

# Impact of Dust Storm on the Atmospheric Boundary Layer over Ahmedabad, a Western Indian Region .

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## Research Article

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# Abstract

The present study focuses on investigating the impacts of a sudden dust storm on the atmospheric boundary layer (ABL) over Ahmedabad (23.02°N, 72.57°E), an urban site located in the western region of India. The accumulation of dust in the atmosphere during the dust storm, originating from the Thar Desert in Rajasthan, led to the decrease in surface temperature as a consequence of dust-radiation interaction. Ambient particulate matter data obtained from Air Quality (AQ) station at Ahmedabad showed a spike of 118.5% and 44.5% in PM<sub>10</sub> and PM<sub>2.5</sub> concentrations, respectively during the event in comparison to the previous control day. Sudden exposure to an anomalous increase in particulate aerosols may cause severe impacts on human health. These surface forcing have been reflected in the stable nocturnal ABL. Backscatter signals recorded by ground-based Ceilometer Lidar at Physical Research Laboratory (PRL), showed that ABL was shallow and collapsed during the dust storm episode. Turbulence was detected in the ABL during the event which further assisted in the vertical mixing of dust aerosols in the ABL. These aerosols got trapped within the residual layer, preventing further percolation in the free atmosphere. Such sub-grid scale changes in the ABL during the dust storm were not reflected in the boundary layer height (BLH) obtained from the ERA-5 reanalysis dataset. A significant association between the ABL and the local radiative budget has been found. It has been substantiated by Coupled Ocean-Atmosphere Radiative Transfer Model (COART) simulations that showed a cooling of the surface. Thus, this study is important as it can be taken as feedback to improve local climate models with respect to dust storm meteorology.

## 1. Introduction

Dust aerosols are complex tiny entities suspended in a small fraction of the atmosphere, however, contributing substantially to the earth's radiative budget as these particles are responsible for both reflecting and absorbing shortwave and longwave radiations (Houghton and T., 1986; Kok et al., 2017). The presence of enormous amounts of dust aerosols in the atmosphere affects the optical properties of the atmosphere such as visibility (Auvermann et al., 2006, Baddock et al., 2014), biogeochemical process and severely impact human health (Zhang et al., 2014; Querol et al., 2019). A huge influx of dust is usually witnessed during dust storm episodes over a region. Dust storms are sporadic meteorological events that transport dust and sand from the hotspots and deposit to areas far away from the source owing to high wind speeds. Dust storms modulate the near-surface atmospheric dynamics and have secondary impacts on human health (Han et al. 2013). In addition to mineral dust and sand, dust storms are also responsible for carrying microbes causing harm to humans (Hua et al. 2007; Arnold 2020). Several studies have been dedicated to understanding the impact of dust storms on the atmosphere at varying scales (Iwasaka et al. 1983; Husar et al. 2001; Yang et al. 2008; Patel and Kumar 2015 and references therein). Despite the efforts, the robust understanding remains elusive. There are several techniques and methods to detect and monitor dust storms (Muhammad Akhlaq et al. 2012). Satellite observations are used to monitor the dust storms (Badarinath et al. 2007; Sharma et al. 2009; Mishra et al. 2015; Di et al. 2016; Sabbah et al. 2018; Abhram and Satapathy 2020), however intricate local effects

are usually obscured by such long distance remote sensing with modest vertical resolution, cloud presence, density and reflectivity of dust plume and so on. Wang et al. (2013) have used wind profiling radar to study the dust storm over Taklimakan desert in detail. Ming et al. (2019) have used a ground-based millimeter wave radar to detect dust storm in the same desert region, where reflectivity factors of dust storms were better estimated in real time in comparison with satellite remote sensing. However, the spatial movement of the dust storm cannot be comprehended by ground based instruments. Thus combined study of satellite and ground observations can give a clearer picture of the dust storms. Chakravarty et al. (2021) have made synergetic use of satellite, radar, ground-based observations and models to study a severe dust storm in Northern India. Aher et al. (2014) have used multiple platforms to study the effect of dust storm on aerosols in western India. The western semi-arid Indian region is frequented by dust storm episodes during pre-monsoon season, originating from the desert in Rajasthan and middle-eastern countries (Dey et al. 2004; Santra et al. 2010; Yadav et al. 2017b).

Previous studies by Sanwlani et al. (2011), Sharma et al. (2012), Singh et al. (2016), Soni et al. (2018), Chhabra et al. (2021) and references therein, have reported the study of dust storms in the western India region using satellites, aerosol spectrometers and so on, with major focus on air quality and radiative forcing. However, little is known about the impact of dust storms on the atmospheric boundary layer over this region. Atmospheric boundary layer is the lowermost region of the Earth's atmosphere that plays a crucial role in exchanging heat, energy and momentum with the free troposphere. Being closest to the Earth's surface, the boundary layer interacts with the biosphere and plays a significant role in the dispersion of pollutants and impacts the radiative budget of the planet (Garratt 1994; Li et al. 2021). Heinold et al. (2008) have studied the dust radiative response on the Saharan boundary layer using a regional dust model LM-MUSCAT. Alizadeh Choobari et al. (2012) have studied feedback of windblown mineral dust and the planetary boundary layer using WRF-CHEM regional model, during a dust event in Australia. Rémy et al. (2015) have reported the modification of boundary layer meteorology during a dust storm event in the east Mediterranean using MACC-II, WGNE and ECMWF models. Chen et al. (2017) have used the WRF-CHEM model to understand the impacts of soil dust on the boundary layer meteorology during a severe dust storm in East Asia. However, with the inherent uncertainties of the models, ground-based remote sensing instruments have an upper hand to measure boundary layer dynamics accurately during dust storm events (Todd et al. 2008; Wang et al. 2008; Yuan et al. 2019; Wu et al. 2020). The usual in-situ methodologies for measuring boundary layer characteristics such as radiosondes cannot be deployed during a dust storm event as strong winds will sway the radiosonde from its desired location. Ground-based Ceilometer lidars have proved to be significantly helpful in measuring boundary layer characteristics during dust storm events (Zhang et al. 2005; Luo et al. 2014; Uzan et al. 2020). Previous studies by Schafer et al. (2004), Emeis and Schäfer (2006), Herrera-Mejía and Hoyos (2019), and references therein have used this instrument to study the characteristics of the boundary layer.

This study is a first-of-a-kind report of the impact of a dust storm on the atmospheric boundary layer in western Indian region. Ground-based observations of the boundary layer have higher precision than reanalysis datasets. Previous studies have reported the limitations of ERA-5 in simulating the atmospheric boundary layer (Chen et al. 2020a). The boundary layer is crucial in the atmosphere as it

helps in dispersing the atmospheric pollutants (Kotthaus et al. 2018). In this study, additional information about the surface forcings and ambient particulate matter has been studied from SAFAR Air Quality Station. The dust storm impact on the local boundary layer further influenced the local radiative budget that has been supported by the COART (Coupled Ocean Atmosphere Radiative Transfer) model. This study has been organized as follows: **Sect. 2** contains a description of the data sources used in this study, followed by results and discussions in **Sect. 3**. **Section 4** includes the conclusion.

## 2. Data Sources

### *Ceilometer Lidar*

An all-weather Ceilometer Lidar (CL31) is operational at Physical Research Laboratory (PRL) (23.02°N, 72.5°E). This lidar is mono-axial, wherein the transmitting of laser and receiving of backscatter signal is done using one lens only. The lidar transmits a laser at 910 nm wavelength that can probe the atmosphere up to a height of 7.5 km. It has a very high vertical resolution of ~10 meters and can record consecutive lidar signals at a temporal resolution of ~16 seconds. More information about this CL31 Ceilometer can be found at <http://www.vaisala.com> (Sharma et al. 2016). For this study, the gradient method has been used to derive the boundary layer from the backscatter signals (Hennemuth and Lammert, 2006; Munkel et al., 2007; Lin et al., 2012).

### *Moderate Resolution Imaging Spectroradiometer (MODIS)*

In this study, visible satellite images for 26-28 April 2021 have been obtained from MODIS, an important instrument on-board the Terra/Aqua satellites. MODIS acquires data in 36 spectral bands within the wavelength range of 0.4~14.4  $\mu\text{m}$  covering visible, NIR, and TIR bands. More information about MODIS can be found at <https://modis.gsfc.nasa.gov/about/>. Aerosol Optical Depth across 470, 550, and 660 nm derived from the deep blue algorithm of MODIS retrievals has also been used in this study to estimate the impact of a dust storm on the aerosol loading over the observation site. AOD from MODIS has also been used as input to the COART model run to study the impact of a dust storm on the radiative budget.

### *2.3 SAFAR AQ Station*

An Ambient Air Quality Monitoring Station has been installed at Space Applications Centre, Ahmedabad, under Ministry of Earth Sciences, System of Air Quality and Weather Forecasting And Research (SAFAR) programme of Govt. of India. This SAFAR station is located at an urban location in western Ahmedabad and is 4 km away from the measurement site (Chhabra et al. 2020). In this study, meteorological parameters such as temperature, relative humidity, wind speed have been taken from this station. In addition, values of PM<sub>10</sub>, PM<sub>2.5</sub> and PM<sub>1</sub> have also been obtained from the AQ station.

## **ERA-5**

ERA-5 is the latest climate reanalysis produced by ECMWF, providing atmospheric parameters at the one-hour temporal resolution,  $0.25^\circ \times 0.25^\circ$  spatial resolution on 37 pressure levels (Hersbach et al. 2020). More information can be found at <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>. In this study, atmospheric boundary layer height over Ahmedabad for 26-28 April has been obtained from ERA-5 for comparison with Ceilometer observations. A one-hour moving average filter has been applied on Ceilometer observations in order to compare with hourly ERA-5 data.

## ***Coupled Ocean-Atmosphere Radiative Transfer (COART) Model***

In this study, the Coupled Ocean and Atmosphere Radiative Transfer (COART) model has been used for simulating radiative forcing estimates for the dust storm event over Ahmedabad. It calculates radiance and irradiance (fluxes) at different levels in the atmosphere and ocean. Model simulations for radiative forcing fluxes have been performed for pre to post dust storm event period using the online available COART model (<https://satcorps.larc.nasa.gov/jin/coart.html>). The model inputs included Aerosol Optical Thickness (AOT) derived from MODIS (Moderate Resolution Imaging Spectroradiometer) on-board AQUA/TERRA, mid-latitude summer atmospheric model, and OPAC (Optical Properties of Aerosols and Clouds) desert mixed layer aerosol. The solar zenith angle was computed from the Julian date, time (in UTC), and considering central latitude/longitude of the study area Ahmedabad. Spectral fluxes (irradiances) up and down ( $Wm^{-2}\mu m^{-1}$ ) at a single wavelength,  $0.55 \mu m$  corresponding to MODIS were computed along with Integrated fluxes ( $Wm^{-2}\mu m^{-1}$ ) in visible range  $0.4$  to  $0.7 \mu m$  at a spectral resolution of  $0.01 \mu m$ . The estimated radiative fluxes were analysed for temporal characteristics.

## **3 Results And Discussion**

Figure 1 shows the visible images obtained from the MODIS onboard Terra satellite during 18-26 April 2021. It is clear from Figure 1 that the observational site was swept by a dust storm on April 27. The dust storm appears in a light brown shade, partially obscuring the dark land targets on 27 April. The storm has originated from the desert plains of Rajasthan, a North-western Indian region, reported by Indian Meteorological Department (IMD), Gujarat. Figure 2 shows the one-day back trajectory of the air mass, calculated using HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model, ending at 500 m from the surface over Ahmedabad, with a new trajectory starting every 3 hours. An influx of air mass from the north of Gujarat and Rajasthan has been observed on 27 April at 1500 UTC, which coincides with the dust storm arrival time over Ahmedabad. Several places in Gujarat (adjacent to the place of origin) experienced rainfall according to IMD reports. However, due to lesser moisture content over

Ahmedabad, this took the form of a dust storm on 27 April. This sudden dust storm had several implications on the local atmosphere, radiation budget as well as human health.

In this study, we have taken 26 and 28 April as the control days and 27 April as event day. The meteorological parameters obtained from SAFAR AQ station in Ahmedabad on all three days have been studied in order to understand the impact during a dust storm. Reduced solar radiation due to the dust layer in the atmosphere led to a decrease in the surface temperature. Figure 3a shows that temperature decreases to 30.7 °C during the dust storm episode associated with cold air advection, correspondingly the relative humidity shows a small peak during the same period. From Figure 3c, strong winds of 5m/s ( $\sim 18\text{km/h}$ ) can be observed after 8 PM (local time, UTC + 5.5 hours) on 27 April over the observational site as compared to control days (Romanic and Hangan 2020). Rémy et al. (2015), in their study of the boundary layer during a dust storm in the eastern Mediterranean, found similar meteorological conditions wherein local surface winds increased due to the thermal wind effect. Reduced maximum temperature of the surface during the night also forced stronger surface winds.

Next, in this study, we have studied the changes in aerosol loading over Ahmedabad due to the dust storm. We have used ambient Particulate Matter (PM) data from the AQ station located in Ahmedabad. Figures 3d and 3e show the concentration of PM<sub>10</sub> and PM<sub>2.5</sub> over the observational site during all control and event days. PM<sub>10</sub> and PM<sub>2.5</sub> concentrations surge on the event day by 118.5% and 44.5%, respectively, as compared to the previous control day during night-time. It has been reported in previous studies that PM<sub>10</sub>, PM<sub>2.5</sub> values in urban areas are usually low during the daytime due to reduced traffic and dispersion in the mixed layer and the concentration of particulate matter aerosols peaks in the night as the boundary layer gets shallow (Yadav et al. 2014; Liu et al. 2015). During this dust storm event, long-range transportation of coarse desert dust in addition to changes in boundary layer contributed to such high values of PM<sub>10</sub> and PM<sub>2.5</sub> (746.5 and 273.8  $\mu\text{g m}^{-3}$ , respectively). PM<sub>1</sub> values increased during the dust episode. However, no significant changes in PM<sub>1</sub> have been observed as compared to control days. A similar increase in PM<sub>10</sub>/PM<sub>2.5</sub> during pre-monsoon season in Udaipur has been reported by Yadav et al. (2017) due to dust storm events. Querol et al. (2019), Achilleos et al. (2014), Aryal et al. (2012), Farahani and Arhami (2020) and references therein have also reported elevated PM concentrations during dust storm events.

Studies in the past have reported adverse health issues such as premature mortality, exacerbate bronchitis, asthma attacks, other respiratory symptoms, cardiovascular attacks, etc., if humans are exposed to the sudden increase of particulate matters (Wilson and Suh, 1997; Bell et al., 2007; Kim et al., 2015; Kumar Rai, 2015; Abel et al. 2018; Chhabra et al., 2020). Aerosol Optical Depth (AOD) values, obtained from MODIS, have been summarized in Table 1. AOD was high on 27 April, surpassing values on control days.

**Table1: AOD obtained from MODIS on-board AQUA/TERRA for 26-28 April 2021 in 1x1 grid over Ahmedabad.**

Date	Satellite	AOD (470 nm)	AOD (550 nm)	AOD (660 nm)
26 April	Terra	0.61	0.53	0.48
27 April	Aqua	0.98	0.74	0.57
27 April	Aqua	1.0	0.81	0.68
28 April	Terra	0.9	0.68	0.52
28 April	Aqua	0.43	0.38	0.35

Another direct impact of the dust storm can be seen in the atmospheric boundary layer over this region. Backscatter from the aerosols has been continuously recorded by the Ceilometer stationed at Physical Research Laboratory, Ahmedabad. Figure 4 shows the range-time intensity plot of the lidar backscatter during 26-28 April 2021. A well-formed boundary layer can be observed on 26 April, with a stable, dense nocturnal boundary layer after the sunset. Similar signatures of the convective mixed layer can be observed on 27 April, except for the shallow and collapse of the boundary layer after 8 PM. The boundary layer, however, rebuilds on the next day. The time of boundary layer collapse is not a mere coincidence with the occurrence of the dust storm (Choi et al. 2008). This dust storm event had a direct impact on the local radiative budget. Desert mineral dust is cooling in nature as they reflect the incoming solar radiation (Mallet et al. 2009), thus reducing the surface temperature (Satheesh and Krishna Moorthy 2005). However, some studies by Kok et al., (2017), Klingmüller et al., (2019), and references therein have reported the uncertainty of dust aerosols in the radiative budget.

Surface temperature and humidity are driving factors of the boundary layer (Garratt 1994). Thus, the decrease in surface temperature, due to the cooling effect of the dust layer, may have led to the sudden collapse of the stable nocturnal boundary layer after 8 PM (local time). However, strong backscatter from the dust in the residual layer within 3.5-4 km can be observed on the event day. The inversion layer prevented dust from percolating in the upper troposphere. Similar observations of dust layer trapped within the inversion layer have been reported by (Kawai et al. 2019) over the Gobi Desert. Aerosols in the nocturnal residual layer on control days show different signatures than that observed on the event day. Strong attenuated backscatter signals can be observed around 1-1.5 km on 26 and 28 April during the night, indicating accumulation of aerosols within that height range. But almost uniform backscatter is recorded by the Ceilometer from the residual layer on 27 April, indicating proper vertical mixing of dust aerosols. Wavelet analysis of the backscatter received by the Ceilometer indicated the presence of significant turbulence around 8 PM on the event day, as shown in Figure 5. Only the night time spectrum

has been shown in Figure 5 to get a clear picture of the effect of turbulence on the vertical mixing in the residual layer (Qiao et al. 2016; Chen et al. 2020; Polnikov 2020). High-speed winds observed during the episode aided dust particles from the surface to suspend in the air. The unstable boundary layer further encouraged dust to rise higher in the air. The floating dust layer cleared the next morning after the dust storm, as seen in Figure 4. This can be substantiated by lower PM values on 28 April (Figure 3 d-f) as compared to the dust storm episode.

Further, we have compared the boundary layer obtained from Ceilometer with ERA-5 reanalysis. Figure 6 shows the diurnal variation of the boundary layer from ERA5 during 26-28 April. The convective boundary layer height during daytime is comparable with the Ceilometer retrievals, however, modulations of the nocturnal boundary layer during the dust episode have not been represented in the ERA-5 reanalysis dataset. Moreover, the stable nocturnal boundary layer height has been highly overestimated in ERA5 in comparison to ground-based observations.

The association of the collapse of the boundary layer with the local radiative budget has been studied using the COART model. Figure 7 illustrates dynamics of the estimated radiative fluxes of diffused down, direct down, total downward, total upward, and the upward/downward ratio during pre (25<sup>th</sup> April) to dust storm event day (27 April) to post-event (29 April). The diffused downward flux increased with increasing aerosol loading in the atmosphere, with a peak on the dust event day. The direct downward flux decreased by 25.1% during 25-27 April and gradually increased post-event. The high AOT due to heavy dust events resulted in alterations in radiative forcing balance by intercepting the sunlight reaching the earth's surface. This is marked by a 94% increase in the up/down ratio during 25-27 April of the study period. Post-dust storm event, this up/down ratio gradually decreased with reduced AOT, thus indicating a 'local cooling effect' due to the scattering-type of aerosols in the atmosphere resulting from a thick dust storm. Chhabra et al. (2021) also reported a 'surface cooling effect' with radiative forcing effects of dust aerosols over Ahmedabad and their likely impacts on the radiative budget at a regional scale. Using WRF Chem model simulations, Kedia et al., (2018) estimated dust storm-induced cooling effect at the surface in shortwave resulted from severe dust storm over India and surrounding oceanic regions of the Arabian Sea and Bay of Bengal.

## 4. Conclusion

This is a case study on the implications of a sudden dust storm on the boundary layer over Ahmedabad. During this episode of a dust storm, the surface temperature dropped, accompanied by a rise in relative humidity and strong surface winds. These winds forced the surface dust-up in the air. The aerosol loading over this region has been studied using Air Quality data over Ahmedabad. PM10 and PM2.5 concentrations hiked by 118.5% and 44.5%, respectively as compared to the previous control day. Sudden exposure to high concentrations of particulate matter in the ambient air can cause serious health issues. In addition to changes in the meteorological parameters, the nocturnal boundary layer collapsed during the dust storm episode. The unstable boundary layer further encouraged dust higher in the air. Wind shear and differential heating in the boundary layer gave rise to turbulence during the dust storm episode,

which aided in vertical mixing throughout the residual layer. Dust aerosols got trapped in the inversion layer, which prevented the percolation of dust in a free atmosphere. The sudden accumulation of dust particles in the atmosphere reduces the surface temperature over this region as dust particles are cooling in nature. The forcing in surface temperature has been reflected in the boundary layer dynamics. This episode had a significant impact on the local radiative budget, causing surface cooling.

## Declarations

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### Conflicts of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

## References

- Abel DW, Holloway T, Harkey M, et al (2018) Air-quality-related health impacts from climate change and from adaptation of cooling demand for buildings in the eastern United States: An interdisciplinary modeling study. *PLoS Med* 15:e1002599. <https://doi.org/10.1371/journal.pmed.1002599>.
- Abhiram D, Satapathy J (2020) Extreme dust storm events monitoring using space based remote sensing through INSAT-3D. In: *AIP Conference Proceedings*. American Institute of Physics Inc., p 020004.
- Achilleos S, Evans JS, Yiallourous PK, et al (2014) PM10 concentration levels at an urban and background site in Cyprus: The impact of urban sources and dust storms. *J Air Waste Manag Assoc* 64:1352–1360. <https://doi.org/10.1080/10962247.2014.923061>.
- Aher GR, Pawar G V., Gupta P, Devara PCS (2014) Effect of major dust storm on optical, physical, and radiative properties of aerosols over coastal and urban environments in Western India. *Int J Remote Sens* 35:871–903. <https://doi.org/10.1080/01431161.2013.873153>.
- Alizadeh Choobari O, Zawar-Reza P, Sturman A (2012) Feedback between windblown dust and planetary boundary-layer characteristics: Sensitivity to boundary and surface layer parameterizations. *Atmos*

Environ 61:294–304. <https://doi.org/10.1016/j.atmosenv.2012.07.038>.

Arnold C (2020) Dust storms and human health: A call for more consistent, higher-quality studies. *Environ. Health Perspect.* 128:1–2.

Aryal R, Kandel D, Acharya D, et al (2012) Unusual Sydney dust storm and its mineralogical and organic characteristics. *Environ Chem* 9:537–546. <https://doi.org/10.1071/EN12131>.

Auvermann BW, Paila A, Bush J, et al Visibility as a Surrogate Measure of Ambient Dust Concentrations.

Badarinath KVS, Kharol SK, Kaskaoutis DG, Kambezidis HD (2007) Case study of a dust storm over Hyderabad area, India: Its impact on solar radiation using satellite data and ground measurements. *Sci Total Environ* 384:316–332. <https://doi.org/10.1016/j.scitotenv.2007.05.031>.

Baddock MC, Strong CL, Leys JF, et al (2014) A visibility and total suspended dust relationship. *Atmos Environ* 89:329–336. <https://doi.org/10.1016/j.atmosenv.2014.02.038>.

Bell ML, Goldberg R, Hogrefe C, et al (2007) Climate change, ambient ozone, and health in 50 US cities. *Clim Change* 82:61–76. <https://doi.org/10.1007/s10584-006-9166-7>.

Chakravarty K, Vincent V, Vellore R, et al (2021) Revisiting Andhi in northern India: A case study of severe dust-storm over the urban megacity of New Delhi. *Urban Clim* 37:100825. <https://doi.org/10.1016/j.uclim.2021.100825>.

Chen C, Zhang M, Perrie W, et al (2020a) Boundary Layer Parameterizations to Simulate Fog Over Atlantic Canada Waters. *Earth Sp Sci* 7:e2019EA000703. <https://doi.org/10.1029/2019EA000703>.

Chen L, Zhang M, Zhu J, Skorokhod A (2017) Model analysis of soil dust impacts on the boundary layer meteorology and air quality over East Asia in April 2015. *Atmos Res* 187:42–56. <https://doi.org/10.1016/j.atmosres.2016.12.008>.

Chen S, Qiao F, Huang C, Song Z (2020b) Contribution of surface wave-induced vertical mixing to heat content in global upper ocean. *J Oceanol Limnol* 38:307–313. <https://doi.org/10.1007/s00343-019-9003-2>.

Chhabra A, Turakhia T, Chauhan P (2021) Impacts of a Mesoscale Dust Storm on Aerosols Characteristics, Optical and Radiative Properties Over a Semiarid Region, Western India. *J Indian Soc Remote Sens* 1–9. <https://doi.org/10.1007/s12524-021-01313-w>.

Chhabra A, Turakhia T, Sharma S, et al (2020) Environmental impacts of fireworks on aerosol characteristics and radiative properties over a mega city, India. *City Environ Interact* 7:100049. <https://doi.org/10.1016/j.cacint.2020.100049>.

- Choi H, Zhang YH, Kim KH (2008) Sudden high concentration of TSP affected by atmospheric boundary layer in Seoul metropolitan area during duststorm period. *Environ Int* 34:635–647. <https://doi.org/10.1016/j.envint.2007.12.023>.
- Dey S, Tripathi SN, Singh RP, Holben BN (2004) Influence of dust storms on the aerosol optical properties over the Indo-Gangetic basin. *J Geophys Res D Atmos* 109:20211. <https://doi.org/10.1029/2004JD004924>.
- Di A, Xue Y, Yang X, et al (2016) Dust aerosol optical depth retrieval and dust storm detection for Xinjiang Region using Indian national satellite observations. *Remote Sens* 8:702. <https://doi.org/10.3390/rs8090702>.
- Emeis S, Schäfer K (2006) Remote sensing methods to investigate boundary-layer structures relevant to air pollution in cities. *Boundary-Layer Meteorol* 121:377–385. <https://doi.org/10.1007/s10546-006-9068-2>.
- Farahani VJ, Arhami M (2020) Contribution of Iraqi and Syrian dust storms on particulate matter concentration during a dust storm episode in receptor cities: Case study of Tehran. *Atmos Environ* 222:117163. <https://doi.org/10.1016/j.atmosenv.2019.117163>.
- Garratt JR (1994) Review: the atmospheric boundary layer. *Earth Sci Rev* 37:89–134. [https://doi.org/10.1016/0012-8252\(94\)90026-4](https://doi.org/10.1016/0012-8252(94)90026-4).
- Han L, Tsunekawa A, Tsubo M, Zhou W (2013) An enhanced dust index for Asian dust detection with MODIS images. *Int J Remote Sens* 34:6484–6495. <https://doi.org/10.1080/01431161.2013.802055>.
- Heinold B, Tegen I, Schepanski K, Hellmuth O (2008) Dust radiative feedback on Saharan boundary layer dynamics and dust mobilization. *Geophys Res Lett* 35: <https://doi.org/10.1029/2008GL035319>.
- Hennemuth B, Lammert A (2006) Determination of the atmospheric boundary layer height from radiosonde and lidar backscatter. *Boundary-Layer Meteorol* 120:181–200. <https://doi.org/10.1007/s10546-005-9035-3>.
- Herrera-Mejía L, Hoyos CD (2019) Characterization of the atmospheric boundary layer in a narrow tropical valley using remote-sensing and radiosonde observations and the WRF model: the Aburrá Valley case-study. *Q J R Meteorol Soc* 145:2641–2665. <https://doi.org/10.1002/qj.3583>.
- Hersbach H, Bell B, Berrisford P, et al (2020) The ERA5 global reanalysis. *Q J R Meteorol Soc* 146:1999–2049. <https://doi.org/10.1002/qj.3803>.
- Hines CO, Reddy CA (1967) On the propagation of atmospheric gravity waves through regions of wind shear. *J Geophys Res* 72:1015–1034. <https://doi.org/10.1029/jz072i003p01015>.
- HOUGHTON, T. J (1986) IPCC (Intergovernmental Panel on Climate Change). *Sci Clim Chang*.

- Hua NP, Kobayashi F, Iwasaka Y, et al (2007) Detailed identification of desert-originated bacteria carried by Asian dust storms to Japan. *Aerobiologia (Bologna)* 23:291–298. <https://doi.org/10.1007/s10453-007-9076-9>.
- Husar RB, Tratt DM, Schichtel BA, et al (2001) Asian dust events of April 1998. *J Geophys Res Atmos* 106:18317–18330. <https://doi.org/10.1029/2000JD900788>.
- Iwasaka Y, Minoura H, Nagaya K (1983) The transport and spacial scale of Asian dust-storm clouds: a case study of the dust-storm event of April 1979 (China, Japan Islands). *Tellus, Ser B* 35 B:189–196. <https://doi.org/10.3402/tellusb.v35i3.14594>.
- Kawai K, Nishio Y, Kai K, et al (2019) Ceilometer observation of a dust event in the Gobi Desert on 29-30 April 2015: Sudden arrival of a developed dust storm and trapping of dust within an inversion layer. *Sci Online Lett Atmos* 15:52–56. <https://doi.org/10.2151/SOLA.2019-011>.
- Kedia S, Kumar R, Islam S, et al (2018) Radiative impact of a heavy dust storm over India and surrounding oceanic regions. *Atmos Environ* 185:109–120. <https://doi.org/10.1016/j.atmosenv.2018.05.005>.
- Kim KH, Kabir E, Kabir S (2015) A review on the human health impact of airborne particulate matter. *Environ. Int.* 74:136–143.
- Klingmüller K, Lelieveld J, Karydis VA, Stenchikov GL (2019) Direct radiative effect of dust-pollution interactions. *Atmos Chem Phys* 19:7397–7408. <https://doi.org/10.5194/acp-19-7397-2019>.
- Kok JF, Ridley DA, Zhou Q, et al (2017) Smaller desert dust cooling effect estimated from analysis of dust size and abundance. *Nat Geosci* 10:274–278. <https://doi.org/10.1038/ngeo2912>.
- Kotthaus S, Haliouk CH, Barlow JF, Grimmond CSB (2018) Volume for pollution dispersion: London's atmospheric boundary layer during ClearFLo observed with two ground-based lidar types. *Atmos Environ* 190:401–414. <https://doi.org/10.1016/j.atmosenv.2018.06.042>.
- Kumar Rai P (2015) Multifaceted Health impacts of Particulate Matter (PM) and its management: An overview. *Multifaceted health impacts of Particulate Matter (PM) and its management: An overview*.
- Kuroda T, Medvedev AS, Yiğit E (2020) Gravity Wave Activity in the Atmosphere of Mars During the 2018 Global Dust Storm: Simulations With a High-Resolution Model. *J Geophys Res Planets* 125:e2020JE006556. <https://doi.org/10.1029/2020JE006556>.
- Li Q, Zhang H, Cai X, et al (2021) The impacts of the atmospheric boundary layer on regional haze in North China. *npj Clim Atmos Sci* 4:. <https://doi.org/10.1038/s41612-021-00165-y>.
- Lin W, Chen-Bo X, Zhen-Zhu W, et al (2012) Application of Gradient Method to Detect Height Distribution of Atmospheric Boundary Layer with Lidar. *J Atmos Environ Opt* 161.

- Liu Z, Hu B, Wang L, et al (2015) Seasonal and diurnal variation in particulate matter (Pm10 and pm25) at an urban site of Beijing: Analyses from a 9-year study. *Environ Sci Pollut Res* 22:627–642. <https://doi.org/10.1007/s11356-014-3347-0>.
- Luo T, Yuan R, Wang Z (2014) Lidar-based remote sensing of atmospheric boundary layer height over land and ocean. *Atmos Meas Tech* 7:173–182. <https://doi.org/10.5194/amt-7-173-2014>.
- Mallet M, Tulet P, Serça D, et al (2009) Atmospheric Chemistry and Physics Impact of dust aerosols on the radiative budget, surface heat fluxes, heating rate profiles and convective activity over West Africa during March 2006.
- Ming H, Wei M, Wang M (2019) Quantitative detection of dust storms with the millimeter wave radar in the Taklimakan Desert. *Atmosphere (Basel)* 10:511. <https://doi.org/10.3390/atmos10090511>.
- Mishra MK, Chauhan P, Sahay A (2015) Detection of Asian dust storms from geostationary satellite observations of the INSAT-3D imager. *Int J Remote Sens* 36:4668–4682. <https://doi.org/10.1080/01431161.2015.1084432>.
- Muhammad Akhlaq, Sheltami TR, Mouftah HT (2012) A review of techniques and technologies for sand and dust storm detection. *Rev. Environ. Sci. Biotechnol.* 11:305–322.
- Münkel C, Eresmaa N, Räsänen J, Karppinen A (2007) Retrieval of mixing height and dust concentration with lidar ceilometer. *Boundary-Layer Meteorol* 124:117–128. <https://doi.org/10.1007/s10546-006-9103-3>.
- Patel PN, Kumar R (2015) Estimation of aerosol characteristics and radiative forcing during dust events over Dehradun. *Aerosol Air Qual Res* 15:2082–2093. <https://doi.org/10.4209/aaqr.2015.02.0077>.
- Plougonven R, Teitelbaum H, Zeitlin V (2003) Inertia gravity wave generation by the tropospheric midlatitude jet as given by the Fronts and Atlantic Storm-Track Experiment radio soundings. *J Geophys Res Atmos* 108:4686. <https://doi.org/10.1029/2003jd003535>.
- Polnikov VG (2020) Model of Vertical Mixing Induced by Wind Waves. *Fluid Dyn* 55:20–30. <https://doi.org/10.1134/S0015462820010103>.
- Qiao F, Yuan Y, Deng J, et al (2016) Wave-turbulence interaction-induced vertical mixing and its effects in ocean and climate models. *Philos Trans R Soc A Math Phys Eng Sci* 374:. <https://doi.org/10.1098/rsta.2015.0201>.
- Querol X, Tobías A, Pérez N, et al (2019) Monitoring the impact of desert dust outbreaks for air quality for health studies. *Environ. Int.* 130:104867.
- Rémy S, Benedetti A, Bozzo A, et al (2015) Feedbacks of dust and boundary layer meteorology during a dust storm in the eastern Mediterranean. *Atmos Chem Phys* 15:12909–12933.

<https://doi.org/10.5194/acp-15-12909-2015>.

Romanic D, Hangan H (2020) Experimental investigation of the interaction between near-surface atmospheric boundary layer winds and downburst outflows. *J Wind Eng Ind Aerodyn* 205:

<https://doi.org/10.1016/j.jweia.2020.104323>.

Sabbah I, Léon JF, Sorribas M, et al (2018) Dust and dust storms over Kuwait: Ground-based and satellite observations. *J Atmos Solar-Terrestrial Phys* 179:105–113. <https://doi.org/10.1016/j.jastp.2018.06.006>.

Sanwlani N, Chauhan P, Navalgund RR (2011) Dust storm detection and monitoring using multi-temporal INSAT-3A-CCD data. *Int J Remote Sens* 32:5527–5539. <https://doi.org/10.1080/01431161.2010.504756>.

Satheesh SK, Krishna Moorthy K (2005) Radiative effects of natural aerosols: A review. *Atmos Environ* 39:2089–2110. <https://doi.org/10.1016/j.atmosenv.2004.12.029>.

Schafer K, Emeis SM, Rauch A, et al (2004) Determination of mixing layer heights from ceilometer data. In: Comeron A, Carleer MR, Picard RH, Sifakis NI (eds) *Remote Sensing of Clouds and the Atmosphere IX*. SPIE, p 248.

Sharma AR, Kharol SK, Badarinath KVS (2009) Satellite observations of unusual dust event over North-East India and its relation with meteorological conditions. *J Atmos Solar-Terrestrial Phys* 71:2032–2039. <https://doi.org/10.1016/j.jastp.2009.09.010>.

Sharma D, Singh D, Kaskaoutis DG (2012) Impact of two intense dust storms on aerosol characteristics and radiative forcing over Patiala, Northwestern India. *Adv Meteorol* 2012:

<https://doi.org/10.1155/2012/956814>.

Sharma S, Vaishnav R, Shukla M V, et al (2016) Evaluation of cloud base height measurements from Ceilometer CL31 and MODIS satellite over Ahmedabad, India. *Atmos Meas Tech* 9:711–719.

<https://doi.org/10.5194/amt-9-711-2016>.

Singh A, Tiwari S, Sharma D, et al (2016) Characterization and radiative impact of dust aerosols over northwestern part of India: a case study during a severe dust storm. *Meteorol Atmos Phys* 128:779–792.

<https://doi.org/10.1007/s00703-016-0445-1>.

Soni VK, Bist S, Bhatla R, et al (2018) Effect of unusual dust event on meteorological parameters & aerosol optical and radiative properties.

Todd MC, Bou Karam D, Cavazos C, et al (2008) Quantifying uncertainty in estimates of mineral dust flux: An intercomparison of model performance over the Bodélé depression, northern Chad. *J Geophys Res Atmos* 113:24107. <https://doi.org/10.1029/2008JD010476>.

Uzan L, Egert S, Khain P, et al Ceilometers as planetary boundary layer detectors and a corrective tool for ECMWF and COSMO NWP models. <https://doi.org/10.5194/acp-2019-790>.

- Wang M, Wei W, Ruan Z, et al (2013) Application of wind-profiling radar data to the analysis of dust weather in the Taklimakan Desert. *Environ Monit Assess* 185:4819–4834.  
<https://doi.org/10.1007/s10661-012-2906-4>.
- Wang YQ, Zhang XY, Gong SL, et al (2008) Surface observation of sand and dust storm in East Asia and its application in CUACE/Dust. *Atmos Chem Phys* 8:545–553. <https://doi.org/10.5194/acp-8-545-2008>.
- Wilson WE, Suh HH (1997) Fine particles and coarse particles: Concentration relationships relevant to epidemiologic studies. *J Air Waste Manag Assoc* 47:1238–1249.  
<https://doi.org/10.1080/10473289.1997.10464074>.
- Wu C, Lin Z, Liu X (2020) The global dust cycle and uncertainty in CMIP5 (Coupled Model Intercomparison Project phase 5) models. *Atmos Chem Phys* 20:10401–10425.  
<https://doi.org/10.5194/acp-20-10401-2020>.
- Yadav R, Sahu LK, Beig G, et al (2017a) Ambient particulate matter and carbon monoxide at an urban site of India: Influence of anthropogenic emissions and dust storms. *Environ Pollut* 225:291–303.  
<https://doi.org/10.1016/j.envpol.2017.01.038>.
- Yadav R, Sahu LK, Beig G, et al (2017b) Ambient particulate matter and carbon monoxide at an urban site of India: Influence of anthropogenic emissions and dust storms \*.  
<https://doi.org/10.1016/j.envpol.2017.01.038>.
- Yadav R, Sahu LK, Jaaffrey SNA, Beig G (2014) Temporal variation of Particulate Matter (PM) and potential sources at an urban site of Udaipur in Western India. *Aerosol Air Qual Res* 14:1613–1629.  
<https://doi.org/10.4209/aaqr.2013.10.0310>.
- Yang YQ, Hou Q, Zhou CH, et al (2008) Sand/dust storm processes in Northeast Asia and associated large-scale circulations. *Atmos Chem Phys* 8:25–33. <https://doi.org/10.5194/acp-8-25-2008>.
- Yuan T, Chen S, Huang J, et al (2019) Sensitivity of simulating a dust storm over Central Asia to different dust schemes using the WRF-Chem model. *Atmos Environ* 207:16–29.  
<https://doi.org/10.1016/j.atmosenv.2019.03.014>.
- Zhang JK, Sun Y, Liu ZR, et al (2014) Atmospheric Chemistry and Physics Characterization of submicron aerosols during a month of serious pollution in Beijing, 2013. *Atmos Chem Phys* 14:2887–2903.  
<https://doi.org/10.5194/acp-14-2887-2014>.
- Zhang R, Arimoto R, An J, et al (2005) Ground observations of a strong dust storm in Beijing in March 2002. *J Geophys Res D Atmos* 110:1–8. <https://doi.org/10.1029/2004JD004589>.

## Figures



**Figure 1**

Visual satellite images obtained from MODIS onboard TERRA on 26-28 April 2021. The image obtained for 27 April shows dust cover in and around the observation site.

NOAA HYSPLIT MODEL  
 Backward trajectories ending at 1500 UTC 27 Apr 21  
 GDAS Meteorological Data

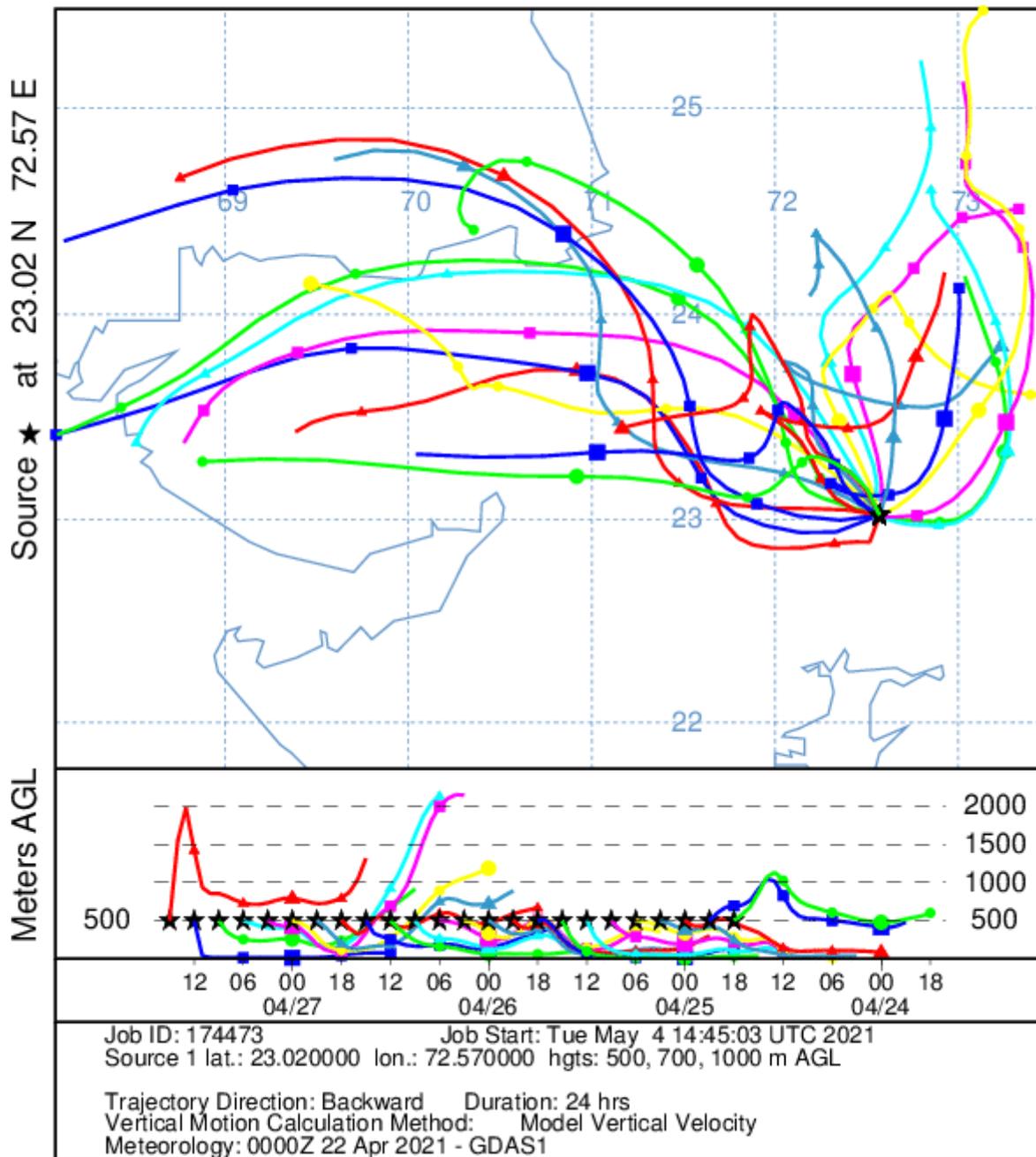


Figure 2

One-day back-trajectory of air mass ending at 500 m above the surface over Ahmedabad during 15UTC April 27, 2021.

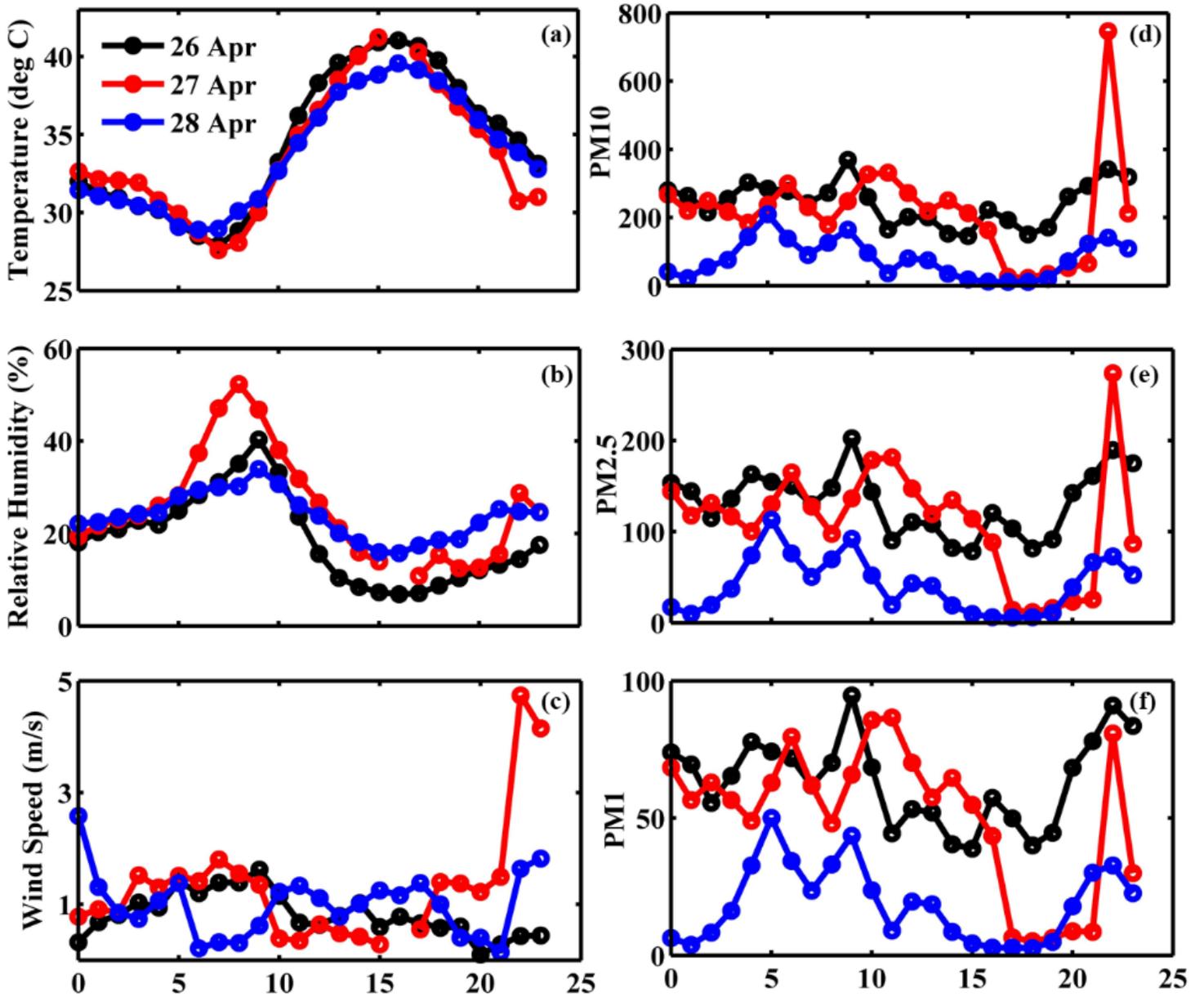


Figure 3

Time series of (a) surface temperature, (b) relative humidity, (c) wind speed, (d) PM10, (e) PM2.5, (f) PM1 obtained from SAFAR AQ station in Ahmedabad during 26-28 April.

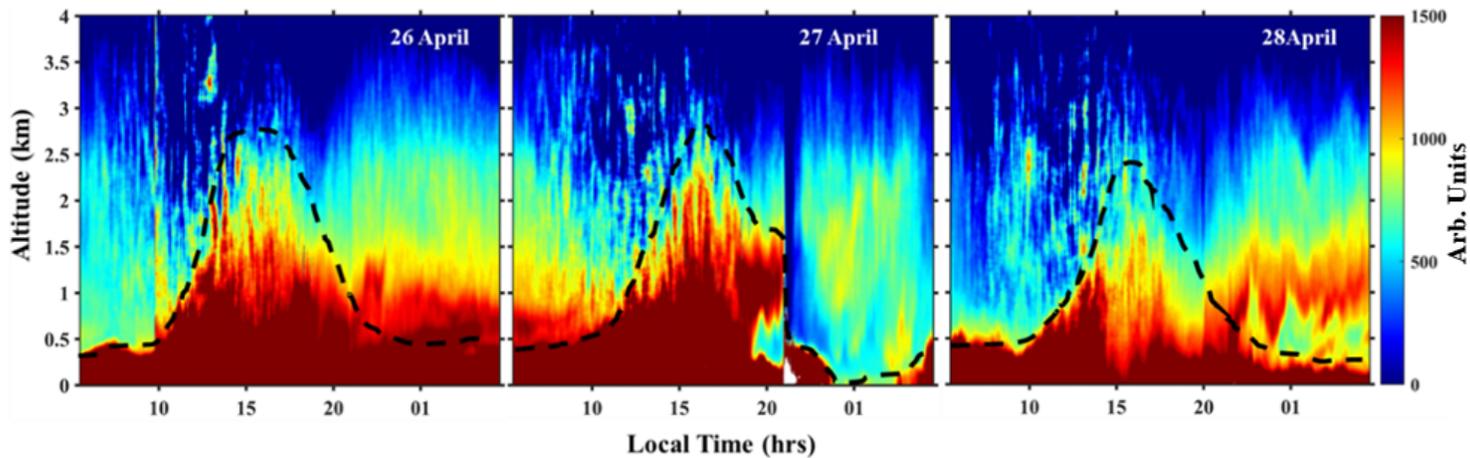


Figure 4

Range-Time intensity plot of the backscatter received by Ceilometer over Ahmedabad.

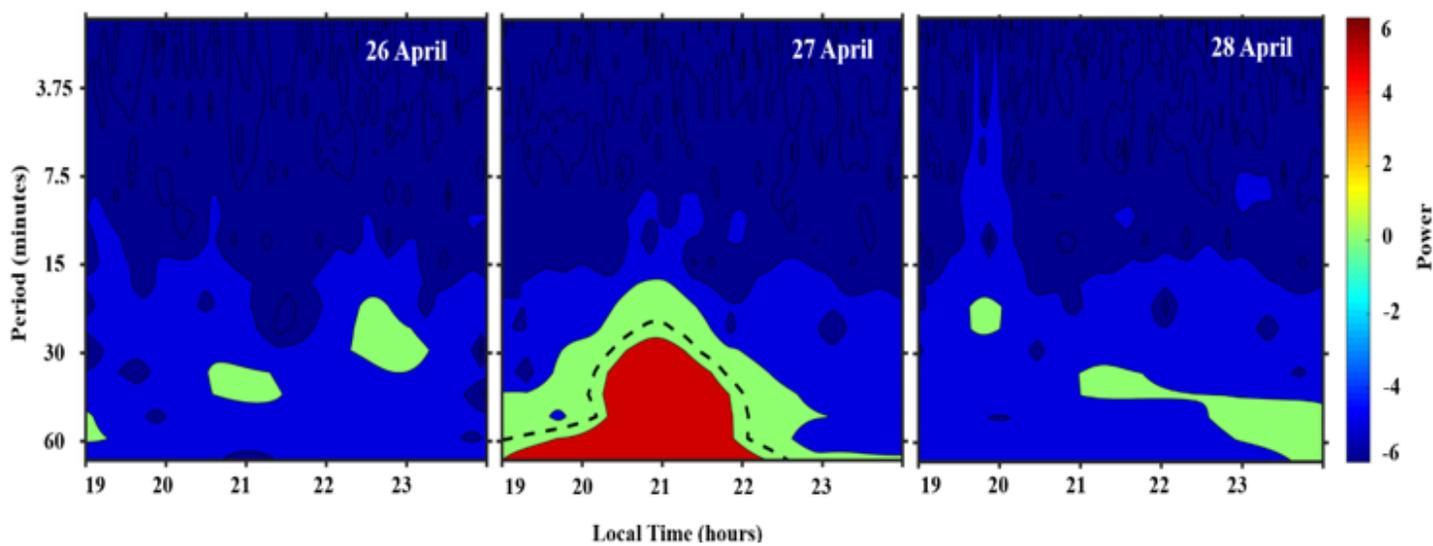


Figure 5

Wavelet power spectrum of the backscatter signals received by the Ceilometer on 26, 27 and 28 April, 2021.

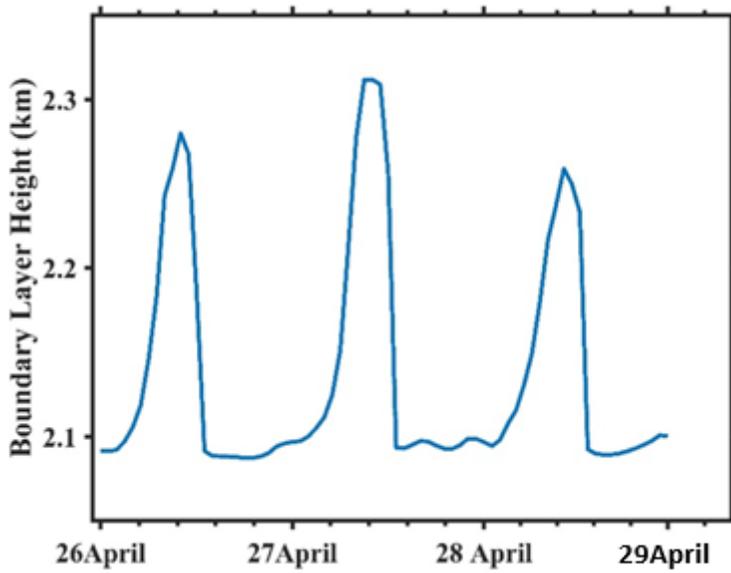


Figure 6

Boundary Layer Height obtained from ERA5 reanalysis for 26-28 April 2021.

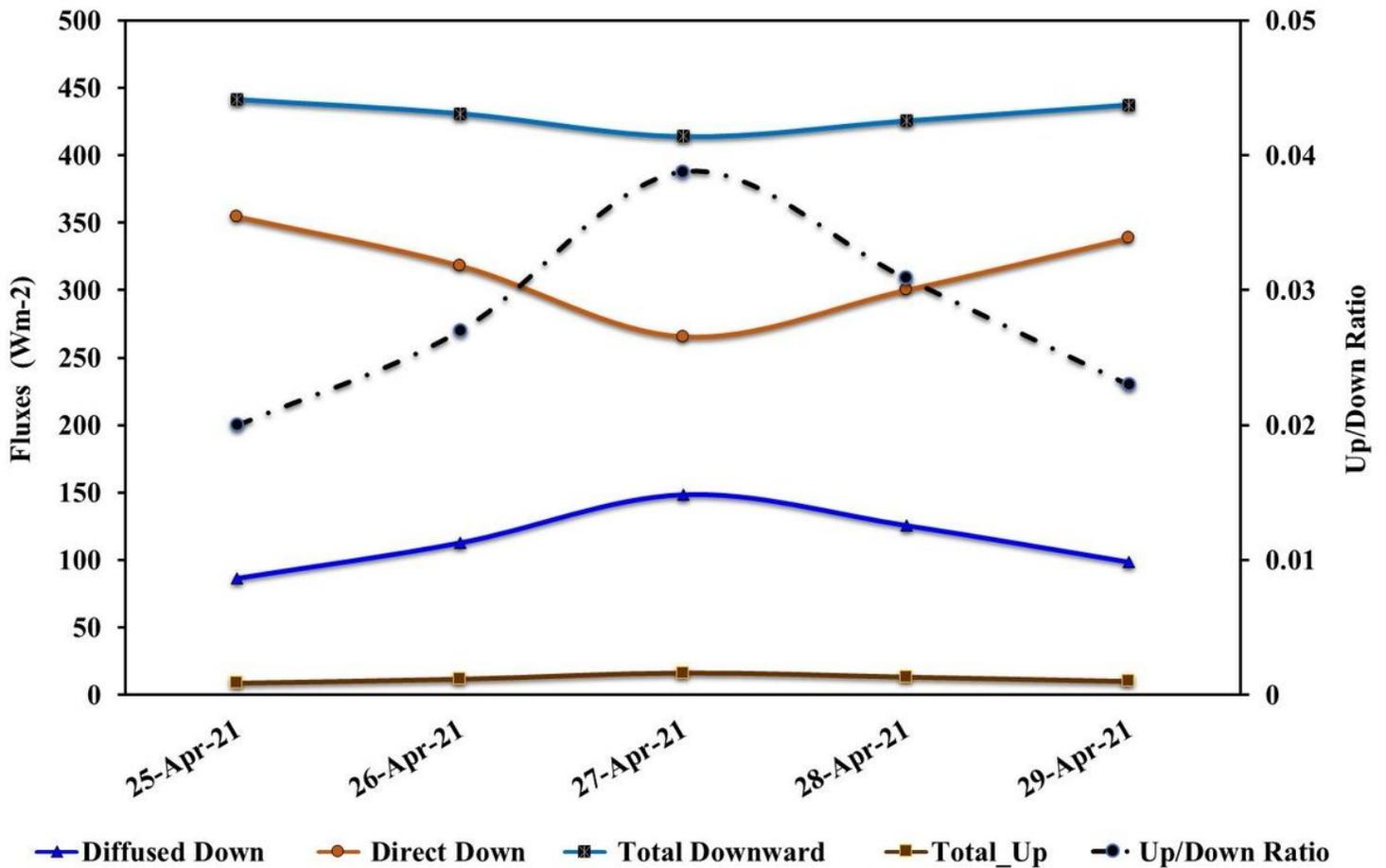


Figure 7

Aerosol Radiative forcing Integrated fluxes (Wm<sup>-2</sup>) estimated for dust storm event over Ahmedabad.