown and that the restrictions were not effective in those regions.

The aerosols in India show a sudden increase during Unlock 1.0, except in southern and northeastern India (Figure 3 middle panel). Furthermore, due to the gradual removal of lockdown restrictions in different phases of Unlock, the emissions due to human activities increased throughout India. The IGP region shows the highest increase in AOD in Unlock 1.0 compared to that in the lockdown period in 2020. AOD during Unlock 3.0 over India is, however, lower than that in lockdown. This reduction in AOD during Unlock 3.0 was due to the wet deposition of particulates from the monsoon rains.

There was a slight reduction in the amount of BC in India during lockdown 2020 as compared to its climatology (Figure 4, top panel). The reduction was about 10% in IGP, the hilly region and some parts of PI in this period with respect to their climatology and 2019, due to the drop in vehicular and industrial emissions (Figure 4, bottom panel). Conversely, a continuous increase in BC was observed during the unlock periods. As observed with AOD, BC was also smaller during lockdown relative to Unlock 4.0 (Figure 4, middle panel).

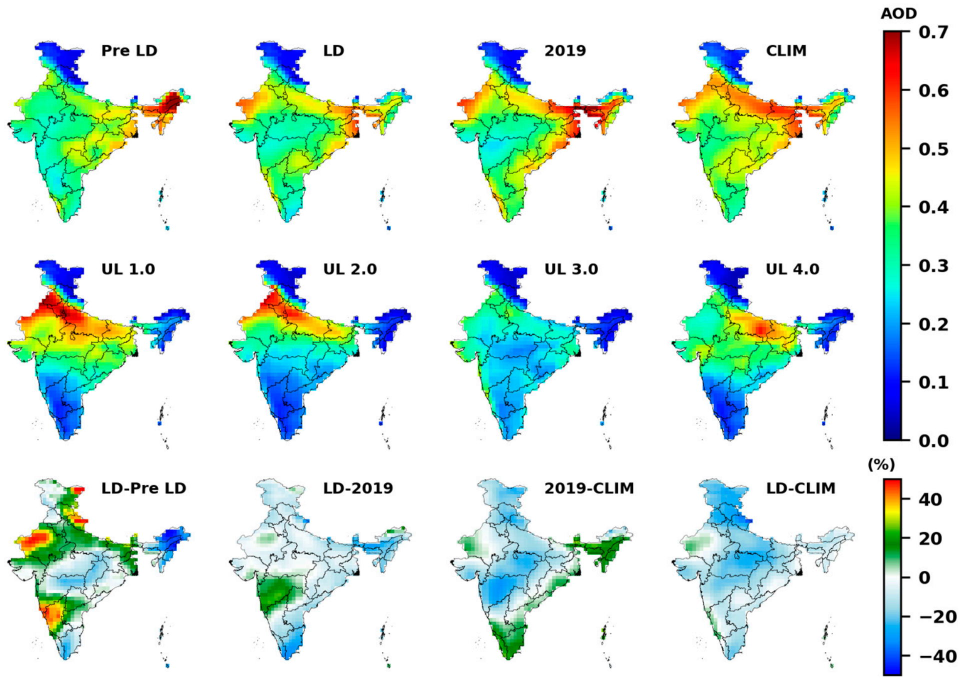

Figure 3. The average total aerosol (AOD) distribution in India during different periods: pre-lockdown (pre LD), lockdown (LD), corresponding lockdown period of 2019 (2019), climatology for the lockdown (CLIM) and unlock (UL 1.0, 2.0, 3.0 and 4.0) periods. The differences between AOD during lockdown and pre-lockdown (LD—Pre LD), 2019 (LD—2019) and climatology (LD—CLIM), and the differences in AOD concentration between 2019 and climatology (2019—CLIM) are shown in the bottom panel.

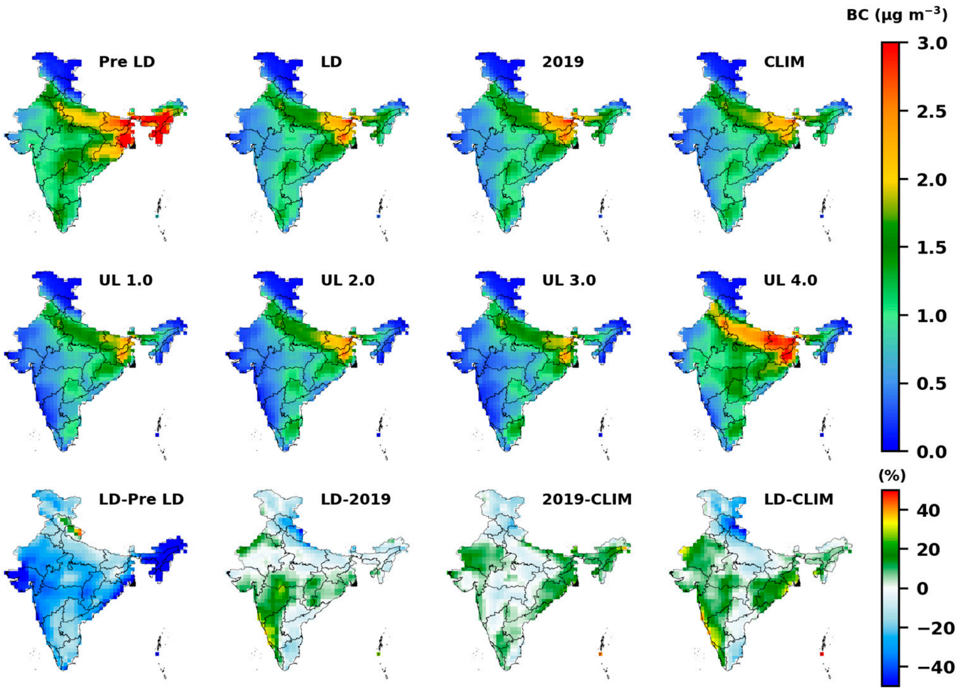

Figure 4. The average BC distribution in India during different periods: pre-lockdown (pre LD), lockdown (LD), corresponding lockdown period of 2019 (2019), climatology for the lockdown (CLIM) and unlock (UL 1.0, 2.0, 3.0 and 4.0) periods. The difference between BC concentration during lockdown and pre-lockdown (LD—Pre LD), 2019 (LD—2019) and climatology (LD—CLIM), and the difference in BC concentration between 2019 and climatology (2019—CLIM) shown in the bottom panel.

We also examined the time series of particulates, which are shown in Figure 5. For instance, aerosols were higher in IGP during pre-lockdown, primarily due to anthropogenic emissions. During lockdown, aerosols were gradually reduced because of the reduction in emissions, which were due to restrictions in various activities. Therefore, the decrease in AOD was highest during lockdown, and it increased thereafter due to a relaxation in human activities [16]. The general distribution of AOD in the unlock periods illustrates an increase in IGP owing to the dust particles carried by winds from the Sahara and Thar deserts [41,42]. A similar distribution of AOD can be found in CI and NEI. However, the aerosols in NWI were not reduced during lockdown, which could be due to dust particles from the desert regions. Furthermore, during lockdown, AOD was nearly constant in PI, but a sudden decrease in AOD was observed during the unlock period because of the wet scavenging process by monsoon rains.

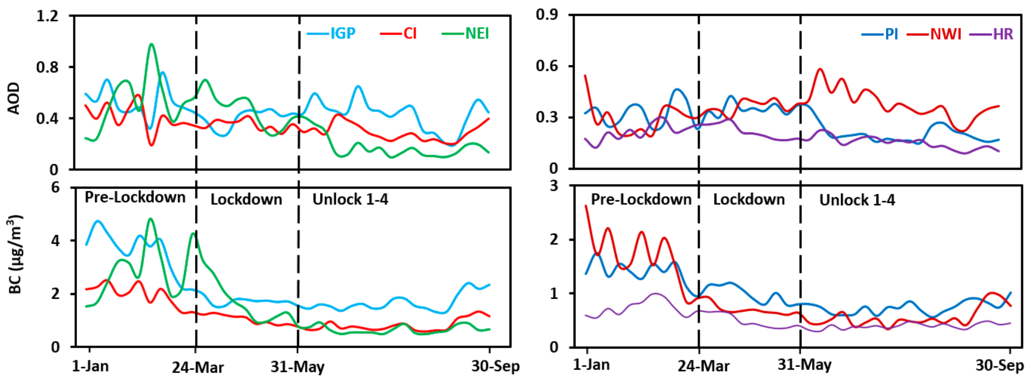

Figure 5. Temporal evolution of AOD and BC in different regions of India during pre-lockdown, lockdown and unlock (Unlock 1–4) periods. IGP, Indio-Gangetic Plain; CI, central India; NEI, northeast India; PI, peninsular India; NWI, northwest India; HR, hilly regions. Dates in the year 2020 were shown in the x-axes.

In the case of BC, each region experiences a sharp decrease from pre-lockdown to lockdown. However, due to the monsoon rains, no such increase in BC was observed during the unlock period (Figure S1). The general cycle of BC follows a very similar pattern to that of AOD: highest in winter, a gradual decrease in pre-monsoon, the lowest in monsoon and again an increase thereafter. Lockdown did not affect the general cycle of BC, but it accelerated the rate of decline in BC from winter (pre-lockdown) to pre-monsoon (lockdown). During lockdown, aerosols (AOD), BC and dust decreased in comparison to their concentrations in that past two decades (Figure S1 top panel).

Dust ($PM_{2.5}$) is the most dominant pollutant in much of India [43,44]. The sources of dust are regional recirculation, dust resuspension or long-range transport, secondary aerosol formation, mining activities, constructions, and biogenic and marine emissions [38]. There was a major decrease of dust in IGP, CI and NEI (by 10–20%) during lockdown as compared to its climatology (Figure S2). Similarly, a discernible decrease in dust, except for a few hilly areas of Jammu and Kashmir, was also found during lockdown relative to its climatology. Furthermore, the amount of dust was decreased by up to 30% and 10% in the PI and IGP regions, respectively, in the lockdown period in comparison to that in the same period of 2019. Previous studies for Delhi (in the IGP region) also exhibited 35–39% reductions in $PM_{2.5}$ during lockdown relative to that in the same period in 2019 [11,16,45].

3.2. Changes and Impact on Meteorology: T, RH, P, UV, TCC and Winds

Figure 6 (top panel) shows the changes in temperature during the lockdown and unlock periods of 2020 and its climatology. There were strong seasonal differences in temperature between the lockdown and unlock periods. In general, temperature during the lockdown period was about 25°–30 °C in the IGP, west coast and some regions in the east coast, i.e., Orissa and West Bengal. The temperatures were about 35 °C in other parts of India, mainly in CI and NW India during lockdown of 2020, except for the northeast and northernmost states, where the temperatures showed high variability between 5 and 30 °C. The temperatures in Kashmir varied from −5 to −15 °C, and the lowest temperature of India was also recorded there. The temperature distribution in 2020 shows slightly lower values (1–5 °C) in IGP and eastern India compared to that in 2019 and its 20-year climatology, but it was relatively higher than that of 2018. However, temperature during lockdown in IGP was decreased by about 1–3 °C compared to its climatology for the same period (Figure 6, bottom panel). The decrease in temperature in IGP was mainly due to the reduction in absorbing aerosols such as BC [46]. However, the temperature increased by 1–2 °C (during lockdown) compared to its climatology in PI, areas of CI and NWI, where the non-absorbing aerosols dominated the total particulates in the atmosphere. The reduction of total aerosol loading allowed more solar radiation to the surface and thus enhanced the temperature there [47]. Note that the increase in temperature beyond 1–2 °C is still higher than the background warming or cooling. The presence of dense monsoon clouds during the unlock period blocked radiation and reduced the temperature. As a result, the temperature was lower during unlock as compared to that in lockdown in 2020. During Unlock 1.0, a decrease in temperature was observed, particularly in CI and IGP compared to its climatology. However, the entirety of India shows an increase in temperature during other phases of unlock compared to its climatology.

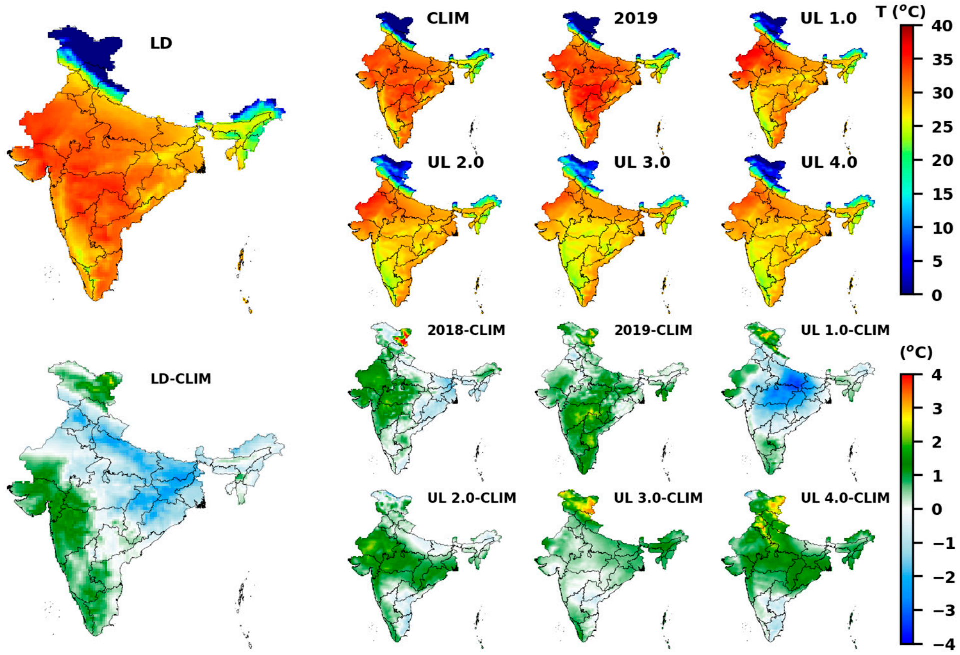

Figure 6. The average surface temperature distribution in India during different periods: lockdown (LD), climatology for the lockdown period (CLIM), corresponding lockdown period of 2019 (2019), and unlock (UL 1.0, 2.0, 3.0 and 4.0) periods. The difference in temperature between the periods of its climatology and lockdown (LD—CLIM), same LD period in 2018 (2018—CLIM), same LD period in 2019 (2019—CLIM) and each phase of unlock periods (e.g., UL 1.0—CLIM).

As humidity is closely related to temperature, we have shown the RH distributions across India during the lockdown and unlock periods, and their comparison with climatology (Figure S3). In general, the coastal regions and NEI show high humidity that decreases toward CI. The lowest humidity records were in NW, IGP and CI during lockdown, at about 30–40%. The situation during lockdown was similar to its climatology, but slightly higher values were registered in IGP. The increase in RH in IGP and NW India was about 30–40%, which was in agreement with the comparatively higher temperatures in those regions. Except for Unlock 1.0 in central IGP and a part of CI, no noteworthy change in RH was found during the unlock period relative to its climatology.

The TCC analysis shows that there were 20–40% more clouds in the regions of lower temperatures during lockdown when compared to the same period climatology (Figure S4). The clouds were also about 30–40% higher in 2020 in most parts of India than that of climatology, except in some areas of PI, NW and NEI, which reduced local temperatures during the lockdown period. A huge increase in cloud cover, due to monsoon weather, over India was observed during the unlock period as compared to the lockdown period in 2020. About 30–40% enhancement in TCC was found over central IGP and north CI during Unlock 1.0 compared to its climatology, where RH was also correspondingly higher. Our finding is consistent with Khatri et al. [46], in which they reported that the cloud cover had increased over IGP during lockdown due to a high reduction in aerosols.

The UV incidence was 1–5% lower in the lockdown period, except in some parts of PI, NE and the northernmost regions (Figure S5), but higher temperatures were observed there. This could be due to the humidity changes there. The largest difference of about −5% was found in the lower IGP, which could be attributed to the cloud cover during lockdown. The presence of monsoon clouds blocks solar radiation, which resulted in lower UV radiation during the unlock period. The lower temperature regions also coincide with the lower UV incidence areas, consistent with previous discussions. During Unlock 1.0, UV over lower IGP and CI was reduced by 10–20%. However, a considerable increase in UV was found during Unlock 2.0 over CI and NWI, although no noteworthy change was found in other regions. The CI, NWI, and PI regions exhibited a drop in UV during Unlock 3.0, whereas IGP and CI showed a modest increase in UV during Unlock 4.0. About a 10–15% drop in UV was observed in PI as compared to its climatology during Unlock 4.0.

Since it was the pre-monsoon period, isolated rains were present in different regions of India, which might have influenced the temperature in the lockdown period (Figure S6). The precipitation was higher in the NE (10–14 mm), IGP (2–4 mm) and hilly (2–6 mm) regions, but the rest of India hardly had any rainfall during lockdown. The precipitation analyses show about a 50–70% increase of rain in IGP and about 10–50% in some areas of NW and CI during lockdown compared to its climatology. Therefore, the regions with the largest temperature change also have significant variation in precipitation during lockdown. During Unlock 1.0, 2.0 and 3.0, PI exhibited a 30–70% increase in rainfall with respect to its climatology, as it was the monsoon season. During Unlock 1.0, precipitation increased by 50–70% in the lower IGP and CI, but showed a decrease in the NWI and upper IGP regions. Except for PI, no significant change in rainfall was observed during Unlock 2.0, although noticeable changes were observed in CI, NWI and at a few places in IGP during Unlock 3.0. These changes in precipitation throughout the unlock period relative to its climatology could be attributed to the changes in atmospheric composition due to lockdown restrictions. Precipitation helps in cleaning the environment by scavenging pollutants from the atmosphere, and it reduces the temperature.

The temporal evolution of different meteorological parameters during the pre-lockdown, lockdown and unlock periods are shown in Figure 7. During lockdown, no significant change was observed in UV and wind speed in IGP and PI. However, in the case of precipitation, a sharp increase from 1 to 5 mm was observed in PI. Similarly, a rise in TCC was also observed in PI during lockdown. A sharp decrease in relative humidity was observed in IGP (from 64 to 50%). A decrease in average temperature (from 27.8 to 26.7 °C) was also found in India as compared to that in the previous year (Figure S1, top panel).

The wind shows high speed in parts of NWI and CI along with the coastal regions during lockdown 2020 (Figure 8 first row). The west coast shows about 3–4 m/s with the highest wind speed of about 6 m/s at the Gujarat coast. During lockdown, the slowest winds were found in IGP, PI and NE India, at about 1 m/s. The wind distribution in 2019 was very similar to that of its climatology, but was slightly different in 2020. The winds in CI, NWI and some areas of PI were about 25–50% weaker than that in 2019, 2018 and its climatology (Figure 8, third row). On the other hand, in lower IGP, and parts of PI show stronger winds, about 20–50% increase from its climatological values. The wind direction also slightly changed during lockdown, particularly in eastern PI. The analysis thus shows noticeable changes in temperature, RH, TCC, UV and winds during the lockdown period as compared to their long-term climatology and previous year distribution, indicating the impact of lockdown on regional weather.

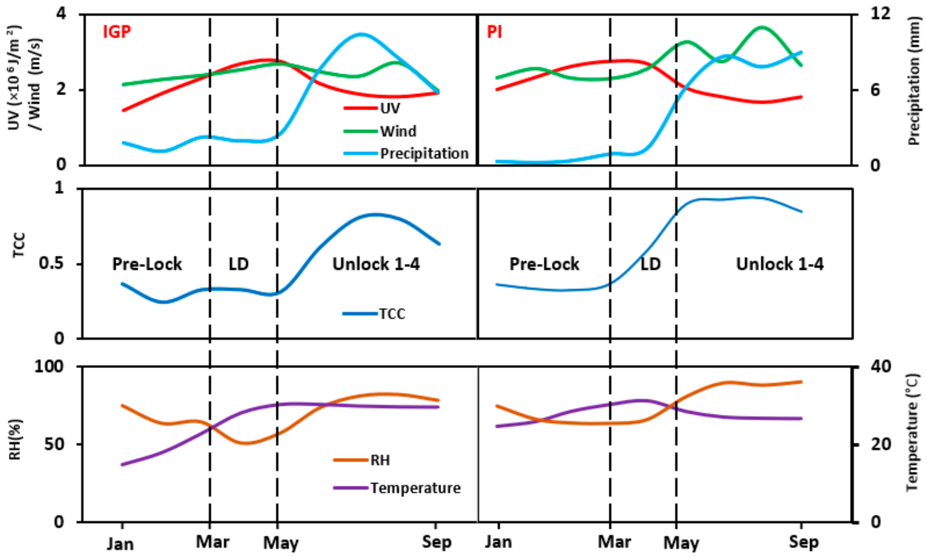

Figure 7. Temporal evolution of meteorological parameters in Indo-Gangetic Plain (IGP, left panel) and peninsular India (PI, right panel) during the pre-lockdown (Pre-Lock), lockdown (LD) and unlock (Unlock 1–4) periods. Dates shown on the *x*-axis are for the year 2020.

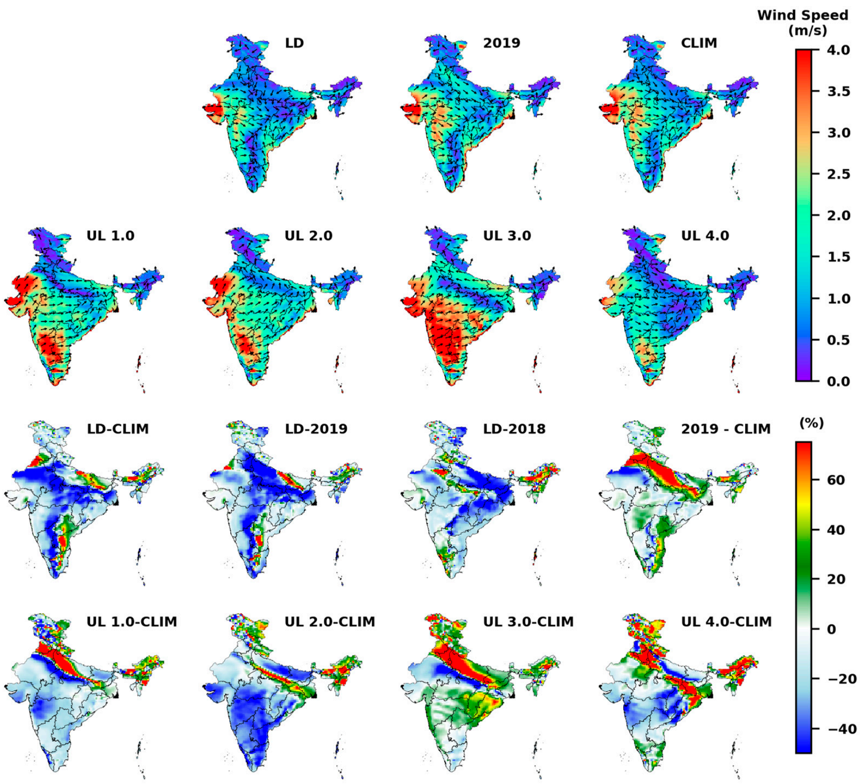

Figure 8. The average surface wind (2 m) distribution in India during different periods: lockdown (LD), corresponding lockdown period of 2019 (2019), climatology for lockdown period (CLIM), and unlock (UL 1.0, 2.0, 3.0 and 4.0) periods. The difference in winds between the periods of its climatology and lockdown (LD—CLIM), same LD period in 2019 (LD—2019), same LD period in 2018 (LD—2018), and the difference in temperature during lockdown period climatology and the same LD period of 2019 (2019—CLIM), and each phase of unlock periods (e.g., UL 1.0—CLIM).

As BC warms the atmosphere by its positive radiative forcing, its high concentration in the atmosphere can increase the temperature. On the other hand, reduction of its concentration in the atmosphere can also relatively decrease the temperature. Here, we observe a noticeable reduction in BC concentration with an associated decrease in temperature in different regions of India. ANOVA also reveals that BC significantly impacted temperature during the lockdown period in India (Table S2). Similarly, AOD affects cloud cover and precipitation by acting as a cloud condensation nuclei., but its relation is heterogeneous. For instance, high positive correlation of about 0.6 was estimated in the western and central regions (Figure S7), but negative correlation (−0.2–−0.4) was found in the eastern regions of India. The analysis also indicates that the decline in AOD influences precipitation by modifying cloud cover. In addition, precipitation during the lockdown period modified the temperature (Table S2). In general, the reduction in AOD allowed for more incoming solar radiation at the surface, which was also found in our analysis for the lockdown period. Therefore, our analyses show a close link between air quality and meteorology.

3.3. Implications for Energy Consumption

A burning issue that is attracting intensified curiosity from businesses and environmental authorities, as well as from the public and policymakers, is the connection between air quality and energy use. In order to design and analyse environmental strategies and connect environmental externalities such as atmospheric emissions and meteorological parameters, energy use is critical. Our analyses focused largely on the direct and indirect effects of change in human behaviour and technologies during lockdown, owing to COVID-19's impact on energy. The temporal changes in energy consumption during the pre-lockdown, lockdown and unlock periods were analysed to capture the effect of lockdown on energy use. During the pre-lockdown period, India's energy demand was comparable to that in 2019. Since the beginning of lockdown (24 March 2020), the energy demand reduced. The sudden drop in demand on 22 March 2020 was due to the public curfew announced by the GOI. The energy use on that day was about 25–30% lower than that in 2019. Energy demand was also reduced by about 25–30% during the first phase of lockdown, as demonstrated in Figure 9. The average decrease in energy demand was about 20% during the complete lockdown. A gradual increase in energy demand was observed during the subsequent unlock phases due to the gradual relaxation of restrictions in anthropogenic activities. A decrease in energy demand corresponded to an improvement in air quality during lockdown, clearly suggest that the energy sector is one of the main reasons for the deteriorating air quality in India.

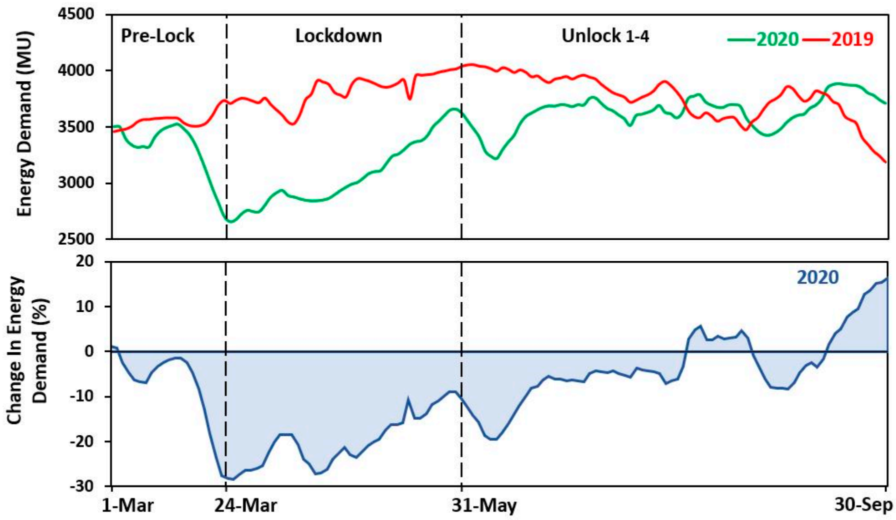

Figure 9. Energy demand (in MU, top panel) and change in energy demand (in %, bottom panel) in India during pre-lockdown (Pre-Lock), lockdown and unlock (Unlock 1–4) periods for the years 2020 and 2019.

4. Conclusions

Our analysis reveal that trace gas and particulates decreased during the lockdown period in 2020 compared to its climatology and those present in the previous year. The meteorological factors such as wind and temperature also showed unusual behaviour from their climatology and previous year distribution during the lockdown period in 2020. For instance, the wind speed was decreased by almost 25–50% over CI, NWI and some areas in PI. In general, the temperature decreased by about 1–3 °C in IGP during lockdown, indicating that the changes in regional weather due to lockdown induced alterations in environment. Statistical diagnosis with ANOVA also uncovered that both BC and AOD significantly affected the local weather during the lockdown period in India. Lockdown had a greater impact on energy demand, as all industrial activities were suspended during the period. The average decrease in energy demand was about 20% during the lockdown period in India.

The COVID-19-induced lockdown was a natural experiment to explore the link between air quality and meteorology. Our analysis finds that stringent regulation and restrictions on human activities can create a rapid response in the environment and regional weather systems. Furthermore, good air quality not only benefit human health but also provide a clean environment for future generations. This study also helps to understand the connection between energy demand, air quality and meteorology. This comprehensive assessment on the reduction in air pollution and its impact on regional weather can assist policymakers in drafting regulations based on the experiences gained from lockdown.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/air1020010/s1.

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