scientific reports

OPEN

Characteristics and optical properties of atmospheric aerosols based on long-term AERONET investigations in an urban environment of Pakistan

Bahadar Zeb[1], Khan Alam[2]✉, Rehana Khan[3], Allah Ditta[4,5]✉, Rashid Iqbal[6], Mohamed Farouk Elsadek[7], Ahsan Raza[8,10]✉ & Mohamed Soliman Elshikh[9]

Radiative balance, local climate, and human health are all significantly influenced by aerosol. Recent severe air pollution over Lahore, a city in Pakistan calls for more thorough research to determine the negative impacts brought on by too many aerosols. To study regional aerosol characteristics and their differences from various aspects, in-depth and long-term (2007–2020) investigations of the columnar aerosol properties over the urban environment of Lahore were carried out by using AERONET data. The Aerosol Optical Depth (AOD_{400}) and Angstrom Exponent ($AE_{400–870}$) vary from low values of 0.10 to a maximum value of 4.51 and from 0.03 to 1.81, respectively. The huge differences in the amount of AOD_{440} as well as $AE_{440–870}$ show the large fluctuation of aerosol classes because of various sources of their emission. During the autumn and winter seasons, the decreasing trend of the optical parameters of aerosols like Single Scattering Albedo (SSA) and Asymmetry Parameter (ASY) with increasing wavelength from 675 to 1020 nm indicates the dominance of light-absorbing aerosols (biomass burning (BB) and industrial/urban (UI). Due to the long-distance dust movement during spring, summer, and autumn, coarse mode particles predominated in Lahore during the study period. Dust type (DD) aerosols are found to be the dominant one during spring (46.92%), summer (54.31%), and autumn (57.46%) while urban industry (BB/UI) was dominant during the winter season (53.21%). During each season, the clean continental (CC) aerosols are found to be in negligible amounts, indicating terrible air quality in Lahore City. The present research work fills up the study gap in the optical properties of aerosols in Lahore and will help us understand more fully how local aerosol fluctuation affects regional climate change over the urban environment of Lahore.

Keywords AERONET, Aerosols, Metropolitan, Clean continental, Aerosol optical depth, Angstrom exponent

Aerosols encompass solid or liquid particles suspended in the atmosphere, comprising industrial waste, vehicle exhaust, and globally dispersed dust, with a recognized significant impact on climate change[1]. The Earth's energy equilibrium may be affected by the absorption or scattering of these aerosols[2,3]. The various aerosols in

[1]Department of Mathematics, Sheringal Dir (Upper), Shaheed Benazir Bhutto University, Khyber Pakhtunkhwa, Pakistan. [2]Department of Physics, University of Peshawar, Khyber Pakhtunkhwa, Pakistan. [3]Department of Physics, Higher Education Colleges, Govt. of Khyber Pakhtunkhwa, Peshawar, Pakistan. [4]Department of Environmental Sciences, Shaheed Benazir Bhutto University Sheringal, Dir (U), Khyber Pakhtunkhwa 18000, Pakistan. [5]School of Biological Sciences, The University of Western Australia, 35 Stirling Highway, Perth, WA 6009, Australia. [6]Department of Agronomy, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan. [7]Department of Biochemistry, College of Science, King Saud University, P.O. 2455, 11451 Riyadh, Saudi Arabia. [8]Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Bonn, Germany. [9]Department of Botany and Microbiology, College of Science, King Saud University, 11451 Riyadh, Saudi Arabia. [10]Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374, Müncheberg, Germany. ✉email: khanalam@uop.edu.pk; allah.ditta@sbbu.edu.pk; araza@uni-bonn.de

our atmosphere play a crucial role in processes such as precipitation, the land-atmospheric water cycle, and visibility constraints4. Globally, the substantial effects of aerosols cannot be ignored[4]. The temporal and spatial fluctuations of aerosols have noteworthy consequences on specific climatic conditions, and consequently, on human health[2]. Further research is necessary to comprehensively understand the diverse optical, physical, and chemical characteristics of aerosols and their various climatic implications[1,5]. Given the pivotal role of aerosols in climate change, it is essential to explore their various crucial optical parameters, including Aerosol Optical Depth (AOD), Phase Function (PF), Single Scattering Albedo (SSA), Asymmetry Parameter (Asy), as well as scattering and extinction parameters[6,7].

Generally, AOD exhibits larger values in the hot season and decreases during the dry and cold seasons across diverse locations of Asia, as indicated by geographical and temporal variations in aerosol content[8–10]. Various aerosol properties were utilized to differentiate between distinct types of aerosols[7,11]. Both AOD and Angstrom Exponent (AE) are crucial parameters for comprehending diverse aerosol types, their origins, and their distribution in the atmosphere[12]. AE serves as a valuable metric for assessing aerosol properties such as formation, growth, size, and effective radius[4,13].

The size of the aerosol particle, its effective radius, and its production and growth mechanisms can all be learned via AE[4,13]. By combining AERONET-derived AAE, EAE, and SSA, cluster analysis is used to produce several aerosol classifications[13–17]. Pakistan is experiencing significant environmental issues because of rapid industrial growth and urbanization[18–23] with big cities like Karachi, Lahore, and Peshawar, being particularly hard hit[24–27]. These significant environmental problems have detrimental effects on both transportation[28,29] and human health[3,30]. Various aerosol loadings that cause long-lasting heavy haze, deteriorated visibility, and other pollution events have been identified in many studies. A recent study[31–34] attributed around 80% (by mass) of the total transport emissions ($PM_{10}/PM_{2.5}$) in Lahore to motorcycles and scooters. Numerous studies have revealed a variety of aerosol loadings that result in persistently high haze, declining visibility, and other pollution occurrences. The varying climatic circumstances may also be to blame for all these issues, in addition to the rising anthropogenic activities[35,36].

Based on these results, the main objective of this research is to investigate the long-term (2007–2020) climatology of aerosol properties and affiliated effects of different aerosol types over the megacity of Pakistan. To distinguish and categorize different aerosols, their numerous sources, and transformation mechanisms, long-term analysis of aerosol parameters is required[10,37]. Previously, numerous methods were used to distinguish between various forms of aerosols and their effects on regional climate[17,38]. Atmospheric forcing obtained from ground-based sensors and their absorption capability are useful techniques to characterize the heterogeneity of atmospheric aerosols[30,39–41.] The seasonal classification of aerosols is also carried out to monitor the dominating kind and its effects on the climate and monsoon circulation. AOD and AE clustering have been the subject of numerous studies to classify and measure various aerosols[39–42], while others have involved EAE and AAE clustering[15,17,43–45]. Relatively few studies have been recorded to characterize the numerous aerosols in Pakistan. This indicates that more research and analysis are still needed. This paper employs a clustering technique to examine in-depth details of distinct aerosols over Lahore by using long-term AERONET data from 2007 to 2020. The dominating aerosols and their seasonal changes over the site are investigated using a variety of aerosol characteristics. Conducting this type of analysis is essential to distinguish between different aerosol types, their distribution patterns, and their primary sources by considering a range of features. The present study seeks to offer an updated account of the optical characteristics of aerosols, their daily and seasonal variations, and their clustering (aerosol types) in the urban atmosphere of the mega-city, Lahore, Pakistan. Further, the findings aim to shed light on the mechanisms contributing to aerosol pollution in Lahore. To evaluate the quality of the retrieved data, numerous studies[31,32,46,47] have been conducted in the recent past for comparison of AERONET with the ground base (CARSNET, CARE-China, CSHNET), Model (MERRA-2) and satellite data (MODIS, MISR, CALIPSO) for short to long term study period and found it compatible in all the cases, so it (Data Comparison/validation) has been omitted from the present work to prevent redundancy.

Results and discussion

Monthly variation in AOD_{440} and $AE_{440–870}$

AOD and AE provide information about atmospheric columnar aerosol load and aerosol size, respectively. The monthly variation of AOD_{440}, AE $_{440–870}$ is shown in Fig. 1. During the whole study period, AOD_{440} varied from a minimum value of 0.10 to a maximum value of 4.51. Low values of AOD_{440} i.e. < 0.01 indicate a clean air background, while its high values i.e. > 0.5 or even > 0.1 show harsh atmosphere aerosols load because of the effects of anthropogenic pollutants or transported dust[15]. The strong fluctuation in the AOD_{440}, and AE $_{440–870}$ values during the study period represents regular changes in the aerosol types in Lahore brought on by its diverse emission sources.

The seasonal average AOD and AE are over Lahore as indicated in Fig. 1. The maximum AOD is found during summer (0.95 ± 0.39) with corresponding moderate AE (0.79 ± 0.37). This suggests that coarse mode particles associated with the mixing of anthropogenic contaminants and transportable dust characterize aerosols throughout this season[48,49]. On the other hand, the lowest AOD (0.61 ± 0.28) with the corresponding lowest AE (0.77 ± 0.30) was investigated during spring seasons. During the spring season, the nature of the aerosol particles seems to be similar to in the summer season but with the lowest aerosol burden. The moderate value of AOD $_{400}$ (0.75 ± 0.47) with the highest value of AE (1.25 ± 0.21) during the winter season implies that the aerosol particles are in the fine mode, which is created by transported aerosols, vehicle exhaust, and industrial emissions[50]. Similarly, conditions like a high value of AOD (0.91 ± 0.54) and high AE (1.10 ± 0.25) during autumn are favorable for fine-mode aerosol particles.

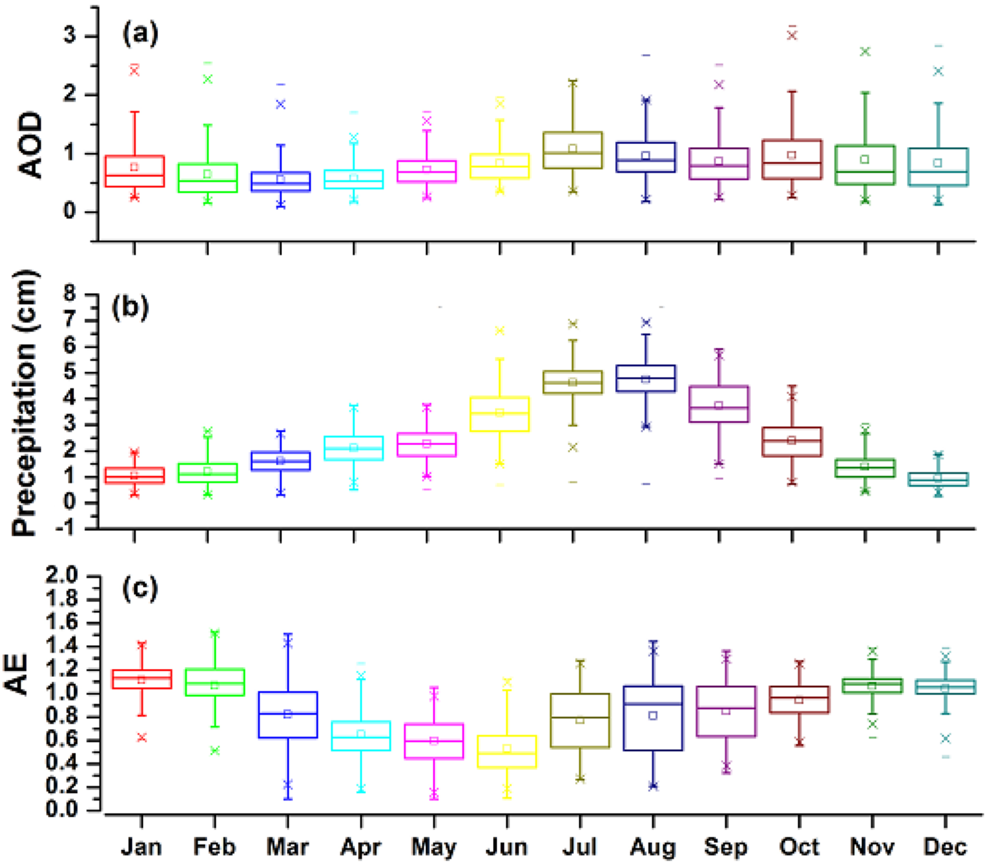

Figure 1. Monthly fluctuations in (**a**) AOD at 440 nm (**b**) Precipitation (cm) (**c**) AE at 440–870 nm. The first and third quartiles, respectively, represent the bottom and upper bounds of each box, while the median is represented by the central line. The vertical lines that stretch out from the box represent the distribution's spread, and their length is equal to 1.5 times the difference between the first and third quartiles. The geometric means are denoted by asterisk symbols.

Winter season faces severe pollution and is found in more stagnant weather conditions as compared to other seasons[51]. The AE values are found to be consistent at around 1.2 throughout the winter, indicating the dominance of fine-mode particles across the research area[52]. The winter season in Lahore is very cold and dry and does not provide favorable conditions for the hygroscopic growth of atmospheric aerosols. Likewise, summertime has the lowest AE values, which can be attributed to strong winds (Fig. 1) that mix anthropogenic emissions from the local area with dust that has been carried[53].

Seasonal variation in single scattering albedo

Single Scattering Albedo (SSA) is the ratio of scattering to total solar radiation extinction and is the most important optical parameter for determining the scattering and absorption characteristics of aerosol particles[54]. The greater value of SSA_{440} (> 0.95) corresponds to weakly absorbing particles for example sulfate. On the other hand lower values of SSA_{440} (< 0.85) correspond to strongly absorbing particles i.e. black carbon/soot. The SSA value in the range from 0.85 to 0.90 and 0.90–0.95 corresponds to moderately absorbing and slightly absorbing aerosol particles, respectively[53]. The variations of SSA with a wavelength of solar radiation can be used for the understanding of prominent aerosol types i.e. dust, sulfate, and black carbon, and can further be used in combination with AE for the separation of atmospheric aerosol classes[54]. The SSA is obtained over Lahore at four wavelengths, 440, 675, 870, and 1020 nm, to examine aerosol fluctuations. Figure 2 displays the seasonal mean variation of the SSA. The overall mean values of SSA at 400 nm are found to be 0.90 ± 0.02 indicating moderately absorbing aerosols and is comparable with the results of the urban environment i.e. Xianghe (0.90) and less than Shanghai (0.91), Tongyu (0.91) and Harbin (0.93)[53,55–57]. The SSA_{440} during spring, summer, autumn, and winter are found to be 0.86 ± 0.03, 0.91 ± 0.03, 0.89 ± 0.02 and 0.89 ± 0.03, respectively. The variation in SSA values indicates various classes of aerosol particles during the study period over Lahore.

There are absorbing and scattering components in aerosol particles, as seen by the SSA_{440}'s seasonal variations with wavelength changes [52]. The increasing trend of SSA_{440} with wavelength during spring and summer indicates the presence of coarse particles. Conversely, the near-infrared region's declining SSA_{440} trend with increasing wavelength indicates the presence of absorbing aerosol particles. Other researchers in Pakistan, India, and China also reported spectral variation of SSA during various seasons[16,52,54,58].

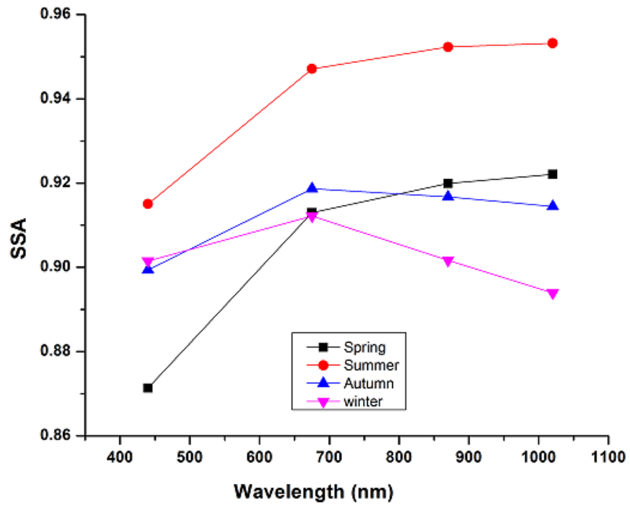

Figure 2. Single scattering albedo seasonal spectral fluctuation over Lahore, Pakistan during the study period (2007–2020).

Seasonal variation in asymmetry parameter

The Asymmetry Parameter (ASY) is an extremely important optical parameter that represents the angular distribution of solar light scattered by aerosol particles and is crucial in regulating aerosol radiative forcing, which in turn modifies regional climate[59]. ASY_{440}, which is defined as the weighted average of the scattered phase function, is dependent upon the shape, size, and chemical composition of the aerosol particles. The values of ASY_{440} vary from − 1 (completely backscattering) to + 1 (completely forward scattering), with 0 representing symmetric scattering[54].

The seasonal average variation of ASY_{440} with the wavelength of solar radiation during the study period over Lahore is shown in Fig. 3. The ASY440 during spring, summer, autumn, and winter are found to be 0.73 ± 0.02, 0.75 ± 0.01, 0.72 ± 0.02 and 0.71 ± 0.02, respectively. During winter and autumn seasons, the ASY_{440} decreases with wavelength and indicates strong wavelength dependency, which shows that the aerosol particles are absorbing. However, the ASY440 exhibits minimal wavelength fluctuation in the near-infrared region during the spring and summer, indicating the presence of transported coarse dust aerosol. Lahore experiences cool autumn and winter seasons, with AE 400–870 values greater than 1.0 suggesting the presence of fine aerosol particles. The values of ASY440 during autumn (0.72 ± 0.02) and winter (0.71 ± 0.02) are well in line with the values reported by D´Almeida et al.[60], according to which the ASY440 values nearly equal to 0.72 indicates fine mode dry aerosol particles. The obtained results are similar to the results reported during the dusty days over different locations like Shirahama, SACOL, Noto, and Beijing[55,61].

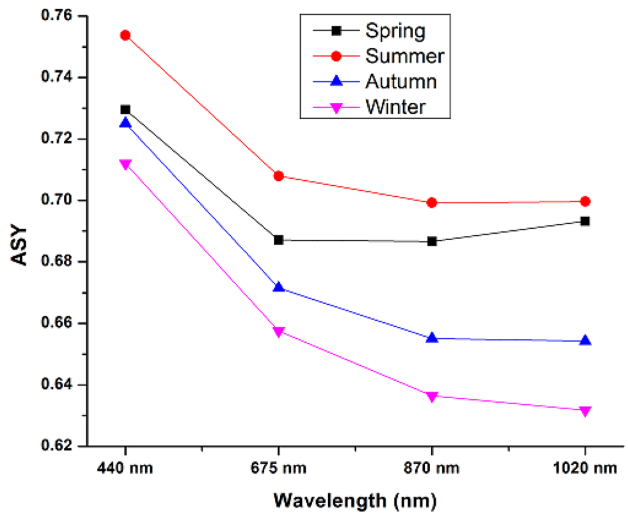

Figure 3. Asymmetry factor seasonal spectral fluctuation over Lahore during the study period.

Seasonal variation in volume size distribution

The columnar aerosol size distribution, which is strongly related to AE and its changes, is a crucial factor in determining the aerosol optical characteristics[61]. Compared to the fine mode particles, which are mainly associated with anthropogenic activities like fuel combustion and vehicle exhaust, the coarse mode particles are more likely to consist of locally suspended dust that is carried over great distances by strong winds or released during building construction[56]. Figure 4 shows the seasonal mean of the aerosol volume size distribution over urban Lahore. The fine mode radius is found to be < 0.6 µm and the coarse mode radius to be > 0.6 µm, indicating that the aerosol volume size distributions have a bimodal logarithm normal structure. During spring and summer, the volume concentration of fine mode particles peaks at a radius of 0.11 µm, while in the autumn and winter, it peaks at a radius of 0.19 µm. Similarly, during spring, autumn, and winter the coarse mode, the peak occurs at radii of 3.9 µm, and during summer it occurs at 2.9 µm. During spring, the coarse mode particles dominate over urban Lahore mostly because of the presence of transport dust particles, which have comparable seasonal mean volume size distribution at the SACOL and Beijing sites[55,62,63]. Because of its geographic location, which is marked by flatter rain, a predominate wind that is acquainted with the west side of SACOL[55,62,63], Harbin has frequently been influenced by the carried dust during the study period.

The presence of suspended snow crystals and long-range dust aerosols is suggested by the coarse mode particles, which are still predominant in the spring, autumn, and winter and have a larger coarse mode radius[55,62]. Winter has a slightly higher volume concentration of fine modes than other seasons. This suggests that heating causes anthropogenic emissions such as soot particles and that frequently occurring weather conditions that are detrimental to the diffusion of pollutants also cause aerosols to coagulate[54].

Determination of aerosol classes

Aerosol type can be determined using information on the optical and physical features of the aerosols' spectrum fluctuation. The most often used technique for differentiating between different types of aerosols is to combine AOD and AE, which stand for aerosol loading and aerosol size, respectively[54,64].

Figure 5 shows the scatter plot of the daily mean value of AOD $_{440}$ and AE$_{440\text{-}870.}$ A broad range of AE $_{440–870}$ values for low to high AOD $_{440}$ demonstrates the great diversity in aerosol properties and also indicates that different forms of aerosol are mixing in the atmosphere above Lahore's metropolitan environment. To quantify the contribution of the main aerosol kinds, some threshold values should be considered before determining the aerosol types. Clean continental aerosols (CC) are defined as AOD $_{440} < 0.2$, representing the average conditions over Lahore, and long-range transported desert dust aerosols (DD) as AOD $_{440} > 0.4$ and less than 0.5 and AE $_{440–870} < 0.8$. Cases involving transportable biomass-burning aerosols or thick urban/industrial plumes (BB/UI) are taken into consideration for AOD$_{440} > 0.4$ and AE$_{440\text{-}870} > 1.0$, whereas cases that do not fit into any of the aforementioned categories are called mixed-type aerosols (MIX)[65,66].

The seasonal percentage contributions of four aerosol types over Lahore during the long-term study period are shown in Fig. 6. During the winter season, the BB/UI has the topmost contribution (53%) followed by MIX (42.1%) aerosols, it is likely that local and transported pollutants, such as the burning of agricultural crop residues, vehicle exhaust, and soot particles from heating, have a significant impact on the amount of anthropogenic aerosols that are present in Lahore. In addition, DD aerosols make up a sizeable component, accounting for a relatively high percentage i.e. 57%, 50%, and 39%, during autumn, summer, and spring, causing Lahore to frequently experience dust aerosols.

The fact that CC aerosols only make up very little i.e. 1.60% in the spring, 0.19% in the summer, 0.14% in the autumn, and 1.21% in the winter, indicates that Lahore's air quality is far worse than that of the majority of

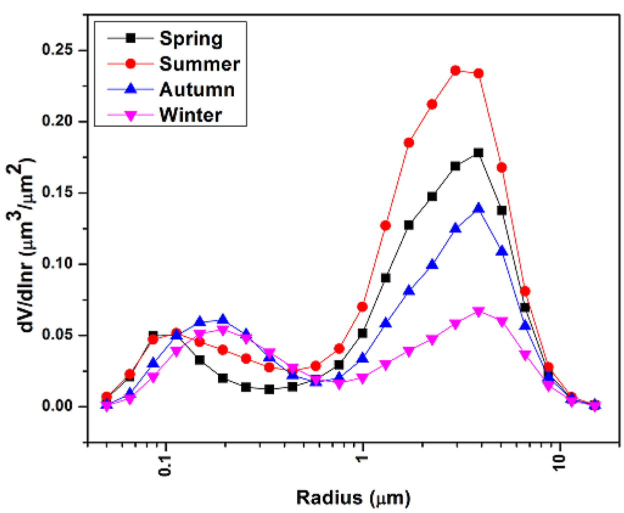

Figure 4. Seasonal variations in the volume charge distribution in Lahore, Pakistan during the research period (2007–2020).

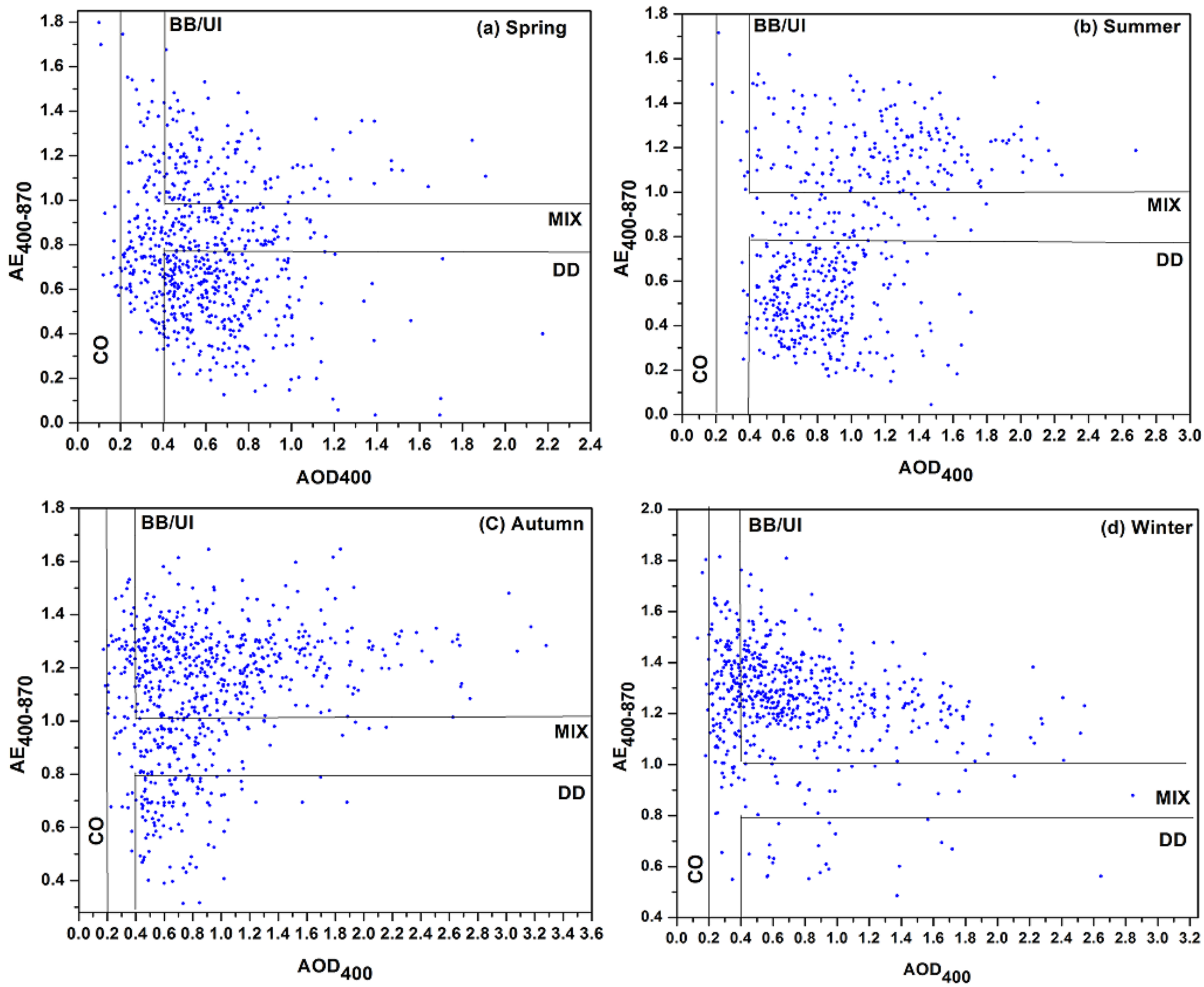

Figure 5. A scatter chart of the daily average values of AOD_{440} and $AE_{400\text{-}870}$ shows the predominant aerosol classes over Lahore, Pakistan, in the (**a**) spring, (**b**) summer, (**c**) autumn, and (**d**) winter.

south Chinese cities (low aerosol load with $AOD_{440} < 0.2$)[52]. The results presented above mostly depend on the threshold used, and modifications to the threshold value may have a significant impact on the contribution[54].

Conclusions

Thirteen years of ground-based observations from AERONET over the urban environment of Lahore, Pakistan, from 2007 to 2020 were used to analyze regional aerosol optical features (AOD, AE, SSA, ASY, and VSD) and classify aerosol species. The values of AOD_{440} in four seasons i.e. spring, summer, autumn, and winter are found to be 0.61, 0.95, 0.91, and 0.74 with corresponding $AE_{440-870}$ values of 0.77, 0.78, 1.10, and 1.25, respectively. The significant variation in both $AE_{440-870}$ and AOD_{440} shows how frequently the types of aerosols over Lahore change. The $SSA_{400\,nm}$ in spring, summer, autumn, and winter are found to be 0.87, 0.91, 0.89, and 0.90, respectively with an overall average of 0.89 ± 0.03, indicating that the aerosols over Lahore are absorbing. Similarly, the mean ASY during spring, summer, autumn, and winter are found to be 0.72, 0.75, 0.72, and 0.71, respectively. The results show that the values of ASY decrease with increasing wavelength during the winter season showing that the particles are of absorbing nature. The summer and springtime near-infrared values of ASY exhibit a little reduction, indicating the impact of transported coarse-mode dust particles. Bimodal logarithmic behavior characterizes the aerosol volume size distribution, with a fine mode radius of 0.11 µm in the spring and summer and 0.19 µm in the autumn and winter. Likewise, the coarse mode radius of 3.9 µm was investigated during spring, autumn, and winter and 2.9 during summer. This implies that during the study period, fine and coarse-mode aerosols over Lahore were equally significant. Aerosol type discrimination results showed that during spring, summer, and autumn, DD aerosol predominated, as did BB/UI aerosol during winter, whereas CC aerosols made up a very small part, indicating poor air quality in Lahore city. Our knowledge of the local aerosol characteristics, regional movement, and their climatic consequences over Lahore would be enhanced by the current study efforts.

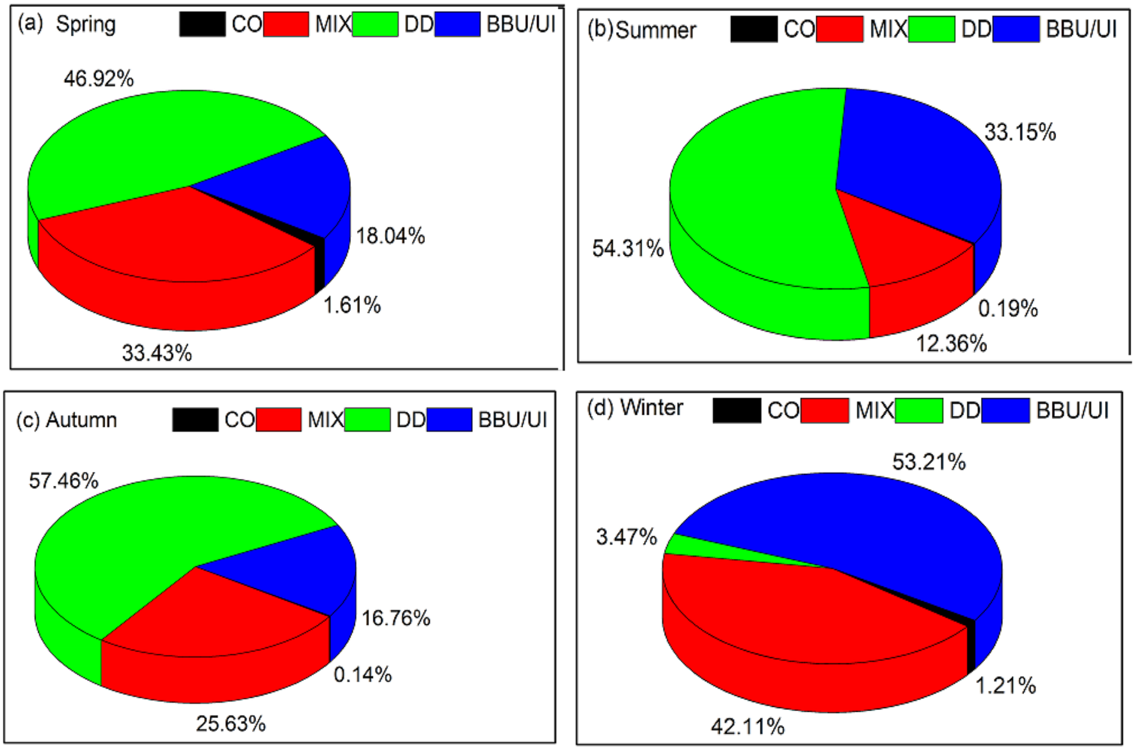

Figure 6. Percentage contribution of different types of aerosols during (**a**) spring (**b**) summer (**c**) autumn (**d**) winter.

Materials and methods

Description of the study location

The study region is the urban location of Lahore, the capital of Punjab province and a major hub of trade in Pakistan, located at 31.5204°N latitude and 74.3587°E longitude. Lahore is a medieval metropolis spanning 1772 square kilometers and is located on the western bank of the River Ravi at an elevation of 217 m above sea level. Lahore is the second-largest city in Pakistan and one of the most populated cities in the world, with an estimated 12.64 million people and a growth rate of 3.83%. Lahore is the commercial hub of Punjab, where most people work in trade, industry, and commerce, hence more people are moving there from all over the country. The population of the city is gradually increasing, and the city's quick expansion and development are increasing the amount of vehicles that travel through it.

Paper, textiles, steel, cigarettes, chemicals, steel, textiles, construction materials, medicines, and industrial food processing are the main industries in the center of Lahore. Lahore city is the hub of offices, schools, colleges, and different kinds of residential neighborhoods, which makes it vulnerable to vehicle emissions from heavy traffic. In addition, rush-hour traffic is still bad in the morning and late afternoon as most people head home from work, school, and college (Fig. 7).

The city center experiences primarily hot weather from May to August[24,25,67], with an average temperature of 40 °C. The monsoon season (July and September) is when a series of wet spells starts[68,69]. The winter season begins in December and lasts through February, with an average temperature of 6 °C[24,25,70]. The wintertime is typically chilly and cloudy[22].

Meteorological condition of the study location

We collected local meteorological data from the Pakistan Meteorological Department, including relative humidity, temperature, rainfall, and wind speed. Figure 8 shows the mean monthly variation in the ambient temperature (°C), relative humidity (%), rainfall (mm), and wind speed (m/s).

Relative humidity values are observed to follow a bi-model distribution, with two peaks around 61% in July and 48% in February. The temperature can reach up to 37 °C in June. After that, it progressively drops until January, when it reaches its lowest point of 12 °C. According to the distribution, there was a significant concentration of precipitation from June to September, with a peak of 5 mm in July, while very little rainfall from October to December. The shift in the monthly variation in wind speed is observed to be quite slight, with April and May recording the highest monthly wind speed (2.8 m/s). The four seasons that are the subject of this study, are spring (March–May), summer (June–August), autumn (September–October), and winter (December–February).

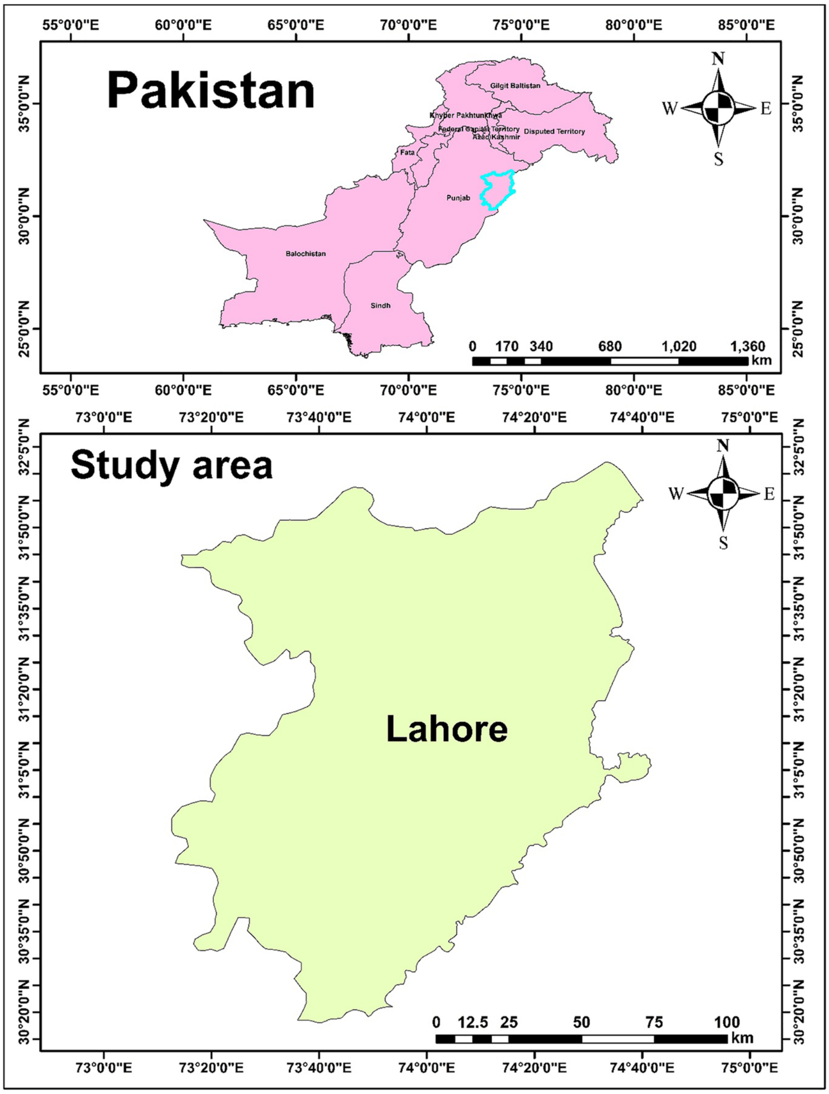

Figure 7. Map of the current study location i.e. Lahore, Pakistan. The map was generated using ArcMap version 10.7.1.

Instrumentation

AERONET

The Aerosol Robotic Network (AERONET) is a NASA-established network of over 400 permanent and temporary locations worldwide that is used for ground-based remote sensing of aerosols. One of the AERONET stations, Lahore was put into service in December 2006 as a result of a partnership between NASA and Pakistan Space and Upper Atmosphere Research Commission (SUPARCO), located in the Institute of Space Technology, Lahore's Space and Atmospheric Sciences Division. A CIMEL sun/sky radiometer, which measures diffuse sky radiance from 440 to 1020 nm and direct sun radiance from 340 to 1020 nm spectral ranges, is the component of an AERONET device[71]. AERONET provides aerosol data at three levels i.e. level 1.0 (unscreened), level 1.5 (cloud screened)[72], and level 2.0 (cloud screened and quality assured)[71]. For the current study, AERONET level 2.0 (cloud screened and quality assured) has been used for the investigation of AOD, AE, perceptible water, SSA, ASY, and volume size distribution during the study 2007–2020. Level 1.0 (unscreened), level 1.5 (cloud screened)[72], and level 2.0 (cloud screened and quality assured) are the three levels of aerosol data that AERONET offers. AOD, AE, noticeable water, SSA, ASY, and volume size distribution have all been investigated for the current study using AERONET level 2.0 (cloud screened and quality certified) during the study 2007–2020.

Consent to participate

The authors have given their approval to take part in this study.

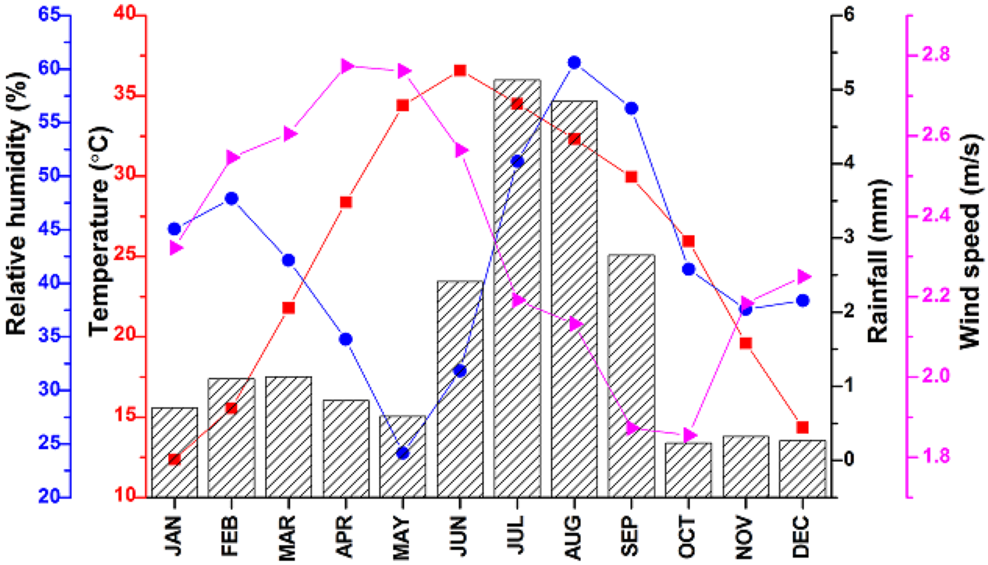

Figure 8. The meteorological distribution of relative humidity (%), Temperature (°C), rainfall (mm), and wind speed (m/s) during the study period from 2007 to 2020 over urban Lahore.

Data availability

The corresponding author is agreeable to grant the data utilized in this research work on behalf of realistic appeal.

Received: 9 December 2023; Accepted: 5 April 2024
Published online: 12 April 2024

References

1. Wu, J. H. *et al.* Widespread air pollutants of the North China plain during the Asian summer monsoon season: A case study. *Atmos. Chem. Phys.* **18**, 8491–8504 (2018).
2. Che, H. *et al.* Variation of aerosol optical properties over the Taklimakan Desert in China. *Aerosol Air Qual. Res.* **13**(2), 777–785 (2013).
3. Liu, Z., Lee, K. H., Wang, Y., Xin, J. & Hao, W. M. First observation-based estimates of cloud-free aerosol radiative forcing across China. *J. Geophys. Res.* **101**, 519–533 (2010).
4. Yang, X., Wang, S. J., Zhang, W. Z. & Yu, J. H. Are the temporal variation and spatial variation of ambient SO2 concentrations determined by different factors?. *J. Clean. Prod.* **167**, 824–836 (2017).
5. Pandithurai, G., Pinker, R., Devara, P., Takamura, T. & Dani, K. Seasonal asymmetry in diurnal variation of aerosol optical characteristics over Pune, western India. *J. Geophys. Res. Atmos.* **112,** D08208 (2016)
6. Aïssani, O. & Mokhnache, A. Aerosol size distribution retrieved from optical depth measurements in Tamanrasset and Blida. *J. Renew. Energies* **15**(2), 207–218 (2012).
7. Kumar, K. R. *et al.* Aerosol climatology and discrimination of aerosol types retrieved from MODIS, MISR, and OMI over Durban (29.88° S, 31.02° E), South Africa. *Atmos. Environ.* **117**, 9–18 (2014).
8. Titos, G. *et al.* Effect of hygroscopic growth on the aerosol light scattering coefficient: A review of measurements, techniques and error sources. *Atmos. Environ.* **141**, 494–507 (2016).
9. Ma, Y., Xin, J., Zhang, W. & Wang, Y. Optical properties of aerosols over a tropical rainforest in Xishuangbanna, South Asia. *Atmos. Res.* **178**, 187–195 (2016).
10. Verma, S. *et al.* A new classification of aerosol sources and types as measured over Jaipur, India. *Aerosol Air Qual. Res.* **15**, 985–993 (2015).
11. More, S., Kumar, P. P., Gupta, P., Devara, P. C. S. & Aher, G. R. Comparison of aerosol products retrieved from AERONET, MICROTOPS, and MODIS over a tropical urban city, Pune, India. *Aerosol Air Qual. Res.* **13**, 107–121 (2013).
12. Giles, D. M. *et al.* An analysis of AERONET aerosol absorption properties and classifications representative of aerosol source regions. *J. Geophys. Res. Atmos.* **117**, D17203 (2012).
13. Bibi, H., Alam, K. & Bibi, S. Estimation of shortwave direct aerosol radiative forcing at four locations on the Indo-Gangetic Plains: Model results and ground measurement. *Atmos. Environ.* **163**, 166–181 (2017).
14. Shaheen, K. *et al.* Aerosol clustering in an urban environment of Beijing during (2005–2017). *Atmos. Environ.* **213**, 534–547 (2019).
15. Alam, K., Trautmann, T. & Blaschke, T. Aerosol optical and radiative properties during summer and winter seasons over Lahore and Karachi. *Atmos. Environ.* **50**, 234–245 (2012).
16. Alam, K., Trautmann, T., Blaschke, T. & Subhan, F. Changes in aerosol optical properties due to dust storms in the Middle East and Southwest Asia. *Remote Sens. Environ.* **143**, 216–227 (2014).
17. Alam, K. K. *et al.* Classification of aerosols in an urban environment based on optical measurements. *Aerosol Air Qual. Res.* **16**, 2535–2549 (2016).
18. Zhang, M. *et al.* An investigation of vertically distributed aerosol optical properties over Pakistan using CALIPSO satellite data. *Remote sens.* **12**(14), 2183 (2020).
19. Zeb, B. *et al.* Black Carbon aerosol characteristics and radiative forcing over the high altitude glacier region of Himalaya-Karakorum-Hindukush. *Atmos Environ.* **238**, 117711 (2020).
20. Zeb, B. *et al.* Variation in coarse particulate matter (PM10) and its characterization at multiple locations in the Semiarid Region. *Front. Environ. Sci.* **10**, 843582 (2022).

21. Usman, F. *et al.* In-depth analysis of physicochemical properties of particulate matter (PM10, PM2.5 and PM1) and Its characterization through FTIR, XRD, and SEM–EDX Techniques in the Foothills of the Hindu Kush Region of Northern Pakistan. *Atmosphere.* **13**(1), 124 (2022).
22. Ali, G. *et al.* Assessment of the simulated aerosol optical properties and regional meteorology using the WRF-Chem model. *Arab. J. Geosci.* **14**(18), 1871 (2021).
23. Tariq, S. & Ul-Haq, Z. Ground-based remote sensing of aerosol properties over a coastal megacity of Pakistan. *Adv. Meteo.* **2018**, 1–12 (2018).
24. Ali, G. *et al.* Spatiotemporal trends of aerosols over urban regions in Pakistan and their possible links to meteorological parameters. *Atmosphere* **11**(3), 306 (2020).
25. Ali, N., Adil, I., Magsi, A. & Asif, E. Particle size, morphology, and characterization of indoor and outdoor airborne particulate matter for toxic metals in Karachi. *Int. J. Environ. Sci. Te.* **17**, 3969–3982 (2020).
26. Awais, M. *et al.* Assessment of aerosol optical properties using remote sensing over highly urbanized twin cities of Pakistan. *J. Atmos Sol-Terr Phys.* **173**, 37–49 (2018).
27. Khan, M., Tariq, S. & Haq, Z. U. Variations in the aerosol index and its relationship with meteorological parameters over Pakistan using remote sensing. *Environ. Sci. Pollut. Res.* **30**(16), 47913–47934 (2023).
28. Huang, X. *et al.* Seasonal variation and secondary formation of size-segregated aerosol water-soluble inorganic ions during pollution episodes in Beijing. *Atmos. Res.* **168**, 70–79 (2016).
29. Lee, J. *et al.* Characteristics of aerosol types from AERONET sunphotometer measurements. *Atmos. Environ.* **44**, 3110–3117 (2010).
30. Bai, J. *et al.* Toward characterization of the aerosol optical properties over the Loess Plateau of Northwestern China. *J. Quant. Spectrosc. Radiat. Transf.* **112**, 346–360 (2011).
31. Bibi, H., Alam, K., Chishtie, F., Bibi, S., Shahid, I., Blaschke, T. 2015.Intercomparison of MODIS, MISR, OMI, and CALIPSO aerosol optical depth retrievals for four locations on the Indo-Gangetic plains and validation against AERONET data. *Atmos. Environ.* **11**(113–126).
32. Mangla, R., Indu J, Chakra S.S. 2020. Inter-comparison of multi-satellites and Aeronet AOD over Indian Region. *Atmos. Res.* **240** (104850).
33. Heydari, S., Tainio, M., Woodcock, J. & de Nazelle, A. Estimating traffic contribution to particulate matter concentration in urban areas using a multilevel Bayesian meta-regression approach. *Environ. Int.* https://doi.org/10.1016/j.envint.2020.105800 (2020).
34. Bajwa, A. U. & Sheikh, H. A. Contribution of road transport to Pakistan's air pollution in the urban environment. *Air* **1**(4), 237–257. https://doi.org/10.3390/air1040018 (2023).
35. Lin, Y. *et al.* A multiyear evolution of aerosol chemistry impacting visibility and haze formation over an Eastern Asia megacity, Shanghai. *Atmos. Environ.* **92**, 76–86 (2014).
36. IPCC In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker, T. F. *et al.*) 1535 (Cambridge University Press, 2013).
37. Wang, Y., Jiang, J. H. & Su, H. Atmospheric responses to the redistribution of anthropogenic aerosols. *J. Geophys. Res. Atmos.* **120**, 9625–9641 (2015).
38. Xie, Y., Zhao, B., Zhang, L. & Luo, R. Spatiotemporal variations of PM2.5 and PM10 concentrations between 31 Chinese cities and their relationships with SO2, NO2, CO, and O3. *Particuology* **20**, 141–149 (2015).
39. Zhang, X. Y. *et al.* Atmospheric aerosol compositions in China: Spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols. *Atmos. Chem. Phys.* **12**, 779–799 (2012).
40. Zhang, J., Jeffrey, S., Reid, M. C. & Angela, B. An evaluation of the impact of aerosol particles on weather forecasts from a biomass burning aerosol event over the Midwestern United States: Observational-based analysis of surface temperature. *Atmos. Chem. Phys.* **16**, 6475–6494 (2016).
41. Li, Z. *et al.* Observations of residual submicron fine aerosol particles related to cloud and fog processing during a major pollution event in Beijing. *Atmos. Environ.* **86**, 187–192 (2015).
42. Kedia, S., Ramachandran, S., Holben, B. N. & Tripathi, S. Quantification of aerosol type, and sources of aerosols over the Indo-Gangetic Plain. *Atmos. Environ.* **98**, 607–619 (2014).
43. Russell, P. B. *et al.* Identifying Aerosol Type from Space: Absorption Angstrom Exponent as a Foundation for Multidimensional Supervised Clustering and Mahalanobis Classification. In AGU Fall Meeting Abstracts. **2010**, A11E-0091 (2010).
44. Russell, P. B. *et al.* A multiparameter aerosol classification method and its application to retrievals from spaceborne polarimetry. *J. Geophys. Res. Atmos.* **119**, 9838–9863 (2014).
45. Tiwari, S. *et al.* Variability in optical properties of atmospheric aerosols and their frequency distribution over a megacity "New Delhi," India. *Environ. Sci. Pollut. Res.* **23**, 8781–8793 (2016).
46. Fan, A. *et al.* Evaluation and comparison of long-term MODIS C5.1 and C6 products against AERONET observations over China. *Remote Sensing.* **9**(12), 1269. https://doi.org/10.3390/rs9121269 (2017).
47. Khan, R., Kumar, K. R., Zhao, T., Ullah, W. & de Leeuw, G. Interdecadal changes in aerosol optical depth over Pakistan based on the MERRA-2 reanalysis data during 1980–2018. *Remote Sensing.* **13**(4), 822. https://doi.org/10.3390/rs13040822 (2021).
48. Zhu, J. *et al.* Column-integrated aerosol optical and physical properties at a regional background atmosphere in North China Plain. *Atmos. Environ.* **84**, 54–64 (2014).
49. Zhu, J. *et al.* Study of aerosol optical properties at Kunming in southwest China and long-range transport of biomass burning aerosols from North Burma. *Atmos. Res.* **169**, 237–247 (2016).
50. Payra, W., Kumar, P., Verma, S., Prakash, D. & Soni, M. Potential source identification for aerosol concentrations over a site in Northwestern India. *Atmos. Res.* **169**, 65–72 (2016).
51. Wang, W. Z., Wang, Y. M., Song, W. J. & Shi, G. Q. Evaluation of infrared heat loss of dust-polluted surface atmosphere for solar energy utilization in the mine area. *Int. J. Hydrogen Energy* **41**, 15892–15898 (2016).
52. Xia, X. *et al.* Ground-based remote sensing of aerosol climatology in China: Aerosol optical properties, direct radiative effect, and its parameterization. *Atmos. Environ.* **124**, 243–251 (2016).
53. Chen, Q., Yuan, Y., Huang, X., He, Z. & Tan, H. Assessment of column aerosol optical properties using ground-based sunphotometer at urban Harbin, Northeast China. *J. Environ. Sci.* **74**, 50–57 (2018).
54. Patel, P. N., Dumka, U. C., Babu, K. N. & Mathur, A. K. Aerosol characterization and radiative properties over Kavaratti, a remote island in the southern Arabian Sea from the period of observations. *Sci. Total Environ.* **599**, 165–180 (2017).
55. Che, H. *et al.* Column aerosol optical properties and aerosol radiative forcing during a serious haze-fog month over North China Plain in 2013 based on ground-based sunphotometer measurements. *Atmos. Chem. Phys.* **14**(4), 2125–2138 (2014).
56. Cheng, T. *et al.* Seasonal variation and difference of aerosol optical properties in columnar and surface atmospheres over Shanghai. *Atmos. Environ.* **123**, 315–326 (2015).
57. Zhang, Y. S. *et al.* Emission inventory of carbonaceous pollutants from biomass burning in the Pearl River Delta Region, China. *Atmos. Environ.* **76**, 189–199 (2013).
58. Bibi, H., Alam, K., Blaschke, T., Bibi, S. & Iqbal, M. J. Long-term (2007–2013) analysis of aerosol optical properties over four locations in the Indo-Gangetic plains. *Appl. Opt.* **55**(23), 6199–6211 (2016).
59. Li, J., Carlson, B. E., Dubovik, O. & Lacis, A. A. Recent trends in aerosol optical properties derived from AERONET measurements. *Atmos. Chem. Phys.* **15**, 1599 (2015).

60. D'Almeida, G. A., Koepke, P. & Shettle, E. P. Atmospheric aerosols: Global climatology and radiative characteristics. *J. Med. Microbiol.* **54**, 55–61 (1991).
61. Yu, X. N., Zhu, B. & Zhang, M. G. Seasonal variability of aerosol optical properties over Beijing. *Atmos. Environ.* **43**, 4095–4101 (2009).
62. Li, X., Zhang, L., 2012. Analysis of aerosol sources and optical properties based on backward trajectory method over SACOL. *Acta. Phys. Sin. Chin. Ed*. **61**
63. Yu, X., Kumar, K. R., Lü, R. & Ma, J. Changes in column aerosol optical properties during extreme haze-fog episodes in January 2013 over urban Beijing. *Environ. Pollut.* **210**, 217–226 (2016).
64. Pace, G., di Sarra, A., Meloni, D., Piacentino, S. & Chamard, P. Aerosol optical properties at Lampedusa (Central Mediterranean). 1. Influence of transport and identification of different aerosol types. *Atmos. Chem. Phys.* **6**, 697–713 (2006).
65. Kaskaoutis, D. G., Badarinath, K. V. S., Kharol, S. K., Sharma, A. R. & Kambezidis, H. D. Variations in the aerosol optical properties and types over the tropical urban site of Hyderabad, India. *J. Geophys. Res.* **114**, D22204. https://doi.org/10.1029/2009JD012423 (2009).
66. Li, Z. *et al.* Comparison of aerosol properties over Beijing and Kanpur: Optical, physical properties and aerosol component composition retrieved from 12 years ground-based Sun-sky radiometer remote sensing data. *JGR Atmos.* **120**(4), 1520–1535. https://doi.org/10.1002/2014JD022593 (2015).
67. Ullah, S. *et al.* Observed changes in maximum and minimum temperatures over the China-Pakistan economic corridor during 1980–2016. *Atmos. Res.* **216**, 37–51 (2019).
68. Ullah, S., You, Q., Ullah, W. & Ali, A. Observed changes in precipitation in the China-Pakistan economic corridor during 1980–2016. *Atmos. Res.* **210**, 1–14 (2018).
69. Bhatti, A. S. *et al.* The trend in extreme precipitation indices is based on long-term in situ precipitation records over Pakistan. *Water* **12**(3), 797 (2020).
70. Ullah, W. *et al.* Large-scale atmospheric circulation patterns associated with extreme monsoon precipitation in Pakistan during 1981–2018. *Atmos. Res.* **253**, 1–14 (2021).
71. Holben, B. *et al.* AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sens. Environ.* **66**, 1–16 (1998).
72. Smirnov, A., Holben, B., Eck, T., Dubovik, O. & Slutsker, I. Cloud-screening and quality control algorithms for the AERONET database. *Remote Sens. Environ.* **73**, 337–349 (2000).

Acknowledgements
The authors extend their appreciation to the Researchers supporting project number (RSP2024R349) at King Saud University, Riyadh, Saudi Arabia. The authors are also highly grateful to acknowledge the considerable services of NASA for providing AERONET data. It is noted that the Pakistan Meteorological Department provided meteorological data. The authors appreciate the anonymous reviewers' helpful criticism and improvement of the paper.

Author contributions
The study's inception and design involved input from all authors. Conception, writing, and creation of the first draft by Bahadar Zeb. Methodology, modeling, and simulation by Bahadar Zeb, Rehana Khan, and Allah Ditta. Supervision by Khan Alam. Writing Reviewing and Editing by Bahadar Zeb, Khan Alam, Rehana Khan, Allah Ditta, Rashid Iqbal, Mohamed Farouk Elsadek, Ahsan Raza, and Mohamed Soliman Elshikh. All authors have read and approved the final version of the manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL. The authors extend their appreciation to the Researchers supporting project number (RSP2024R349) at King Saud University, Riyadh, Saudi Arabia.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to K.A., A.D. or A.R.