World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(RESEARCH ARTICLE)

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Investigation of the characteristics of atmospheric and meteorological parameters of a severe dust storm in the Mumbai during January 2022

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World Journal of Advanced Research and Reviews, 2023, 19(03), 1274–1283

Publication history: Received on 13 August 2023; revised on 22 September 2023; accepted on 25 September 2023

Article DOI: https://doi.org/10.30574/wjarr.2023.19.3.1928

Abstract

In recent years, India has experienced frequent dust storms, which have a significant impact on local climatic conditions. This research focuses on a significant dust storm event that took place in January 2022 across the Arabian Sea and its effects on the Mumbai region. The study utilizes a combination of ground-based measurements and satellite observations of optical parameters to investigate different atmospheric and meteorological parameters. The analysis of aerosol optical characteristics observed through Moderate Resolution Imaging Spectroradiometer (MODIS) and Ozone Monitoring Instrument (OMI) data indicates significant variations during the dust storm day in comparison to pre- and post-dust storm days. There is a huge surge in the Aerosol Optical Depth (AOD) values Ångström Exponent (AE) values decrease. This confirms the presence of coarser particles in the affected region. The elevated values of the Aerosol Index (AI) on dusty days shows the presence of UV-absorbing aerosols. The ground-based measurements obtained by Central Pollution Control Board (CPCB) in the Mumbai region shows a rapid surge in the PM concentrations during the dust storm day. This study also highlights the change in the meteorological conditions associated with the occurrence of dust storm. The back trajectory analysis shows that most of the air-mass parcels transported from the Arabian Sea. The findings of this study collectively emphasize the substantial impact of dust storms on local atmospheric chemistry and the climatic system.

Keywords: Dust Storm; Ground-based measurements; Satellite observations; Aerosol optical characteristics; Meteorological conditions

1. Introduction

Clean air is a fundamental requirement for human survival. However, the lower troposphere often contains high levels of air pollutants such as dust aerosols, particulate matter, sulphur, and nitrogen oxides, adversely affecting the air quality. The presence of a substantial amount of dust particles, originating from both man-made sources and natural sources, in the troposphere leads to a prominent concern in the air pollution study [1]. Among the variety of airborne pollutants spread throughout the atmosphere, aerosols are complex particles that exist in both solid and liquid phases, and are widely dispersed throughout the atmosphere. Within aerosols, dust aerosols constitute a large portion, contributing nearly three-quarters of the aerosol mass loadings. Moreover, they contribute up to 30% of the world-wide AOD. These dust aerosols have a major influence on oceanic biogeochemical cycles, nutrient dynamics, and climate variability. Their impact on the global climate is of great concern, as they modify the radiative properties of the atmosphere. Further, these dust aerosols have the capacity to induce warming in the lower troposphere, leading to increased rainfall over various plain regions across the globe. Thus, these aerosols are termed absorbing aerosols [2].

Under specific meteorological conditions, characterized by pressure gradients, surface heating, and longer durations of strong winds, the formation of an extensive dust layer takes place. This formation of a dust layer is called a "dust storm"

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[3]. Dust storms are a prominent meteorological phenomenon predominantly observed globally in the regions of arid and semi-arid climatic conditions [4]. The principal contributors of dust storms across the globe are the Sahara Desert and the Arabian Peninsula. Both of these sources account for approximately half of the dust emissions in the world. The dust storms travel along horizontal distances, spanning different continents, and can even spread vertically up to six to eight kilometres, depending upon wind intensity and prevailing meteorological conditions [5]. Dust storms occur when strong winds uplift substantial quantities of dust from arid and exposed terrain, releasing dust particles into the atmosphere [6, 7].

Further, dust storms are classified based on a visibility threshold of less than 1000 meters, as studied by Safar [8]. The World Meteorological Organization (WMO) introduced a four-level classification system based on visibility criteria: (i) Widespread Dust or Dust Haze: the dust particles suspended in the atmosphere reduces visibility to less than ten kilometres; (ii) Blowing Dust: this is characterised by visibility reductions spanning one to ten kilometres but not below one kilometre; (iii) Dust Storm: this involves a reduction in visibility within the range of 0.2 to one kilometre; and (iv) Severe Dust Storms: this is marked by visibility falling below 0.2 kilometres [9, 10, 11].

The genesis of dust emissions depends on various factors, including soil moisture, wind velocity, vegetation cover, and soil texture. This dust emission can occur when blowing at high speeds results in sudden visibility reductions within the affected region [12]. In the Indian subcontinent, primary sources of dust storms include the Thar Desert, desert regions of Pakistan and Iran, and the Arabian Peninsula [13]. These regions transport substantial volumes of dust particles across India, particularly northern India. These dust storms are called extreme events because of their significant impact on the hydrological system, the Indian monsoon cycle, regional climate, and radiative forces [14]. During the pre-monsoon period, between March and June, dust storms occur frequently in India, affecting northern Indian states including Rajasthan, Uttar Pradesh, Punjab and Haryana. These dust storms are characterised by sudden darkness or drastically reduced visibility [15].

Dust storms in India arise due to both natural and anthropogenic factors. Natural factors like droughts, vigorous winds, and little precipitation, combined with high temperatures, low humidity, and strong winds, created favourable conditions for dust storm formation in the Indo-Gangetic Plain. Anthropogenic contributors, including deforestation, mining, agricultural practices, and soil erosion, result in dust emissions [16, 17]. The dust storm also has a major impact on human health, the environment, and the economy. Dust storms result in various respiratory ailments like asthma, bronchitis, skin irritation, etc. These health impacts can be notable in regions characterised by high air pollution levels, such as the Indo-Gangetic Plain in northern India [18].

Agricultural activities get affected because of the sudden occurrence of dust storms in the area. Furthermore, the infrastructure and transportation networks are also significantly impacted due to the substantial dust emissions. Dust storms enhanced aerosol loading, resulting in reduced visibility and poor air quality. Dust aerosols affect heating rate in the atmosphere and also results in the warming of the lower troposphere. In addition to these effects, dust storms contribute to high concentrations of $PM_{2.5}$ and PM_{10} in the region experiencing a dust storm [19, 20].

The present study on the dust storm event in Mumbai is yet not explored till now. This research work will help to understand the changes in meteorological and atmospheric parameters during dust storm. This will help in exploring the radiative effects of dust storms on the local climate system. Further, this work will help in investigating the variations in aerosol loading and its behaviour during dust storm in the region. It will also deal with the influence of PM concentrations over the region during dust storm.

This research paper introduces dust storms in first section and describes the significance of the research. The next section provides comprehensive detailing of the instruments and datasets used in the study, and validation of the dust storm event in Mumbai with the help of true-colour images taken from NASA WorldView. After this section, paper discusses the analysis of meteorological, atmospheric, and aerosol optical parameters obtained from satellite and ground-based measurements. Further, the back trajectory analysis is useful in tracing the origin, trajectory, and spatial extent of the dust storm event in Mumbai. The last section discusses the conclusions of the study.

2. Material and methods

2.1. ECMWF-ERA interim data

The meteorological conditions are studied using the reanalysis data of ECMWF ERA-5 (European Centre for Medium-Range Weather Forecasts). This dataset provides information about wind patterns, temperature variations, and relative humidity. To assess the local weather conditions in Mumbai, hourly variations of meteorological parameters are taken at a pressure level of 850 hectopascals (hPa). At a same pressure level and horizontal resolution of 0.25° * 0.25°, u-component, and v-component of wind data on hourly basis is taken to study the wind pattern during a dust storm. The surface solar radiation (SSR) is also obtained to study the radiative impact on the region. The obtained synoptic conditions are useful in studying the occurrence, severity, and transportation of dust storms. This data can be accessed through https://cds.climate.copernicus.eu [21].

2.2. Moderate resolution imaging spectroradiometer (MODIS)

The Moderate Resolution Imaging Spectroradiometer (MODIS) is key sensor in analysing the aerosol optical parameters. It operates with Terra and Aqua satellites, which became operational in December 1999 & May 2002, respectively. The MODIS instrument provides daily global data on various dust related properties, capturing radiance across 36 spectral bands spanning from visible to thermal infrared wavelengths ranging from 0.41-14.38 μm. Within the channels ranging from 0.41 μm -2.1 μm, it retrieves essential aerosol characteristics across the globe. The MODIS scans the entire surface of the Earth every day because of its spatial resolution of one kilometre. It also has a swath-width of 2330 kilometres. Over the Indian region, the Terra and Aqua satellites pass at 10:30 a.m. and 01:30 P.M. IST respectively.

The MODIS aerosol product is obtained at Level 3 has a spatial resolution of 1 degree. AOD measurements can be retrieved from a wavelength of 550 nm, while Angstrom Exponent (AE) values is obtained within the spectral bands ranging from 412 nm to 470 nm for terrestrial observations. MODIS uses deep-blue algorithm to examine aerosol and cloud properties over the land. Kaufman and Tanre [22] provide an in-depth information regarding the instrumentation, algorithm, and error estimation of MODIS products. Further revisions are discussed by Remer et al. [23]. The MODIS data is accessed through Giovanni website (https://giovanni.gsfc.nasa.gov/giovanni/).

2.3. Ozone Monitoring Instrument (OMI)

The UV Aerosol Index (AI) data is obtained through the Ozone Monitoring Instrument (OMI) aboard the Aura satellite. The AURA satellite follows a sun synchronous polar orbit at an altitude of 705 kilometres, with a repeat cycle of exactly 16 days. It has an equator crossing time of 13:45 local solar time. OMI has a spectral range spanning from 264 to 504 nanometres. This instrument operates in nadir viewing mode and have wide swath coverage. It also has 20 hyperspectral imaging spectrometers to get daily global observations with high spatial resolutions (13 km x 24 km at nadir).

This instrument has the unique capability to detect the presence of aerosols even above the cloud cover. In this study, Level 3 global-gridded products of OMI UV-AI data are used having spatial resolutions of 0.25° x 0.25°. This data is used to assess the behaviour of aerosols during long-range transportation of dust. The AI values are highly sensitive to mineral dust and carbonaceous aerosols [24]. A positive AI value signifies the presence of UV-absorbing aerosols such as dust and smoke, while a negative value indicates the presence of non-absorbing aerosols like sulphate [25]. This OMI data is accessed through Giovanni website (https://giovanni.gsfc.nasa.gov/giovanni/).

2.4. Ground-based Observations

In India, the Government initiated the National Air Quality Monitoring Programme (NAMP) to closely monitor the air quality across the country. The program is a collaboratively managed the Central Pollution Control Board (CPCB), various State Pollution Control Boards, etc. CPCB has established a network of Continuous Ambient Air Quality Monitoring (CAAQM) stations across the country to provide continuous monitoring of air quality data. To monitor $PM_{2.5}$ and PM_{10} levels, NAMP follows the USEPA Automated Federal Equivalent Method (FEM), which utilizes analyzers based on the beta-ray attenuation principle. In the study, ground-based data during dust storm in Mumbai for PM_{10} and $PM_{2.5}$ concentrations are obtained from CAAQM stations, accessible through the CPCB website (https://cpcb.nic.in/) [26].

2.5. Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT)

The Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT), is designed by the National Oceanic and Atmospheric Administration Air Resources Laboratory. This model helps in investigating the air-mass parcel movement. The transportation and dispersion of the pollutants is mainly computed using this model. The Lagrangian method and the Eulerian method are the two fundamental approaches of this model. The advection and diffusion of air parcel is identified using Lagrangian approach. Meanwhile, a three grid is used to find the concentration of air pollutants in Eulerian approach. To compute the five-day back trajectories of these air parcel, HYSPLIT Model is applied using the Global Data Assimilation System at 11.30 IST. This is accessible through https://www.arl.noaa.gov/hysplit [27].

2.6. Dust storm event and validation

In this current research to validate the dust storm, true-colour images taken by the Terra and Aqua satellites of the MODIS sensors are obtained. These images provide a visual representation of the plume of dust in the affected region. The true-colour images use corrected surface reflectance in the red, green, and blue bands. These images have been accessed through the World View tool of the NASA Earth Observing System Data and Information System (EOSDIS), accessible at https://worldview.earthdata.nasa.gov/. For the dust storm event that occurred on January 23, 2022, in Mumbai, a five-day true colour image was obtained. The imagery clearly shows that a huge plume of dust is visible across the Arabian Sea and is heading towards Mumbai on January 23, 2022. On this day, as visible in the Figure 1, there is a thick layer of dust in Mumbai, resulting in poor visibility in the region.

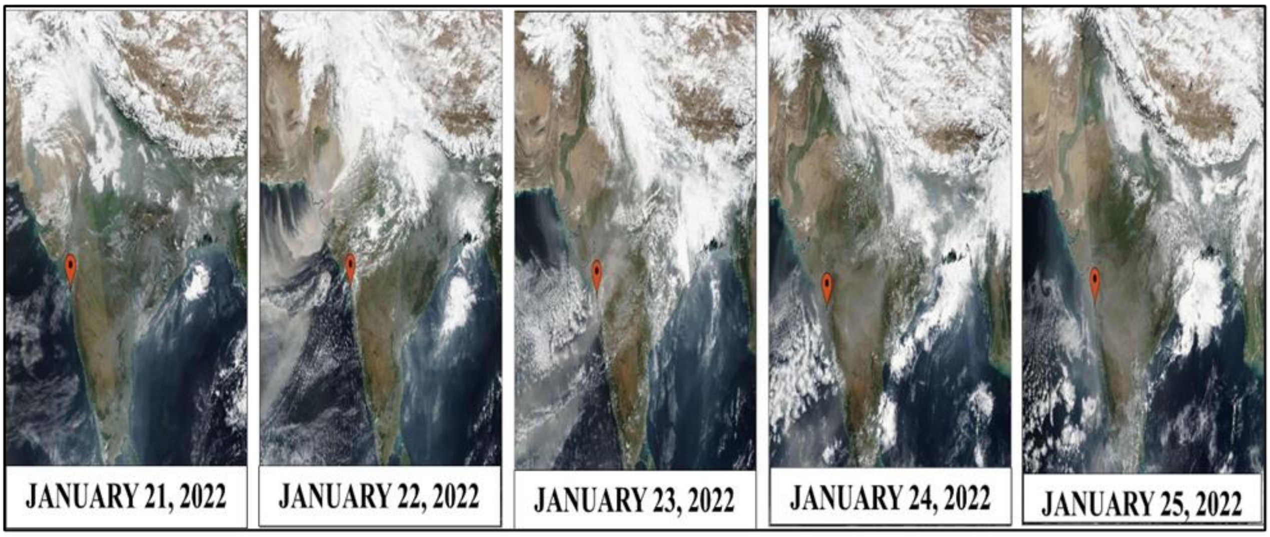

Figure 1 True colour images of Dust Storm in Mumbai obtained from NASA WorldView

3. Results and discussion

3.1. Analysis of Meteorological Conditions

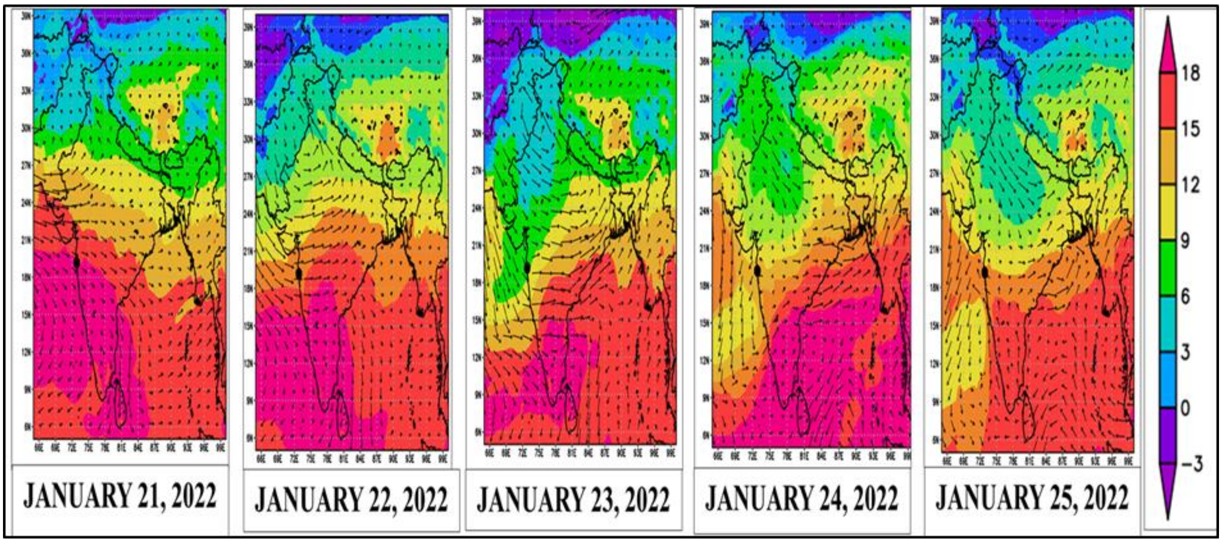

Figure 2(a) Variation in Meteorological Conditions (Temperature vs Wind Variation) obtained by ERA-5 dataset

In this present study, the synoptic meteorological conditions of the Indian subcontinent have been analysed using the ERA-5 reanalysis dataset. The meteorological conditions like temperature, relative humidity, and wind pattern are taken at an 850 hPa pressure level. The wind direction is depicted through the arrows, indicating the magnitude of the wind, while the length of the arrows shows wind speed in metres per second. The relative humidity (RH) is represented through shaded colours on the plots. In this plot, red shows high RH, and blue or violet shows low RH. Similarly, the average temperature (T) is represented by shaded colour regions, with red showing higher temperatures and blue or violet showing lower temperatures. These synoptic plots provide a comprehensive view of the meteorological conditions on the Indian subcontinent. The variation in temperature for the dust storm event is depicted in Figure 2(a). During this dust storm event in Mumbai, the average temperature was in the range of 12–19 °C. However, a significant temperature drop occurred on a dusty day. The temperature dropped from 13.8 °C to 8.6 °C, the dusty day. This drop in temperature mainly occurs due to the blockage of sunlight by large amounts of dust particles in the atmosphere [28].

Additionally, the analysis also shows that there is an increase in relative humidity during a dusty day in Mumbai as compared to the previous day. A relative humidity of 65% was obtained on this day as shown in Figure 2(b). This is because of the presence of moisture-holding air carried by a dust storm in the region. Also, the relative humidity remained in the range of 30–70% during the five-day analysis. Further, the wind patterns during this event are predominantly characterised by westerly to north-westerly winds. These prevailing winds originate from arid regions and transport substantial quantities of mineral dust over the Mumbai area [29].

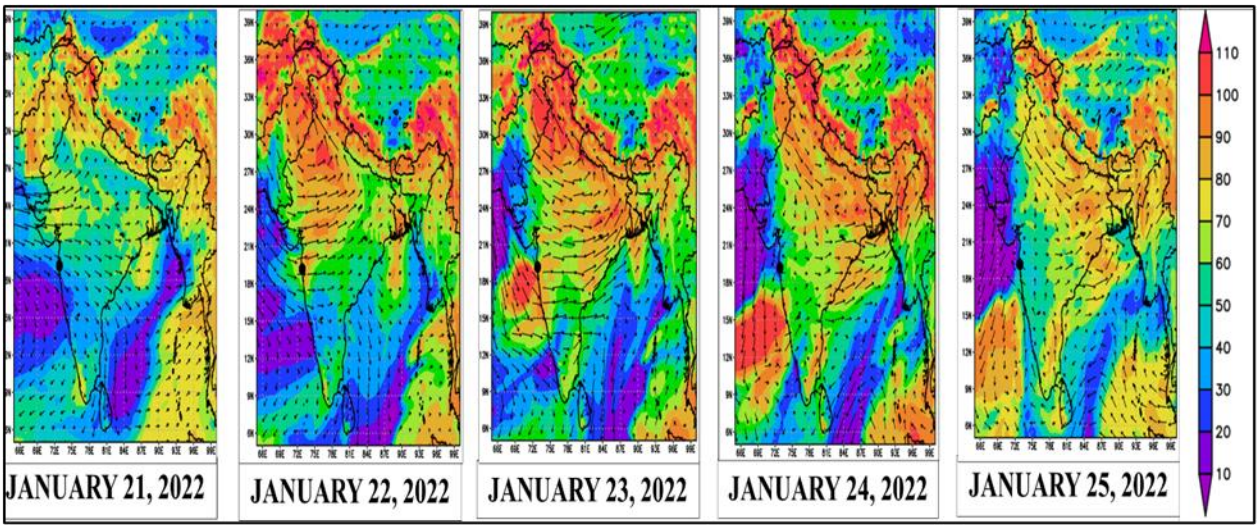

Figure 2(b) Variation in Meteorological Conditions (Humidity vs Wind Variation) obtained by ERA-5 dataset

3.2. Analysis of Surface Solar Radiation (SSR)

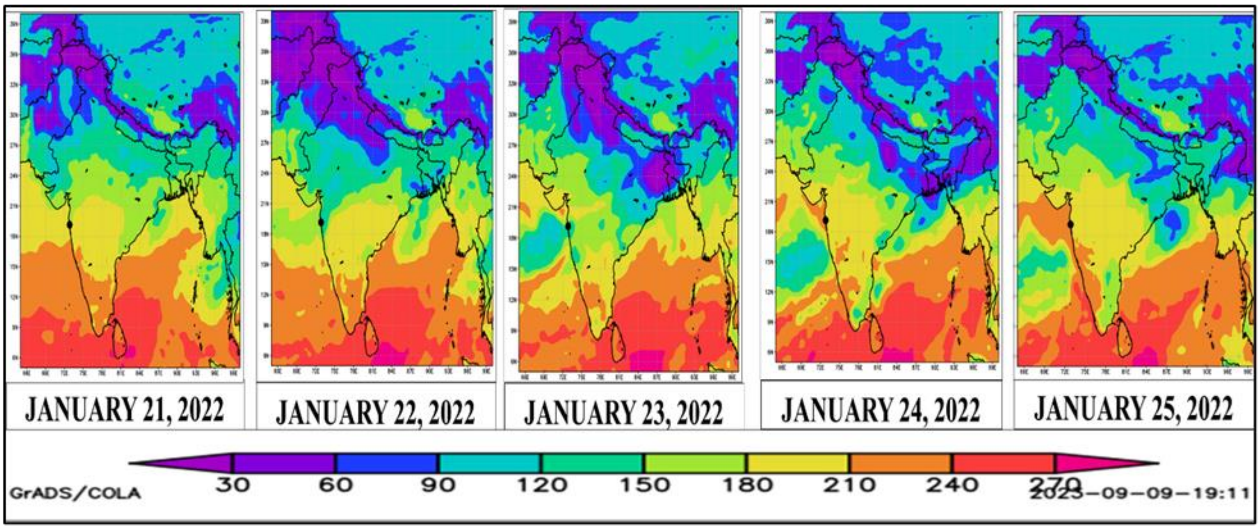

Figure 3 Variation in Surface Solar Radiation obtained by ERA-5 dataset

ERA5 provides comprehensive data for surface solar radiation (SSR). The SSR data contains both diffuse and direct solar radiation. SSR quantifies the amount of solar radiation reaching the surface of the Earth during dusty day. This radiation plays an important role in various environmental processes, including energy balance, climate, and ecological systems.

It is also significant for assessing changes in the radiation budget of Earth, particular dusty day. The dust storm event in Mumbai observed a decline in surface solar radiation as shown in Figure 3. The SSR value shows a reduction on pre-dust storm day from 155.19 W/m^2 to 153.97 W/m^2, the dusty day. This decrease in SSR can be observed due to the presence of dust particles in the atmosphere. The dust particles suspended in the atmosphere have a significant influence on SSR. They scatter and absorb solar radiation and altering the amount of radiation that reaches the surface of Earth.

3.3. Analysis of Variation of Aerosol Characteristics

To quantify the dust storm, the Aerosol Optical Depth (AOD) and the Ångstrom Exponent (AE) are considered significant aerosol optical parameters. The variations in AOD loading and AE values are analysed through the MODIS dataset using the deep-blue algorithm at a wavelength of 550 nanometres. AOD is defined as a measure of the columnar extinction of radiation from the sunlight. It is often described as the extent of aerosol loading in the atmosphere. Higher AOD values show the higher concentration of aerosol particles in the region. On the other hand, AE describes the aerosol size distribution and particle size of the aerosol. It is a qualitative parameter [30].

The variations in AOD and AE over a five-day period during a dust storm event are shown in Figure 4. On the days preceding the dust storm, AOD values remained relatively low at around 0.3. However, a sharp increase in AOD is evident during the dusty day, reaching a peak value of 1.82. Subsequently, it declined to 0.81 on January 24, 2022, following the dust storm event. However, this decline in AOD value after a dust storm day is due to precipitation and the settling of dust particles (Sarkar et al., 2019). In contrast, AE shows the opposite trend during a dust storm. AE values decrease to 0.33 on the dusty day from the pre- and post-dust storm days, i.e., 0.63 and 1.65, respectively. These satellite observations clearly show the presence of large amount of coarser dust particles in the Mumbai area.

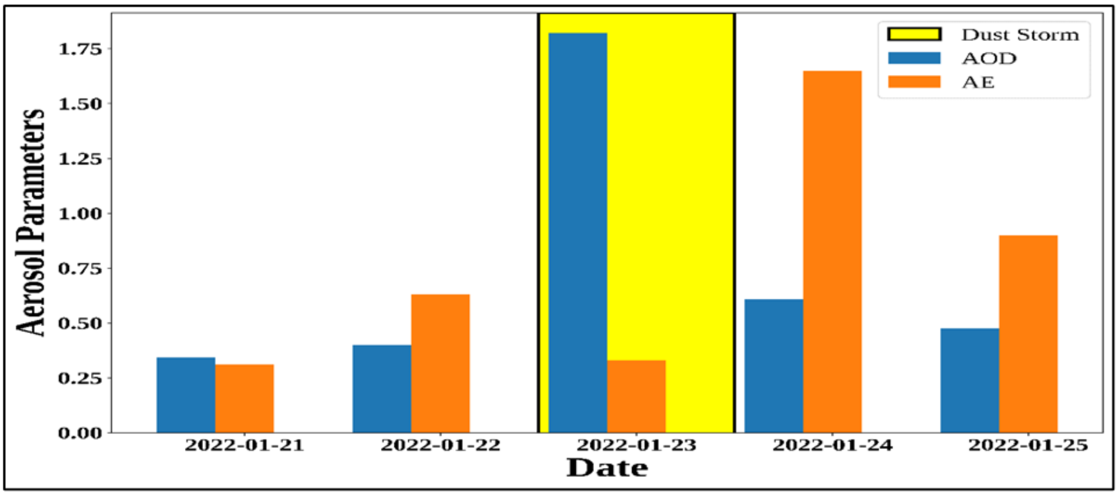

Figure 4 Variation of Aerosol Parameters obtained by MODIS platform

3.4. Analysis of Variation of Aerosol Index

The Aerosol Index (AI) data obtained from the Ozone Monitoring Instrument (OMI), helps in identifying the types of aerosols present in a region experiencing dust storm. A positive value shows the presence of UV-absorbing aerosols such as dust, smoke, and while a negative AI value shows the prevalence of non-absorbing aerosols, like sulphates. The dust storm event, as shown in Figure 5, observed a significant increase in AI values during the dust storm period. It climbed from 0.37 (pre-dust storm day) to a peak value of 2.62 on the dusty day in Mumbai. This high AI values indicate the severity of the dust event. Positive AI value obtained in the study during dusty day shows the presence of UV-absorbing aerosols during the dust storm. Various studies reported significant surge in AI values during dust storm day.

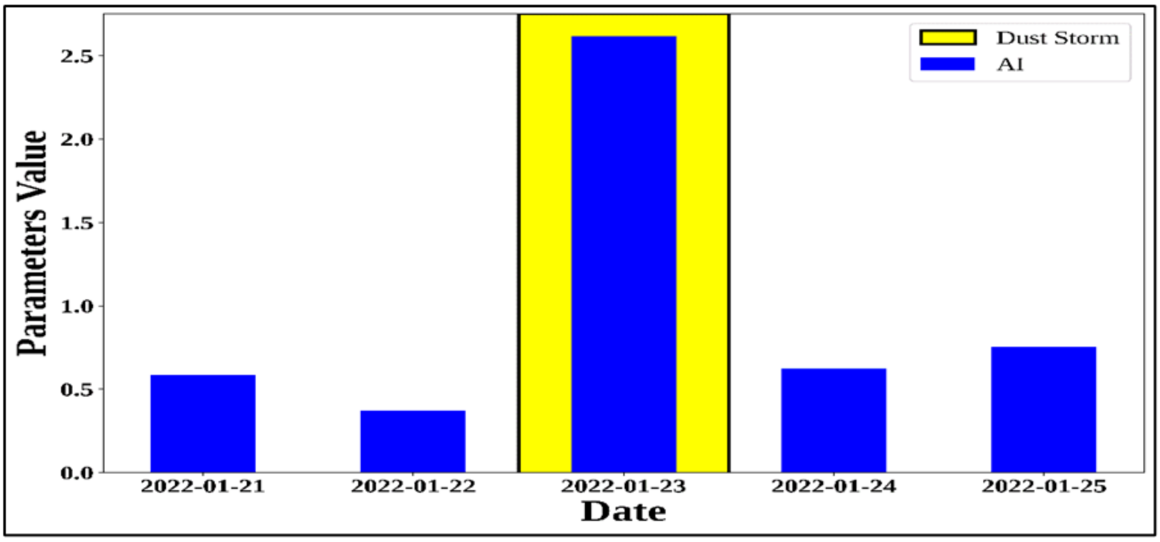

Figure 5 Variation of Aerosol Index obtained by OMI Sensor

3.5. Analysis of Variation of $PM_{2.5}$ and PM_{10}

The $PM_{2.5}$ and PM_{10} obtained from the datasets of the Central Pollution Control Board (CPCB) help in monitoring and evaluating the air quality in Mumbai during the dust storm event. This monitoring of PM is done by the Continuous Ambient Air Quality Monitoring (CAAQM) station at Navi Mumbai. In this study, the variations in $PM_{2.5}$ and PM_{10} concentrations over a five-day period are examined as shown in Figure 6.

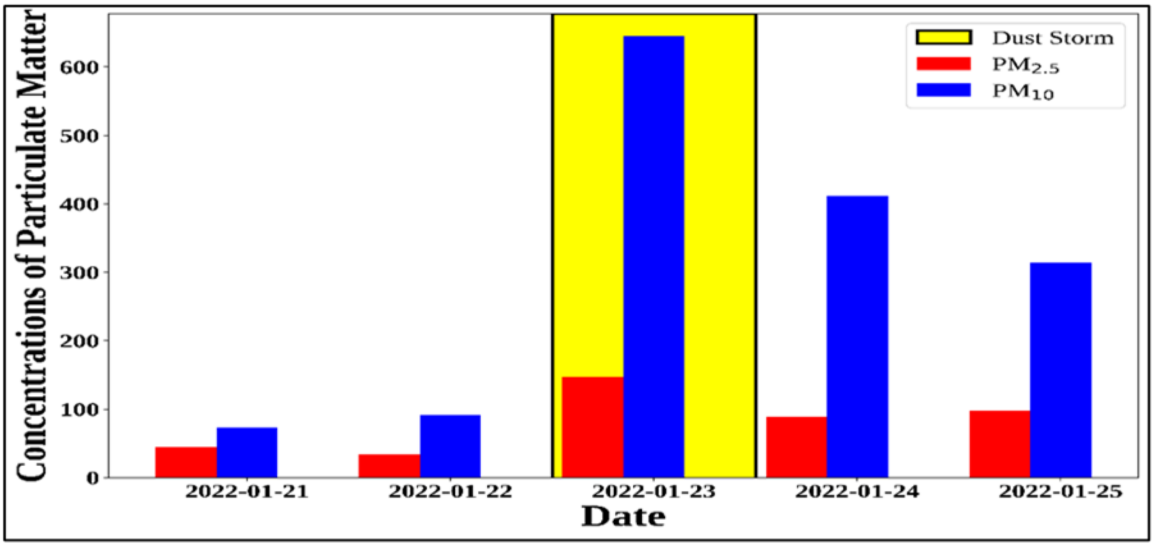

Figure 6 Variation of $PM_{2.5}$ and PM_{10} obtained by CPCB Dataset

On the day of the dust storm, there was a major increase in the daily average concentration of PM_{10}, rising from 91.7 μg/m³ to 645.27 μg/m³. Similarly, the concentrations of $PM_{2.5}$ also showed a significant rise, surging from 33.5 μg/m³ on January 22, 2022, to 147.42 μg/m³ on January 23, 2023. This significant change of nearly 85% in $PM_{2.5}$ and PM_{10} concentrations on dusty day as compared to pre-dust storm day reveals the accumulation of dust particles in the region. However, this higher concentration of PM began to decline following the dust event. This study shows that dust storms have a substantial impact on the air quality of the region. High concentrations of PM lead to poor air quality.

3.6. Assessment of five-day Backward Trajectories of Dust Storm Event:

In order to identify the sources of air-mass particles, five-day back trajectories were computed at an altitude of 1000 meters using the NOAA ARL HYSPLIT model. The back trajectories were computed from January 18, 2022 to January 22, 2022. The results of the back trajectory analysis are shown in Figure 7. Most back trajectories originated from the

Arabian Sea and Arab Peninsula. A few air parcels have also originated from the Thar Desert. This five-day back trajectory confirms the MODIS true colour images that clearly depicts a huge plume of dust in the Arabian Sea (represented by the red line). This also confirms that Arabian Sea is identified as the major contributor of this dust storm that enhances aerosol loading in the Mumbai.

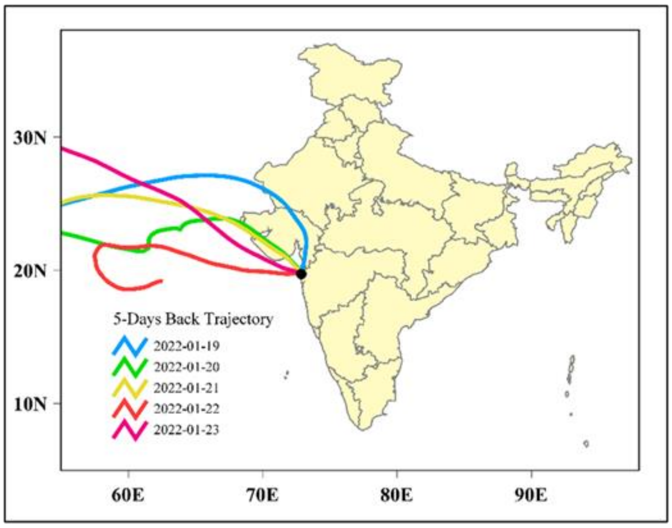

Figure 7 Five-day back trajectory obtained at an altitude of 1000 metres using HYSPLIT Model

4. Conclusion

The present study investigated the influence of the dust storm on meteorological and atmospheric parameters over Mumbai that occurred on January 22, 2022. This study is done using combination of the ground-based measurements and satellite observations. This research study also discussed the five-day back trajectory of dust events. The following primary conclusions are drawn from this research study:

- The average temperature during the dust storm event in Mumbai experienced a decrease, accompanied by an increase in relative humidity. During this event, the average temperature fell from 13.8 °C to 8.6 °C. However, relative humidity increases, reaching nearly 65% on a dusty day. SSR values also saw a decline on a dusty day.
- The accumulation of dust in the Mumbai area has resulted in a sudden rise in the concentrations of $PM_{2.5}$ and PM_{10} levels on January 23, 2023. The PM_{10} levels were 645.27 μg/m^3, while the $PM_{2.5}$ levels reached around 147.42 μg/m^3 in Mumbai.
- A noticeable increase in the AOD values in Mumbai is observed during a dusty day. The AOD value (550 nm) nearly gets doubled (1.82). However, lower AE values (0.1–0.5) suggest that there is an abundance of coarser aerosol particles in Mumbai. Also, higher values of the AI confirm the existence of UV-absorbing aerosols in the Mumbai region.
- Five-day back trajectory analysis confirms the Arabian Sea as the major contributor of the dust particles in this dust storm event. These back trajectories may also bring sea-salt and dust in the region.
- Thus, this dust storm in Mumbai degrades the air quality and has severely impacted the atmospheric dynamics, vegetation, and social life in the region. In order to reduce the loss of human lives, advanced warning systems and proper remedial measures should be adopted.

Compliance with ethical standards

Acknowledgments

The authors are thankful to MODIS and OMI research team for providing various satellite aerosol data. We are acknowledging the use of ERA-5 reanalysis data for synoptic meteorological data and HYSPLIT model for back trajectory analysis. We also extend our regards to Central Pollution Control Board, Ministry of Earth Science and Ministry of Environment, Forest and Climate Change, Government of India for providing data of particulate matter concentrations. The authors are also thankful to the Department of Civil Engineering, Institute of Engineering & Technology, Lucknow for supporting the work. The authors also extend gratitude towards Indian Institute of Tropical Meteorology, New Delhi Branch, New Delhi for providing valuable resources.

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Dumka UC, Kaskaoutis DG, Francis D, Chaboureau J -P., Rashki A, Tiwari S, et al. The Role of the Intertropical Discontinuity Region and the Heat Low in Dust Emission and Transport Over the Thar Desert, India: A Premonsoon Case Study. Journal of Geophysical Research: Atmospheres. 2019; 124(23):13197–219. https://doi.org/10.1029/2019JD030836.

[2] Tiwari S, Kumar A, Pratap V, Singh AK. Assessment of two intense dust storm characteristics over Indo – Gangetic basin and their radiative impacts: A case study. Atmospheric Research. 2019; 228:23–40. https://doi.org/10.1016/j.atmosres.2019.05.011.

[3] Cao H, Amiraslani F, Liu J, Zhou N. Identification of dust storm source areas in West Asia using multiple environmental datasets. Science of The Total Environment. 2015; 502:224–35. https://doi.org/10.1016/j.scitotenv.2014.09.025.

[4] McTainsh GH, Pitblado JR. Dust storms and related phenomena measured from meteorological records in Australia. Earth Surface Processes and Landforms. 1987; 12(4):415–24. https://doi.org/10.1002/esp.3290120407.

[5] Tan S, Li J, Che H, Chen B, Wang H. Transport of East Asian dust storms to the marginal seas of China and the southern North Pacific in spring 2010. Atmospheric Environment. 2017; 148:316–28. https://doi.org/10.1016/j.atmosenv.2016.10.054.

[6] Middleton N, Kashani SS, Attarchi S, Rahnama M, Mosalman ST. Synoptic Causes and Socio-Economic Consequences of a Severe Dust Storm in the Middle East. Atmosphere. 2021; 12(11):1435.. https://doi.org/10.3390/atmos12111435.

[7] Huang XX, Wang TJ, Jiang F, Liao JB, Cai YF, Yin CQ, et al. Studies on a Severe Dust Storm in East Asia and Its Impact on the Air Quality of Nanjing, China. Aerosol and Air Quality Research. 2013; 13(1):179–93. https://doi.org/10.4209/aaqr.2012.05.0108.

[8] Safar MI. Dust and Dust storms in Kuwait. Directorate General of Civil Aviation, Meteorological Department, Kuwait, 1985; 212.

[9] Ozer P. Dust variability and land degradation in the Sahel. Belgeo. 2002; (2):195–210. https://doi.org/10.4000/BELGEO.16124.

[10] Aher GR, Pawar GV, Pradeep Kumar Gupta, Pcs Devara. Effect of major dust storm on optical, physical, and radiative properties of aerosols over coastal and urban environments in Western India. 2014; 35(3):871–903. . http://dx.doi.org/10.1080/01431161.2013.873153.

[11] Albugami S, Palmer S, Cinnamon J, Meersmans J. Spatial and Temporal Variations in the Incidence of Dust Storms in Saudi Arabia Revealed from In Situ Observations. Geosciences. 2019; 9(4):162. . https://doi.org/10.3390/geosciences9040162.

[12] Singh A, Sumit Kumar Singh, Srivastava AK, Swagata Payra, Pathak V, Arvind Kumar Shukla. Climatology and model prediction of aerosol optical properties over the Indo-Gangetic Basin in north India. Environmental Monitoring and Assessment. 2022; 194(11). . https://doi.org/10.1007/s10661-022-10440x.

[13] Prospero JM. Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Reviews of Geophysics. 2002; 40(1). https://doi.org/10.1029/2000RG000095.

[14] Aswini MA, Kumar A, Das SK. Quantification of long-range transported aeolian dust towards the Indian peninsular region using satellite and ground-based data - A case study during a dust storm over the Arabian Sea. Atmospheric Research. 2020; 239:104910. https://doi.org/10.1016/j.atmosres.2020.104910.

[15] Gautam R, Hsu NC, Lau WKM ., Yasunari TJ. Satellite observations of desert dust-induced Himalayan snow darkening. Geophysical Research Letters. 2013; 40(5):988–93. https://doi.org/10.1002/grl.50226.

[16] Gangane A, Pawar SD, Gopalakrishnan V, Saikrishnan KC. Effect of dust particles on lightning flash rate and polarity of dust storms over India. Natural Hazards. 2022; 115(3):2505–29. https://doi.org/10.1007/s11069-022-05651-x.

[17] Saha S, Sharma S, Chhabra A, Kumar KN, Kumar P, Kamat D, et al. Impact of dust storm on the atmospheric boundary layer: a case study from western India. Natural Hazards. 2022; 113:143-155. https://doi.org/10.1007/s11069-022-05293-z

[18] Sravanthi Nukapothula, Yunus AP, Chen C, Raju Attada, Narayana AC. Dust storm induced severe cooling in the northern Arabian Sea during winter 2022. Deep-sea Research Part I-oceanographic Research Papers. 2023; 197:104047. . https://doi.org/10.1016/j.dsr.2023.104047.

[19] Kedia S, Kumar R, Islam S, Sathe Y, Kaginalkar A. Radiative impact of a heavy dust storm over India and surrounding oceanic regions. Atmospheric Environment. 2018; 185:109–20. https://doi.org/10.1016/j.atmosenv.2018.05.005.

[20] Verma S, Swagata Payra, Gautam R, Prakash D, Soni M, Holben BN, et al. Dust events and their influence on aerosol optical properties over Jaipur in Northwestern India. Environmental Monitoring and Assessment. 2013; 185(9):7327–42. https://doi.org/10.1007/s10661-013-3103-9.

[21] Qiu S, Shao X, Cao CY, Uprety S, Wang WH. Assessment of straylight correction performance for the VIIRS Day/Night Band using Dome-C and Greenland under lunar illumination. International Journal of Remote Sensing. 2017; 38(21):5880–98. http://dx.doi.org/10.1080/01431161.2017.1338786.

[22] Kaufman YJ, Tanre D, Mattoo S. Algorithm for Remote Sensing of Tropospheric Aerosol from MODIS. MODIS ATBD: Remote Sensing of Aerosol. https://eospso.gsfc.nasa.gov/sites/default/files/atbd/atbd_mod02.pdf.

[23] Remer LA, Kaufman YJ, Tanre D, Mattoo S, Chu DA, Martins JV, et al. The MODIS Aerosol Algorithm, Products, and Validation. Journal of the Atmospheric Sciences. 2005; 62(4):947–73. https://doi.org/10.1175/JAS3385.1.

[24] Kaskaoutis DG, Rashki A, Francois P, Dumka UC, Houssos EE, Legrand M. Meteorological regimes modulating dust outbreaks in southwest Asia: The role of pressure anomaly and Inter-Tropical Convergence Zone on the 1–3 July 2014 case. Aeolian Research. 2015; 18:83–97. https://doi.org/10.1016/j.aeolia.2015.06.006

[25] Chakravarty K, Vincent V, Vellore R, Srivastava AK, Rastogi A, Soni VK. Revisiting Andhi in northern India: A case study of severe dust-storm over the urban megacity of New Delhi. Urban Climate. 2021; 37:100825. https://doi.org/10.1016/j.uclim.2021.100825.

[26] Singh A, Srivastava AK, Varaprasad V, Kumar S, Pathak V, Shukla AK. Assessment of near-surface air pollutants at an urban station over the central Indo-Gangetic Basin: Role of pollution transport pathways. Meteorology and Atmospheric Physics. 2021; 133(4):1127–42. https://doi.org/10.1007/s00703-021-00798-x.

[27] Y. Yarragunta, Srivastava S. Effects of South Asian dust storm on air quality over the capital city of India. Proceedings of SPIE. 2016 May 6. https://doi.org/10.1117/12.2223548.

[28] He Y, Yi F, Yin Z, Liu F, Yang Y, Zhou J. Mega Asian dust event over China on 27–31 March 2021 observed with space-borne instruments and ground-based polarization lidar. Atmospheric Environment. 2022; 285:11923 Y, Yi F, Yin Z, Liu F, Yang Y, Zhou J. Mega Asian dust event over China on 27–31 March 2021 observed with space-borne instruments and ground-based polarization lidar. Atmospheric Environment. 2022; 285:119238. https://doi.org/10.1016/j.atmosenv.2022.119238.

[29] Sarkar S, Chauhan A, Kumar R, Singh RP. Impact of Deadly Dust Storms (May 2018) on Air Quality, Meteorological, and Atmospheric Parameters Over the Northern Parts of India. GeoHealth. 2019; 3(3):67–80. https://doi.org/10.1029/2018GH000170.

[30] She L, Xue Y, Guang J, Che Y, Fan C, Li Y, et al. Towards a comprehensive view of dust events from multiple satellite and ground measurements: exemplified by the May 2017 East Asian dust storm. Natural Hazards and Earth System Sciences. 2018; 18(12):3187–201. https://doi.org/10.5194/nhess-18-3187-2018.