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Impact of Deadly Dust Storms (May 2018) on Air Quality, Meteorological, and Atmospheric Parameters Over the Northern Parts of India

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Key Points:
- Intense uplift phases were observed associated with displacement of trace and greenhouse gasses
- Increased aerosol loading was associated with changes in aerosol volume size distributions
- Increased surface ozone was observed in areas under the direct influence of dust

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Impact of Deadly Dust Storms (May 2018) on Air Quality, Meteorological, and Atmospheric Parameters Over the Northern Parts of India

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Abstract The northern part of India, adjoining the Himalaya, is considered as one of the global hot spots of pollution because of various natural and anthropogenic factors. Throughout the year, the region is affected by pollution from various sources like dust, biomass burning, industrial and vehicular pollution, and myriad other anthropogenic emissions. These sources affect the air quality and health of millions of people who live in the Indo-Gangetic Plains. The dust storms that occur during the premonsoon months of March–June every year are one of the principal sources of pollution and originate from the source region of Arabian Peninsula and the Thar desert located in north-western India. In the year 2018, month of May, three back-to-back major dust storms occurred that caused massive damage, loss of human lives, and loss to property and had an impact on air quality and human health. In this paper, we combine observations from ground stations, satellites, and radiosonde networks to assess the impact of dust events in the month of May 2018, on meteorological parameters, aerosol properties, and air quality. We observed widespread changes associated with aerosol loadings, humidity, and vertical advection patterns with displacements of major trace and greenhouse gasses. We also notice drastic changes in suspended particulate matter concentrations, all of which can have significant ramifications in terms of human health and changes in weather pattern.

1. Introduction

The Indo-Gangetic Plains (IGP) experiences frequent dust storms every year during the premonsoon season (March–June); (Bhattacharjee et al., 2007; Dey et al., 2004; Gautam et al., 2009; Kumar et al., 2015; Prasad et al., 2007; Singh, 2014; Singh et al., 2004). Dust storms are global phenomena and are observed over most of the continents. Dust originate from the arid and desert areas that are located in many parts of the world (Duce, 1995; Ginoux et al., 2012; Kohfeld & Harrison, 2001; Middleton, 1986). Dust storms observed in India come either from the Thar Desert located in the western parts of India or from distant source of the Arabian Peninsula. The dust storms are generated due to surface heating and by the strong pressure gradient. High heat exists over the Arabian Peninsula and the Thar desert, especially during premonsoon season, without much rainfall. The loose soil/sand particles rise in the atmosphere that are transported through westerly winds over the Indian continent. The long transport of dust from the Arabian Peninsula takes one track, through Afghanistan and Pakistan, and another track, over the Arabian Sea, before entering the Indian subcontinent (Middleton, 1986). Depending upon the wind speed, dust is observed in the IGP from the west and is transported over the eastern parts of India, up to West Bengal. Sometimes, depending upon the wind pattern, dust is diverted to the Central parts of India (Kumar et al., 2015; Prasad & Singh, 2007a, 2007b).

Dust enhances aerosol loading over the IGP (Sikka, 1997; Verma et al., 2013), affecting visibility and air quality. Desert dust constitutes a large fraction (50%) of the naturally occurring tropospheric aerosols (Gobbi et al., 2000) that provide additional cooling effects in the lower troposphere. Dust plays an important role in the middle and upper troposphere, giving rise to additional warming (Gautam et al., 2009; Gobbi et al., 2000). Further, dust is found to reach up to the Himalayan foothills and blanket snow/glaciers in the Himalayan region that are responsible for the accelerated melting of Himalayan glaciers (Gautam et al., 2011, 2013; Kayetha et al., 2007; Prasad & Singh, 2007a, 2007b). Frequent dust storms are known to influence the Indian monsoon, climate, hydrological system, and radiative forcing (Kaskaoutis, Gautam, et al., 2012; Kaskaoutis, Houssos, et al., 2018; Kaskaoutis, Kharol, et al., 2011; Kaskaoutis, Kosmopoulos, et al., 2012; Kaskaoutis, Prasad, et al., 2012; Kaskaoutis, Singh, et al., 2012; Pandey et al., 2017; Patil et al., 2018; Ramanathan et al., 2001; Vinoj et al., 2014). Recently, Kedia et al. (2018) have used the Weather Research and Forecasting model with chemistry and studied the impact of an intense dust storm (on 1–2 April 2015) that originated from the Arabian Peninsula. The model results show pronounced changes in aerosol optical, physical, and radiative properties over the Indian subcontinent and adjoining regions. Similar results were observed by Bhattacharjee et al. (2007) and Prasad and Singh (2007a, 2007b). Further, Kedia et al. (2018) have found that dust aerosols modulate atmospheric heating rates, which was also observed to cause tropospheric warming in the month of May over the northwestern parts, covering Pakistan and India (Gautam et al., 2009). The dust storms while traveling over the Arabian sea blanket the seawater with dust particles that enhance chlorophyll blooming (Kayetha et al., 2007; Singh et al., 2008). In addition, dust storms can severely affect air quality and concentrations of $PM_{2.5}$ and PM_{10} with far-reaching consequences on human health.

Premonsoon dust events have been observed and studied over the north-western parts of India since the late eighties (Middleton, 1986). The study of impacts of dust in IGP and the adjacent regions is important, as over 900 million people live in this area. Given the widespread impact of dust on several key energy balance parameters, it is important to understand and study how these parameters change before, during and after heavy dust events. This becomes more relevant especially when we have three back-to-back severe dust storm events, which are unprecedented in recent history. Hence, in this study, we have carried out detailed analysis of atmospheric, meteorological, and aerosol optical parameters associated with three dust storms that occurred in May 2018, using satellite, ground stations, and AErosol RObotic NETworks (AERONET) data. Pronounced changes in the aerosol optical properties (aerosol optical depth and angstrom exponent (AE); Dey et al., 2004; Gautam et al., 2009; Kumar et al., 2014; Prasad et al., 2007; Singh, 2014), carbon monoxide (Bhattacharjee et al., 2007), water vapor concentrations (Prasad et al., 2007), and meteorological parameters (Chauhan et al., 2016; Prasad et al., 2007; Zheng & Singh, 2018) have been observed along the dust tracks over the IGP, compared to ambient background values.

2. Dust Events During May 2018

The IGP experienced a sequence of dust storms, which occurred on 2–3, 7–8, and 12–13 May 2018 (hereafter referred to as DE1, DE2, and DE3, respectively). These severe dust storms that northern India experienced in May 2018 started around 26 April and reached its maxima on 13 May 2018. Figure 1 shows true color surface reflectance composite of red, green, and blue bands from the Terra sensor onboard the NASA Earth Observing System (EOS) MODIS platform, for 28 April, 3 May, and 13 May, respectively. These images were taken from NASA Global Imagery Browse Services, accessible from NASA Worldview (https://worldview.earthdata.nasa.gov). This dust originated over the Arabian Peninsula and made its way to west and southwestern parts of India through long-range transport. Another branch originated from northwestern regions of Iran and Pakistan and Thar desert in northwestern India. After entering through the western parts of India, the dust spread in the IGP, affecting the air quality of major cities and rural areas.

Two of these dust storms were deadly that killed more than 125 people and injured many. With the strong wind, houses were damaged, trees were uprooted, and electric poles were broken, which caused a fire in one of the villages. Soon after the dust storm, heavy rainfall and lightning occurred. The air quality worsened in many cities, in Rajasthan, Delhi, Agra, and Lucknow. More than 70 flights to Delhi had to be diverted. People living in the IGP region had not experienced dust storms of this magnitude in the last three decades. Soon after the dust storm, the Indian Government offered assistance to the families and made efforts to restore power in the affected areas.

The first dust storm (DE1) hit the northern states of India, that is, Uttar Pradesh, Rajasthan, Delhi, and Haryana between 2 and 3 May and claimed more than 125 lives and injured hundreds. According to the Indian Meteorological Department, the cyclonic winds reached speed up to 100 km/hr during this dust storm. The second dust storm (DE2) hit between late night of 7 May and early morning of 8 May. No fatality was reported during this dust storm. The dust storm was accompanied by hail and rain this time. The third

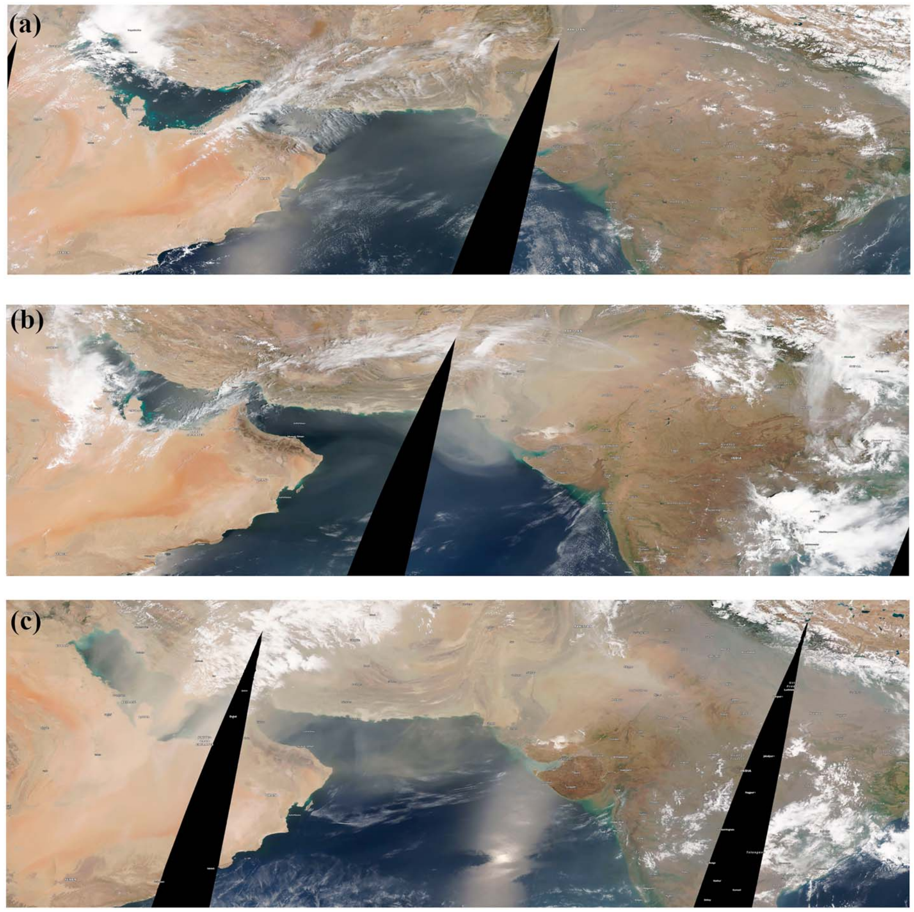

Figure 1. True color corrected reflectance imagery derived from the Terra sensor onboard the NASA Earth Observing System MODIS platform for (a) 28 April, (b) 3 May and (c) 13 May (image courtesy: Global Imagery Browse Services, https://worldview.earthdata.nasa.gov).

dust storm (DE3) hit in the evening of 12 May around 05:00 pm Indian Standard Time, and this storm claimed more than 30 lives in Bareilly District of Uttar Pradesh.

3. Data Used

In the present study, we have used data from space platforms, ground stations, and global climate models. The AERONET Program (http://aeronet.gsfc.nasa.gov/) aims to study aerosols through ground sun photometers, mainly to validate aerosol optical properties, retrieved from satellites (Holben et al., 1998). The NASA AERONET team calibrates the Sun photometers, which are deployed under this program. These data are widely used to understand aerosols characteristics. We have used level 1.5 and version 3 data (direct Sun algorithm) for AERONET stations located in Kanpur (26.51°N, 80.23°E), Jaipur (26.91°N, 75.81°E), Gandhi College (25.87°N, 84.13°E), Delhi (28.59°N, 77.22°E), Karachi (24.87°N, 67.03°E), and Lahore (31.54°N, 74.32°E; Figure 2), obtained through the NASA AERONET website (http://aeronet.gsfc.nasa.gov/). We have used total column aerosols properties, aerosol optical depth (AOD; $\tau_{a500\ nm}$), Angström exponent ($\alpha_{470–870\ nm}$), and water column, volume particle size distribution (dV/dLnR) from the AERONET stations. The detailed methodology of retrieval of aerosol parameters from AERONET stations are discussed in Dubovik and King (2000) and Dubovik et al. (2000).

We have used the balloon radio-sounding data provided by University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html) to analyze the vertical profile of meteorological parameters such as air temperature and wind speed and their association with dust storm over the area of study. The radio-sounding data are available daily for two times morning (00 Z; Indian local time 05.30 am) and evening (12 Z; Indian local time, 05.30 pm).

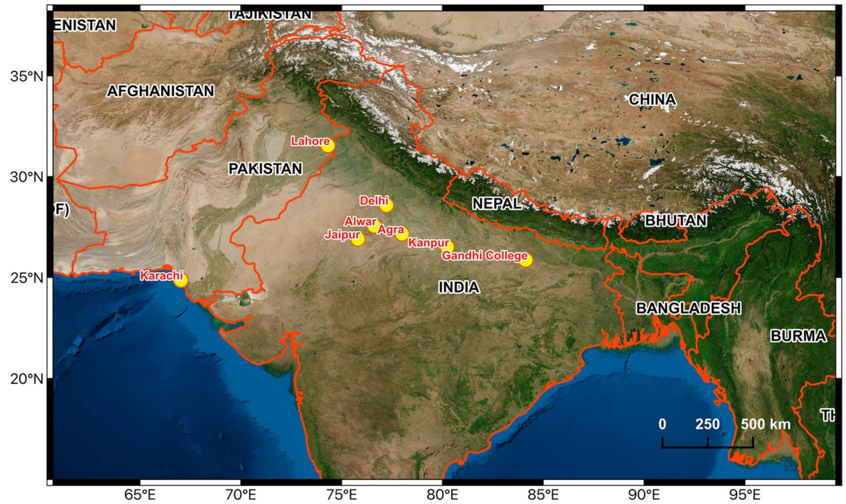

Figure 2. Locations of ground and Aerosol Robotic Networks stations that have been used in the present study.

The particulate matter data (both $PM_{2.5}$ and PM_{10}) for different locations have been obtained from the Central Pollution Control Board, India (http://cpcb.nic.in) as well the United States Embassy in Delhi (https://in.usembassy.gov/embassy-consulates/new-delhi/air-quality-data/). The ground station data for Ozone (O_3), for Delhi and Kanpur, have been taken from the OpenAQ site (https://openaq.org). These data represent the spatial and temporal mean of O_3, averaged daily, over multiple ground stations falling within each city. Individual station data was carefully monitored to remove all invalid values.

Satellite-derived profiles of various trace gases like O_3, and carbon monoxide (CO), have been derived from the Atmospheric InfraRed Sounder (AIRS) onboard the EOS Aqua platform. We have used the AIRS level 3 (L3) daily product (AIRS3STD_V006; AIRS Science Team/Joao Texeira, 2013), which averages daily level 2 swath-based observations whose quality indicators mark them as "best" or "good." The AIRS instrument uses 2,378 spectral channels, between 3.74 and 15.4 μm, to estimate vertical profiles of different trace gasses and water vapor across the globe (AIRS Science Team/Joao Texeira, 2013). These are global gridded data at a spatial resolution of $1° \times 1°$ that have been obtained from the NASA Goddard Data and Information Services Centre. The AOD at 388 and 500 nm and the aerosol index (AI) are derived from the Ozone Monitoring Instrument sensor onboard NASA's EOS Aura space platform. Two specific products, the $1° \times 1°$ OMAERUVd and OMTO3d daily, L3 data set, have been used to obtain the AOD and AI metrics, respectively (Bhartia, 2012; Torres, 2008).

Estimates of daily averages of vertical velocity, hereafter referred to as Omega (Pa/s), have been obtained from the National Centre for Environment Prediction/National Centre for Atmospheric Research Reanalysis 1 data. The National Centre for Environment Prediction/National Centre for Atmospheric Research Reanalysis uses advanced data assimilation system to give out analysis/forecast data since 1948 to present (Kalnay et al., 1996). The daily Omega values we have used for this study are averages over four time steps of 0Z, 6Z, 12Z, and 18Z and are available at a spatial resolution of $2.5° \times 2.5°$ grids. These data were obtained from NOAA Earth System Research Laboratory (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html).

Wind velocity, rainfall, and visibility data have been obtained from the online portal of NOAA's National Centres for Environmental Information (https://www.ncdc.noaa.gov).

4. Results

4.1. Rain Events Following Dusts

In the past, soon after the dust storms, scattered rains have been observed (Dey et al., 2004; Prasad & Singh, 2007a, 2007b). Similar rain events were observed for these three dust events in May 2018 (Figure 3). We have

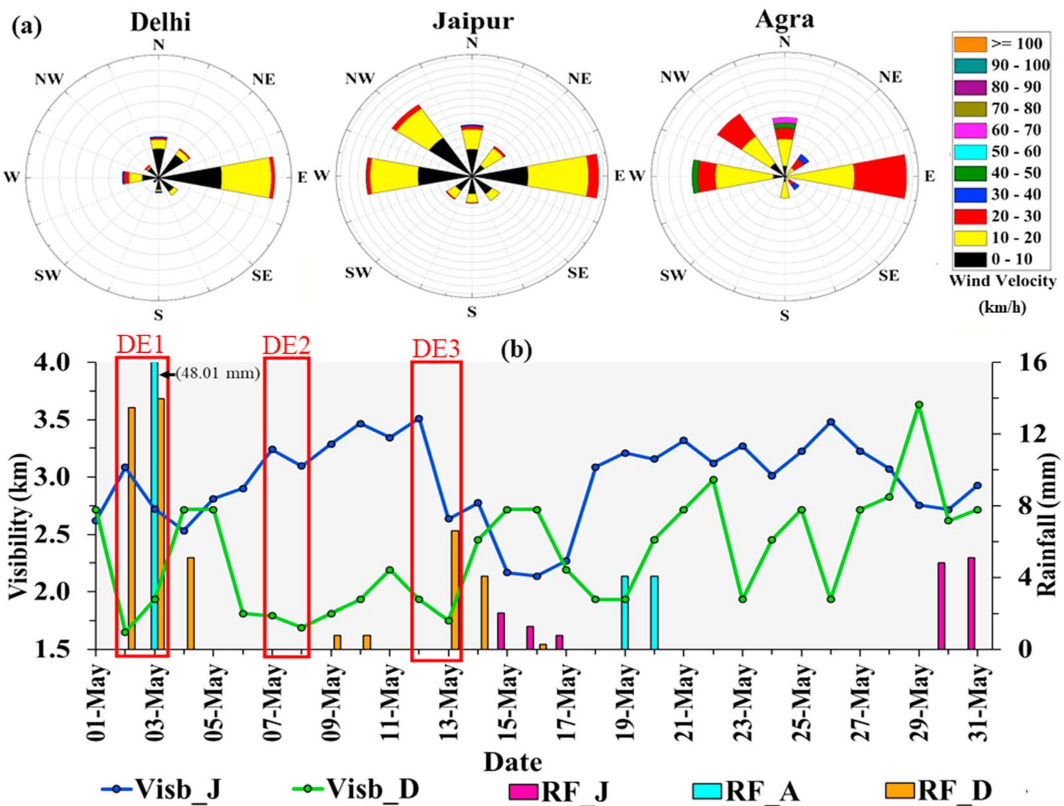

Figure 3. (a) Wind rose diagrams showing dominant westerly winds over Delhi, Jaipur, and Agra; (b) daily rainfall observed in Jaipur (RF_J), Agra (RF_A), and Delhi (RF_D) along with visibility at Jaipur (Visb_J), and Delhi (Visb_D). The rectangles in red demarcate the duration of the three dust events, DE1, DE2, and DE3, respectively.

observed rainfall commencing or peaking in Delhi following these dust events. At Jaipur and Delhi, the visibility is seen to be affected on most of the dust days. Delhi shows this decrease in visibility more consistently, and a decrease in visibility by about 35–40% is observed when compared to normal visibility values. The visibility data used here are daily average data, so sharp changes in visibility are not seen.

4.2. Variation in Meteorological Parameters

Figure 4a shows the relative humidity from the AIRS, over Delhi and adjoining areas. We observed an increase in water vapor that extends up to the upper troposphere, with each dust event. The most prominent changes in relative humidity are observed between pressure levels 825 to 575 hPa, which is mostly in the middle troposphere region. We observe a lag in the increase of relative humidity with increase in the middle troposphere typically following the day of the major dust event. This is particularly true for DE1 and DE2, where we observe a steep increase in the middle troposphere taking place about 1–2 days following the event. Each prominent dust event is associated with intense uplift in the lower troposphere that is responsible for the advection of water vapor (Figure 4a). The zonal anomaly of Omega (Pa/s), computed over Delhi (Figure 4b) shows episodes of intense uplift, marked by negative Omega anomalies of −0.1 Pa/s or less. These are followed by relative stability or subsidence. The water vapor is enhanced in the middle troposphere, following this intense uplift phases, when the water vapor advection stabilizes in the middle troposphere.

Vertical profiles of air temperatures, derived from the radiosonde data for each of the three main dust events, are shown in Figure 5. For clarity, we have only shown the daytime profiles. In each case, we observe a rise in temperature of up to 5 °C, on the day of the dust event or 1 day prior. The increase in temperature prevails over most of the lower and middle troposphere and creates the strong vertical advection pattern (Figure 4b).

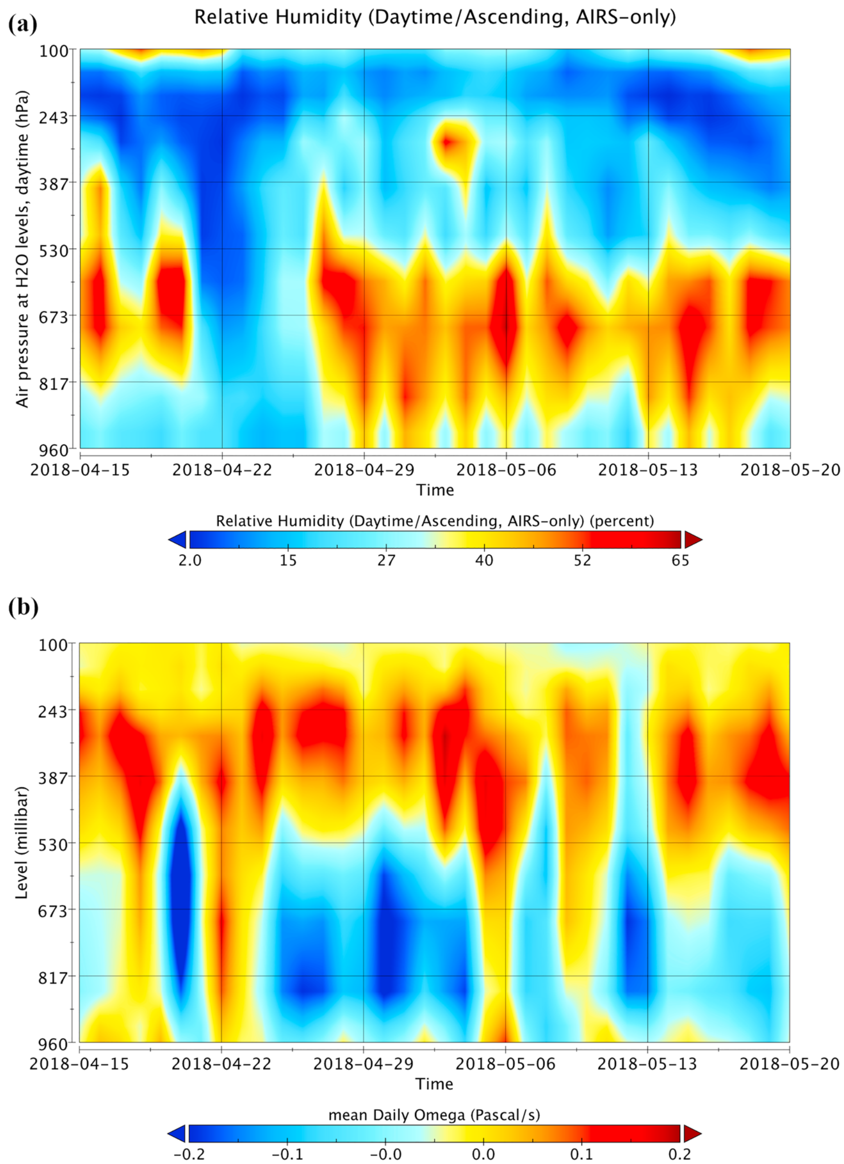

Figure 4. Pressure time variations of (a) Atmospheric InfraRed Sounder (AIRS) relative humidity (percentage) and (b) Omega (Pa/s) zonal anomalies, computed over a bounding box cantered on the city of Delhi. Phases of intense vertical advection seen from variations in Omega are responsible for lifting water vapor to middle and upper troposphere where they settle following the return to stability.

4.3. Variation of Aerosol Characteristics

Figure 6a shows the AOD at 388 and 500 nm and ultraviolet (UV) AI derived from Ozone Monitoring Instrument sensor, composited over 25–30°N and 72–82°E. A gradual increase in AOD from 26 April onward is observed, till it culminates with extremely high AOD values on 13 May. We also see smaller peaks of AOD and AI values, immediately after 1 May and around 8 May, coinciding with the first two dust events (DE1 and DE2), between 2–3 May and 7–8 May, respectively. The final dust event in this series, which took place between 12–13 May, is observed to produce the maximum increase in AOD and AI values. In each case we see a peak in AOD and AI values during the actual dust event that is followed by a sharp decrease, caused by wet deposition. Figure 6b shows variations of AOD, AE, and water vapor (cm) during 1 April to 15 May 2018 for Karachi, Lahore, Delhi, Jaipur, Kanpur, and Gandhi College AERONET stations. A gap in the data shows unavailability of data in some of the stations. Dust and coarser particles are characterized by lower AE

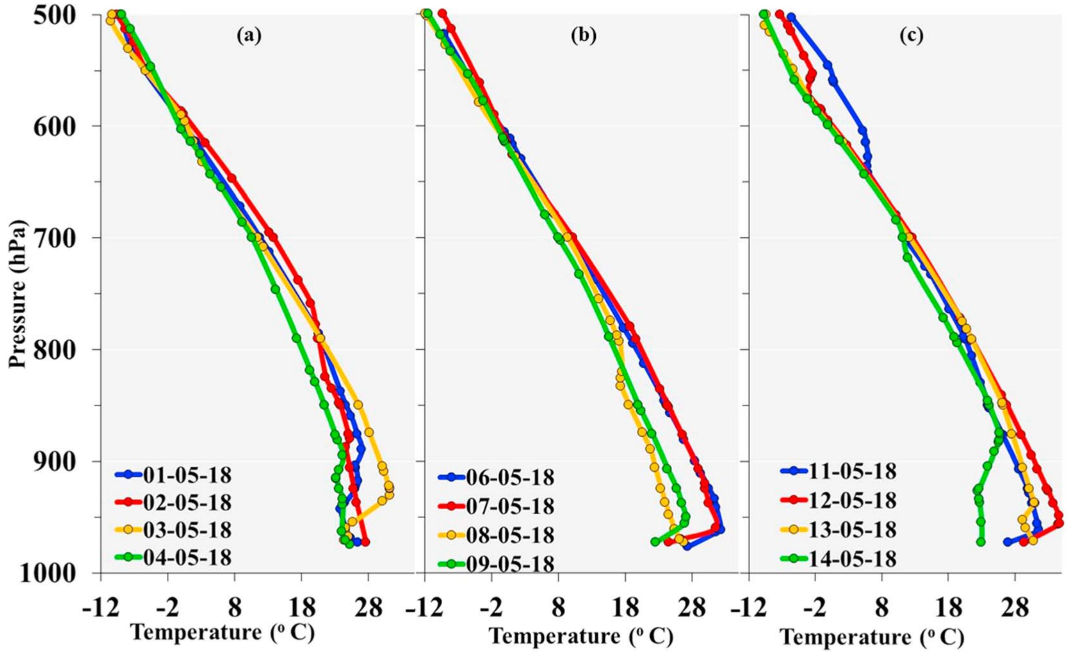

Figure 5. Vertical profiles of air temperature (°C) over Delhi for 4-days window, centered on three dust events of (a) 3 May (DE1), (b) 7 May (DE2), and (c) 13 May (DE3).

values. We can see sharp drops in AE values with higher AOD and water vapor values on 3 May, during 6–8 May and finally on 13 May for all these stations. The general increase in AOD and water vapor is seen to start from 25 April 2018 onward. Moreover, elevated water vapor is observed over Delhi and Kanpur with some time lag, indicating the gradual spread of dust further inland in India.

Particle size retrieved from six AERONET stations shows the dynamics of dust particles over different stations for the periods 1–16 May 2018 (Figure 7). Karachi is located at the coast, in the direct path of dust from the Arabian Peninsula, and shows pronounced peak in the coarser particle range. On the other hand, Gandhi College shows less peak in the coarser particle range. Gandhi College and other areas of IGP located further toward the east get influenced by southeasterly winds from the Bay of Bengal toward the end of spring and is less influenced by dust events from west. Most of the other stations display a bimodal distribution of the particle size, but we can see the gradual decrease of the coarse particles and increase of the finer particles from Karachi to Lahore or Delhi and beyond in the eastern locations of Kanpur and finally to Gandhi College. The dust events, DE1 and DE3, were prominent, and peaks were observed in the coarser particle range for Karachi, Lahore, Delhi, and Kanpur.

4.4. Changes in Air Quality Associated With Dust Storms

Figure 8 shows the $PM_{2.5}$ variation from two stations in Delhi, one over Agra in Uttar Pradesh, southeast of Delhi, and one in Jaipur from the state of Rajasthan. Both the stations from Delhi (USEMBDEL and AVIHDEL) show a rise in $PM_{2.5}$ for DE2 and DE3. The impact of DE3 is higher with a broader peak observed in $PM_{2.5}$. We observe small increase in $PM_{2.5}$ in Agra while Jaipur shows small positive departures from background values during these three dust events. The increase in Jaipur is not clearly visible, as dust inflow in Jaipur during the premonsoon months are more continuous, given its vicinity to the Thar desert. The increase in concentration at the time of dust storm is immediately followed by a sharp decrease, in most cases, because of wet deposition by rain that occurs after each storm. The variations in PM_{10} for Delhi and Jaipur, as shown in Figure 9, is similar to Figure 8, showing prominent increase in Delhi during dust events, DE2 and DE3. Figure 9 also shows sharp troughs, because of wet deposition similar to Figure 8, following each peak. The variations of $PM_{2.5}$ and PM_{10} show that while Delhi was most affected, other cities in India, to the east and south of Delhi, were not affected to that extent. This is similar to what we have

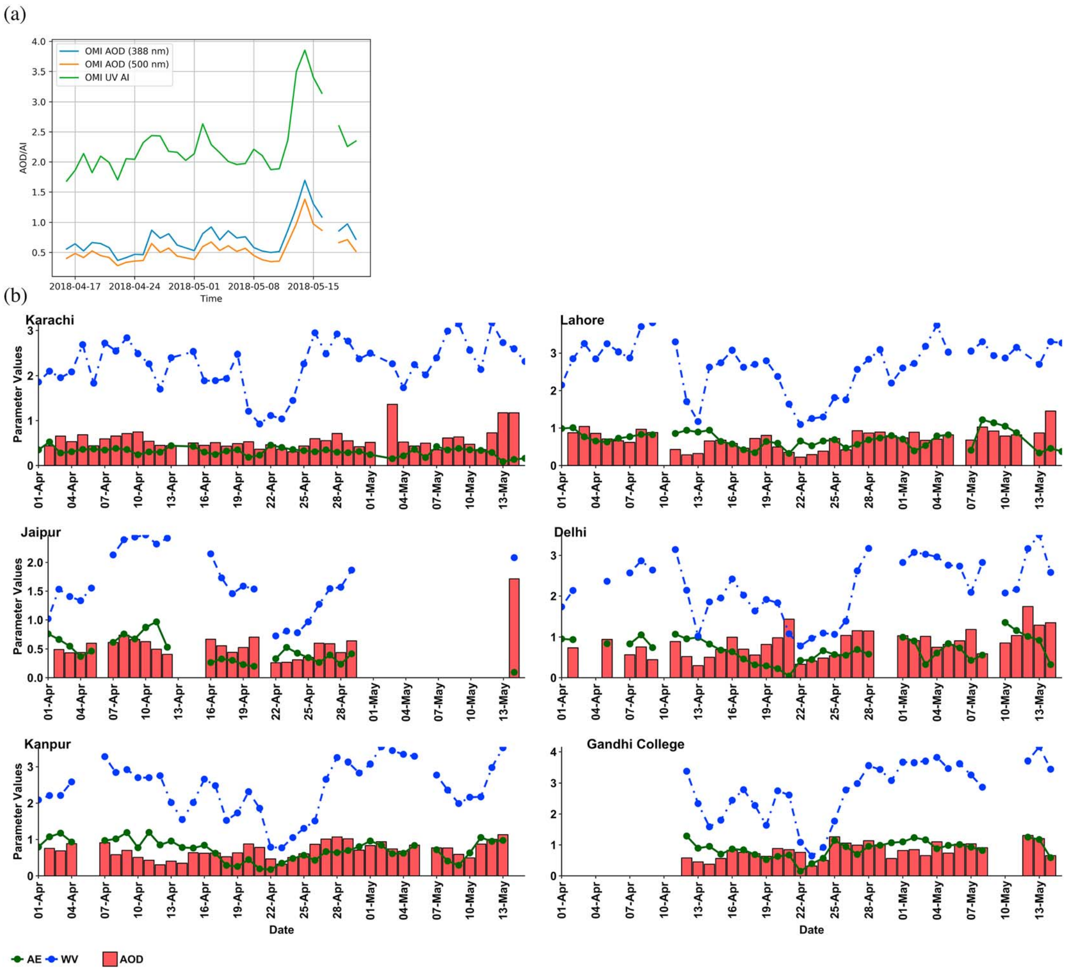

Figure 6. (a) Daily variations of aerosol optical depth (AOD) at 388 and 500 nm and aerosol index (AI), computed over 25–30°N and 72–82°E. This shows the dust event on 13 May (DE3) to be the most prominent of all the three events. (b) Variations of AOD (500 nm), AE (440–870 nm), and water vapor cm are shown during 1 April to 15 May 2018 for Karachi, Lahore, Jaipur, Delhi, Kanpur, and Gandhi College Aerosol Robotic Networks stations. The three dust storm events (3, 8, and 13 May 2018) show higher AOD and water vapor (WV) and low AE. Higher AOD and low AE are characteristics of dust. The dust events are followed by higher water vapor, when scattered rains were experienced. Gap shows non availability of data. OMI = Ozone Monitoring Instrument.

observed from the particle size distributions (Figure 7). Interestingly, we cannot detect any substantial increase in $PM_{2.5}$ or PM_{10} in Delhi from DE1. The cause of this can be inferred from the back trajectories, calculated for Delhi, for all three dust events. These three sets of back trajectories are calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory model (Draxler & Rolph, 2003).

For each day, the Hybrid Single Particle Lagrangian Integrated Trajectory model was run for 120 hr using the forecast model data from the $1° \times 1°$ Global Assimilation System data. Figure 10 shows the frequency of back trajectory crossings for two dust events on 3 (DE1) and 8 May (DE3), respectively; we have not shown the same for 13 May for the sake of brevity. We can see that the Delhi wind pattern on 8 and even on 13 May (not shown) was primarily dominated by dust storms coming in from west and southwest. However, on 3 May, in addition to these northwest-southwest wind components, there was a substantial southeasterly wind component that originated from the Bay of Bengal. Hence, the dilution in the dust-bearing wind, caused by changes in the dominant wind pattern over Delhi on 3 May, resulted in less increase in particulate matter for DE1.

As discussed in the earlier sections, these dust storms cause major changes in the wind speed, temperature, and vertical advection patterns, resulting in changes in concentrations of some greenhouse and trace gases, some of which are harmful to air quality. Figure 11 shows the departures from normal of CO

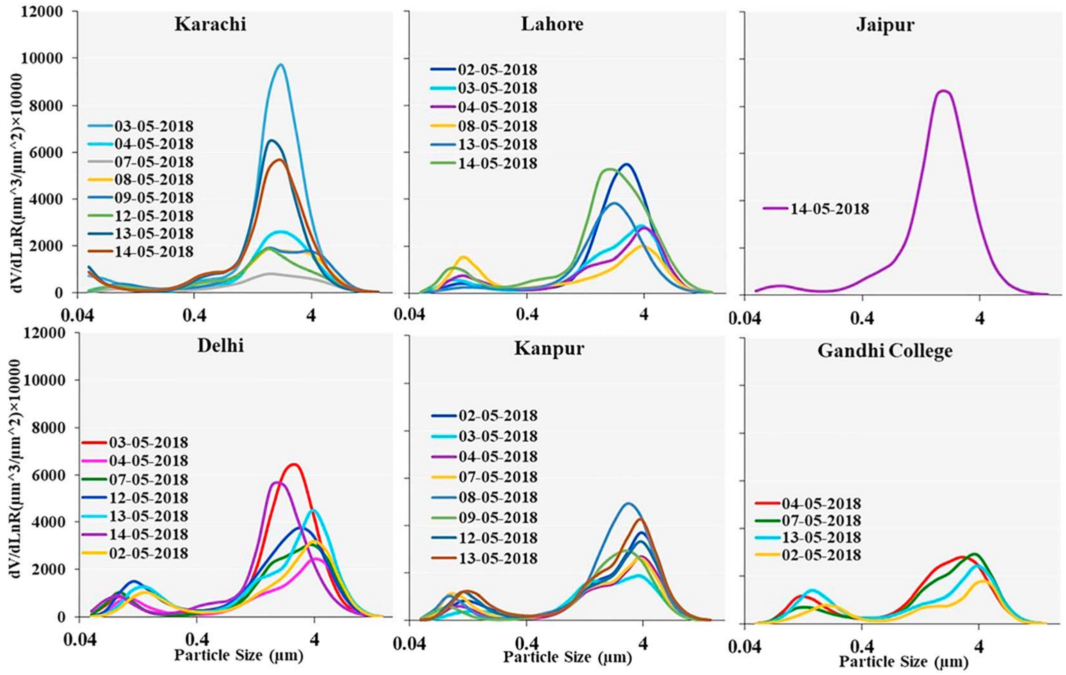

Figure 7. Volume size distributions of aerosols, obtained for different Aerosol Robotic Networks stations. It shows enhancement of coarse particles during dust storms at different Aerosol Robotic Networks stations; the volume density of coarser particles is higher at Karachi or Lahore and decreases as the dust reaches Delhi and beyond.

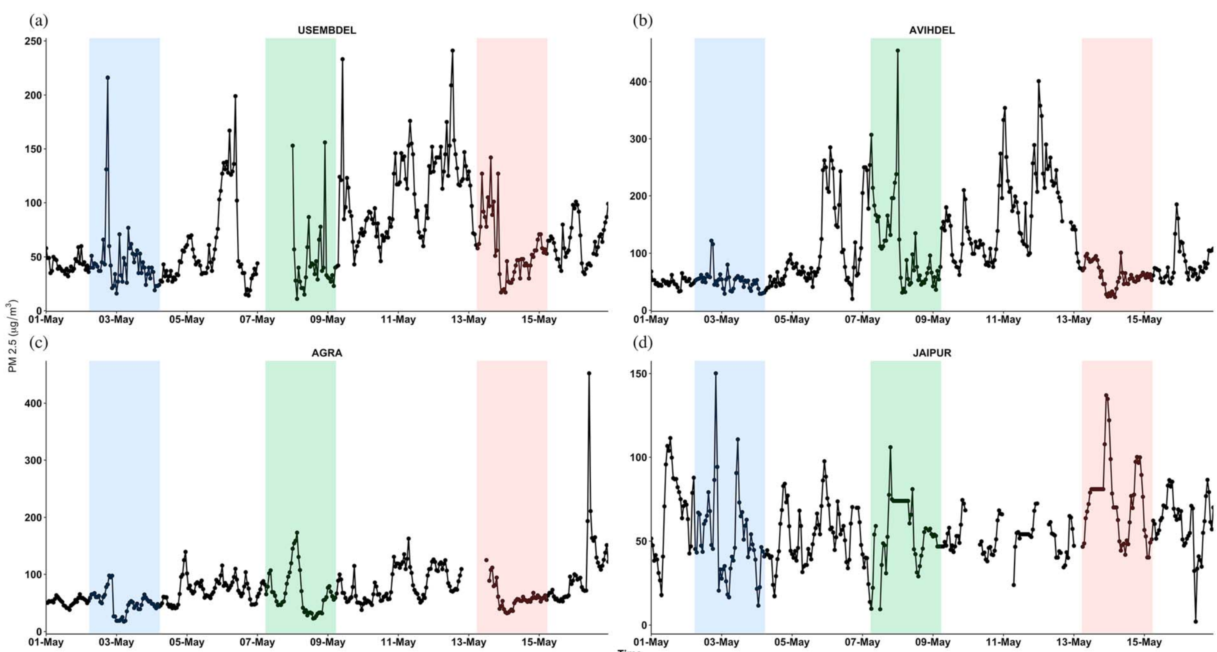

Figure 8. Changes in $PM_{2.5}$ ($\mu g/m^3$) recorded from four ground stations, during the three dust events. The ground stations shown are from (a) U.S. Embassy Delhi (USEMBDEL); (b) Anand Vihar, Delhi (AVIHDEL); (c) Agra; and (d) Jaipur. The U.S. Embassy in Delhi maintains the USEMBDEL station while the other three stations located in Anand Vihar, Delhi; Agra; and Jaipur are maintained by Central Pollution Control Board, India. The shaded areas represent the duration of the three dust events: blue, DE1; green, DE2; and red, DE3.

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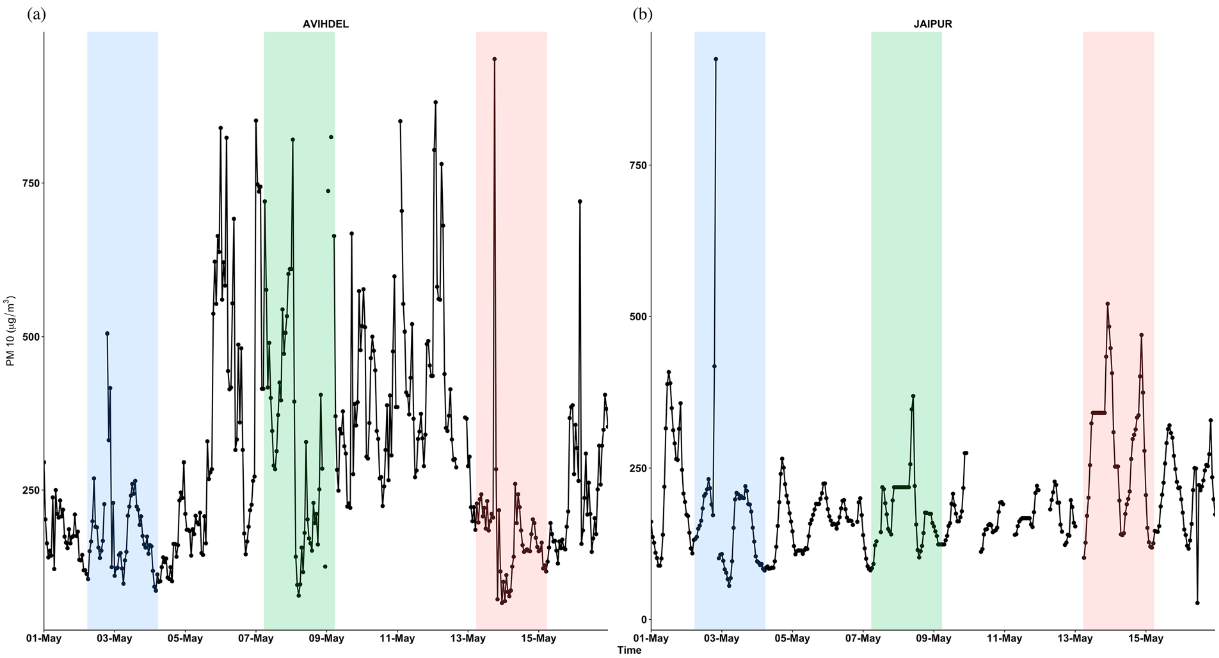

Figure 9. Changes in PM_{10} ($\mu g/m^3$) recorded for (a) a station located in Anand Vihar, Delhi (AVIHDEL), and in (b) Jaipur. The shaded areas represent the duration of the three dust events: blue, DE1; green, DE2; and red, DE3.

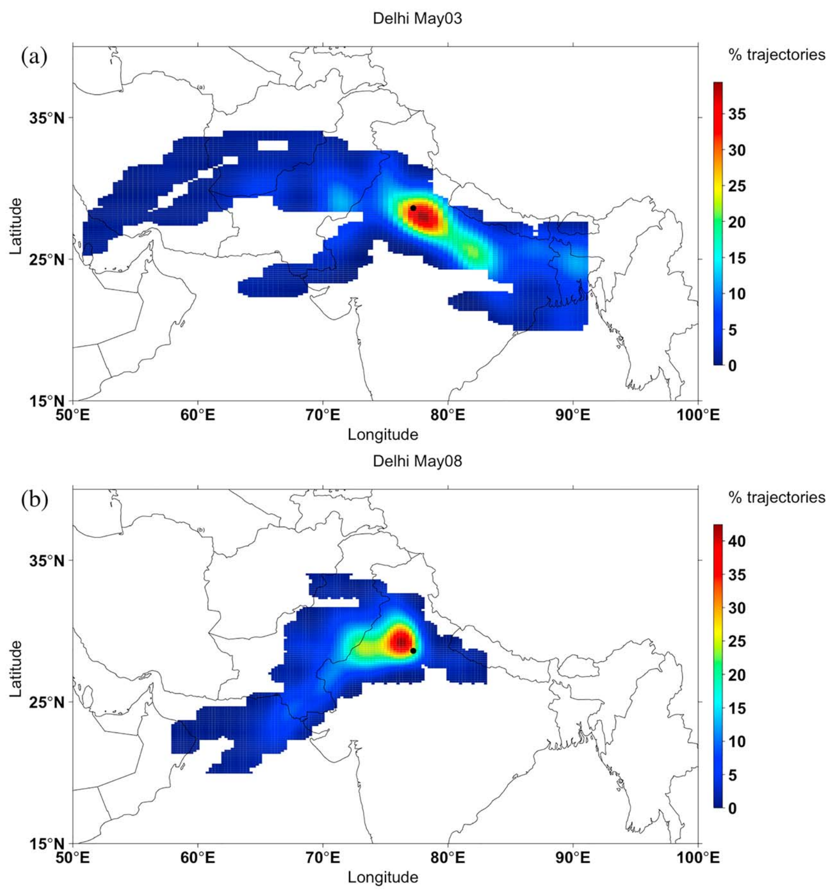

Figure 10. Frequency of back trajectories for two of the dust storm events on (a) 3 May and on (b) 8 May. Delhi, the destination location for these back trajectories, is marked with a black circle.

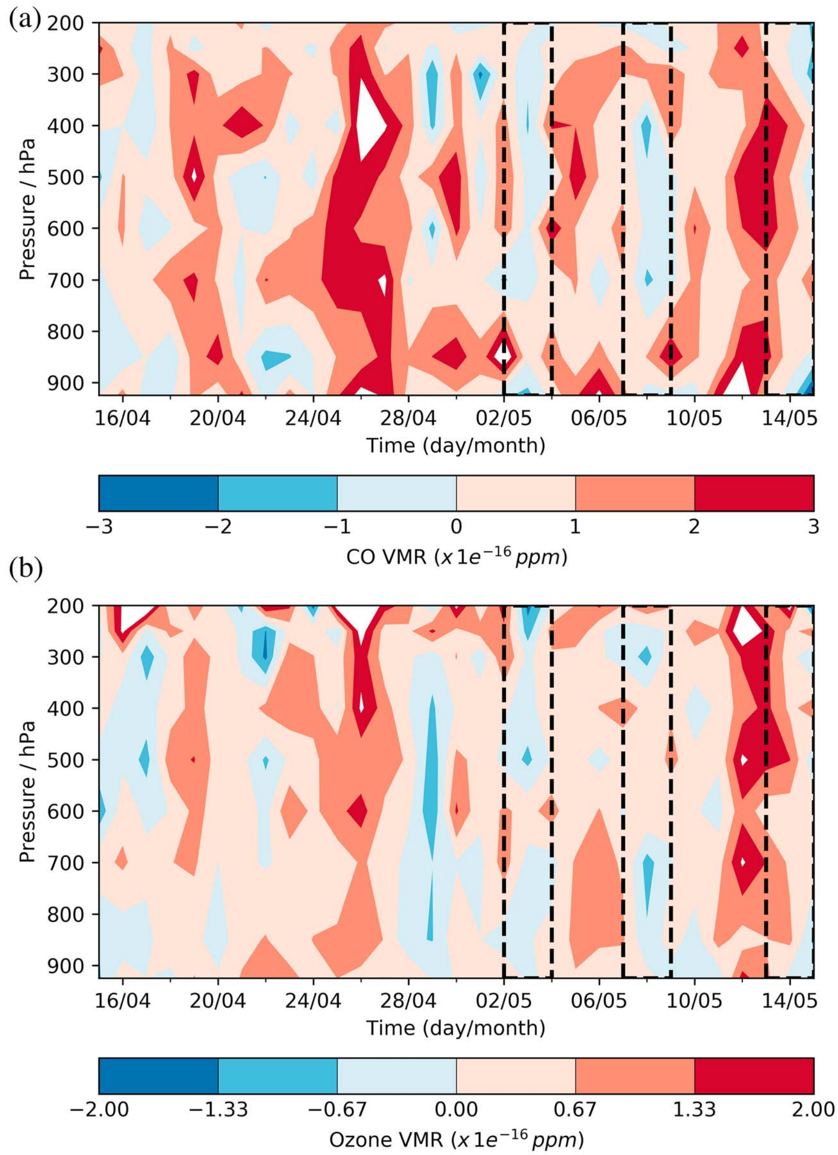

Figure 11. Pressure-time variation showing anomalies in (a) carbon monoxide (CO) and (b) O_3 volume mixing ratio (VMR), derived from the atmospheric infrared sounder ascending (daytime) data. The dotted lines represent the duration of the three dust events: DE1, DE2, and DE3.

(Figure 11a) and O_3 (Figure 11b) volume mixing ratio, over 25–29°N and 72–82°E during 4 April to 15 May. The mean over the bounding box was subtracted at each pressure level and time step to obtain these anomalies.

We observe an increase in CO and O_3, relative to nominal background values, immediately following the uplift associated with the main dust events when high pressure develops in the upper to middle troposphere. In all cases, we see that the strongest increase was after DE3. A similar increase is also seen around 26 April that coincided with another dust storm that preceded the three events. The correlation of an increase in surface O_3 with dust is particularly noteworthy and can be seen during other dust events as well. Plots of O_3 for Delhi and Kanpur, since the start of 2017, show an increase in O_3 during the premonsoon dust season of March–May in both 2017 and 2018 (Figure 12). For Delhi, the increase is particularly strong, while the increase in Kanpur lags the increase in Delhi, indicating the gradual migration of dust storms further inward.

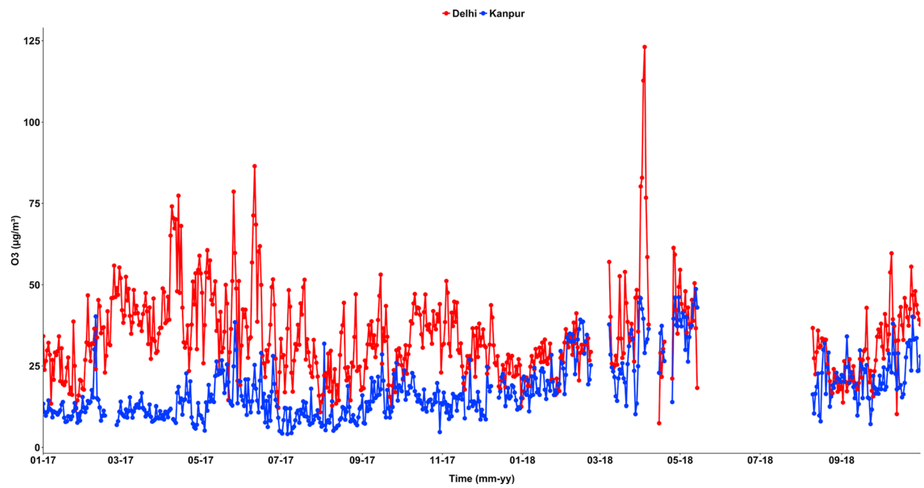

Figure 12. Plots of O_3 from Delhi and Kanpur, obtained as daily average over all available stations in each city for the period January 2017 to May 2018.

5. Discussion and Conclusion

A detailed analysis based on the ground, satellite, and model data reveals a distinct shift in aerosol loadings and size distributions, surface to lower troposphere temperature, and humidity patterns and associated changes in vertical advection. Such shifts are accompanied by changes in the distribution of major trace and greenhouse gasses all of which can lead to perturbations in radiation balance, impacting the lower and middle troposphere regions. Every dust storm is followed by a net radiative cooling at the surface while the absorption of solar radiation by the dust floating in the atmosphere can cause heating in the middle to upper troposphere region. This manifests as a drop in the surface temperature immediately after the dust storms that enhances upper air humidity (Figures 4 and 5). The large-scale shift in the radiation balance further enhances the displacement of greenhouse gasses (CO and O_3) in the middle-upper troposphere (Figure 11). Furthermore, the stability that develops in the middle to upper troposphere, immediately after the dust event (Figure 4b), causes subsidence of certain ozone precursors like CO. The mineral dust originating from Sahara and Thar desert areas are known to be rich in nitrates that convert as NOx by photoinduced "re-noxification" process (Ndour et al., 2009). Hence, an increase in ozone precursors (CO and NOx) takes place after major dust events in IGP that is likely to enhance surface O_3, which is clearly evident from ground station data (Figure 12). Such processes also increase $PM_{2.5}/PM_{10}$ and harmful greenhouse gases (O_3 and CO) at the surface that has an adverse impact on human health (Kessler, 2005; Schwartz et al., 2002).

Given the many consequences of such dust storms, which are quite frequent during premonsoon season March–June, in the northern and north-western parts of India, there is an urgent need for comprehensive monitoring or early warning system in India. In Europe and China, dust warning systems exist, but in India, no such systems exist even though each year, large swaths of people and area get adversely affected by these storms, including the capital region of Delhi. With increasing urbanization and land use/land cover changes and an increase in surface temperature across the western states, frequency of similar dust storm may increase in future. A better understanding of the impact of dust storms on short- and long-term environmental parameters, as have been attempted in this study, can lead to a better formulation of warning and prediction scenarios in the dust affected Indian region where millions of people are suffering with health problem because of poor air quality (Gupta et al., 2012; REVIHAAP, 2013).

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