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Research Article

Ground-Based Remote Sensing of Aerosol Properties over a Coastal Megacity of Pakistan

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Atmospheric aerosols are considered to be an important constituent of Earth's atmosphere because of their climatic, environmental, and health effects. Therefore, while studying the global climate change, investigation of aerosol concentrations and properties is essential both at local and regional levels. In this paper, we have used relatively long-term Aerosol Robotic Network (AERONET) data during September 2006–August 2014 to analyze aerosol properties such as aerosol optical depth at 500 nm (AOD), Ångström exponent (440–870 nm) (AE), refractive index (RI), and asymmetry parameter over Karachi, a coastal megacity of Pakistan. The average annual values of AOD and AE were found to be 0.48 ± 0.20 and 0.59 ± 0.29, respectively. The peak (0.88 ± 0.31) AOD was recorded in July with corresponding AE of 0.30 ± 0.22 representing reasonably higher concentration of coarse size particles over Karachi. The cluster analysis using the scatter plot between absorption AE and extinction AE revealed that desert dust prevailed in the atmosphere of Karachi in spring and summer, while biomass burning aerosols dominate in autumn and winter. The peak values of volume concentrations of coarse and fine-mode particulate matter were found in summer and autumn, respectively. Also, we found significant growing trend in single-scattering albedo with wavelength, indicating the domination of dust particles during summer and spring. The peak value of the real part of the RI was observed in spring (1.53) and modest in winter (1.50). On the contrary, the peak value of the imaginary part of the RI was observed to be constantly elevated in winter and lesser in spring.

1. Introduction

The main component of Earth's atmosphere consists of a mixture of gases. However, it also contains particles of some solid or liquid material. This particulate matter is released into the atmosphere from natural- and human-induced activities. Aerosol particles are considered to be an important constituent of Earth's atmosphere because of their climatic, environmental, and health effects. The net effect of aerosols on climate is usually quantified in terms of radiative forcing. However, due to our poor knowledge regarding the spatial and temporal distribution of aerosols and their characteristics, large uncertainties exist in quantifying the aerosol radiative forcing [1]. Keeping in view the role of aerosols, climate models consider both direct and indirect influences of these particles on radiative forcing [2]. Therefore, while studying the global climate change, investigation of aerosol concentrations and properties is essential both at local and regional levels. The satellite remote sensing (SRS) technique provides global coverage of aerosol properties for longer periods. However ground-based remote sensing is ideal for obtaining authentic and continuous aerosol characteristics over megacities all over the world [3].

As far as aerosol concentrations and their properties are concerned, Karachi is not a well-studied location. In particular, very few studies have used the remote sensing techniques to monitor aerosols over Pakistan (e.g., [4–7]). Alam et al. [5] tried to characterize the aerosol properties by using the data for small duration (1 year). However, multiyear averages are necessary for characterizing a truly representative climatological seasonal cycle [8]. In this paper, we have used relatively long-term AERONET data ranging from September 2006 to August 2014 to analyze aerosol properties over Karachi, the biggest city of Pakistan. In terms of aerosol characteristics, the location of Karachi is of special interest because it is a heavily industrialized city in

Figure 1: Map showing location of Karachi (data source: Google Earth).

the neighbor of Thar desert and the only costal AERONET site in Pakistan.

2. Study Area and Methodology

2.1. Site Description. The megacity of Karachi is located (24°51′ N, 67°00′ E) in southern Pakistan on the coast of Arabian Sea. It is the capital city of province Sindh having the densest population. The location map of the study area has been shown in Figure 1. With a population of 23.5 million and covering an area of 3,527 km^2, it has one of the strenuous ports of the region and is known as a center of trade and industrial activities in Pakistan. Emissions from industries and automobile and dust are the main sources of air pollution in Karachi. High temperature and low pressure during spring and summer seasons lift dust particles from nearby arid areas and cause dust storms in Indo-Gangetic Basin (IGB) [9–11]. On the contrary, low temperature and high pressure along with intense biomass burning during winter and autumn seasons are responsible for the formation of dense haze and fogs [12, 13].

Figure 2 shows variation in monthly average temperature, dew point, relative humidity, mean sea level (MSL) pressure, wind speed, and wind direction over Karachi during the study period. It can be seen in Figure 2 that the highest value (76.7%) of monthly average relative humidity is observed in August and lowest (46.2%) in January. Mean sea level (MSL) pressure decreases gradually from January (1017.9 hPa) to its lowest value (998 hPa) in July and then increases afterwards. The highest monthly average temperature is found to be 32.1°C in June and lowest (19.7°C) in January. Dew point temperature increases gradually from January (6.5°C) and reaches its maximum value (25.7°C) in July and then decreases afterwards. Maximum monthly average wind speed is observed in August (16.8 km/h) and minimum in November (3.7 km/h). The winds from the southeast direction have prevailed over Karachi during the study period.

2.2. AERONET. The AERONET instrument, a ground-based CIMEL sky radiometer, was established in Karachi (Pakistan) by NASA in August 2006. It operates in the wavelength ranges of 340 nm–1020 nm and 440 nm–1020 nm to record direct sun and sky radiances, respectively [14]. AERONET inversion algorithm developed by Dubovik and King [15] is employed to retrieve the wide number of aerosol optical properties from the measurements of direct and diffuse radiation. The inversion algorithm provides both retrieved aerosol properties such as size distribution, complex refractive index, and partition of spherical/nonspherical particles and is computed on the basis of the retrieved aerosol properties such as single-scattering albedo (SSA), asymmetry parameter, and broad-band fluxes.

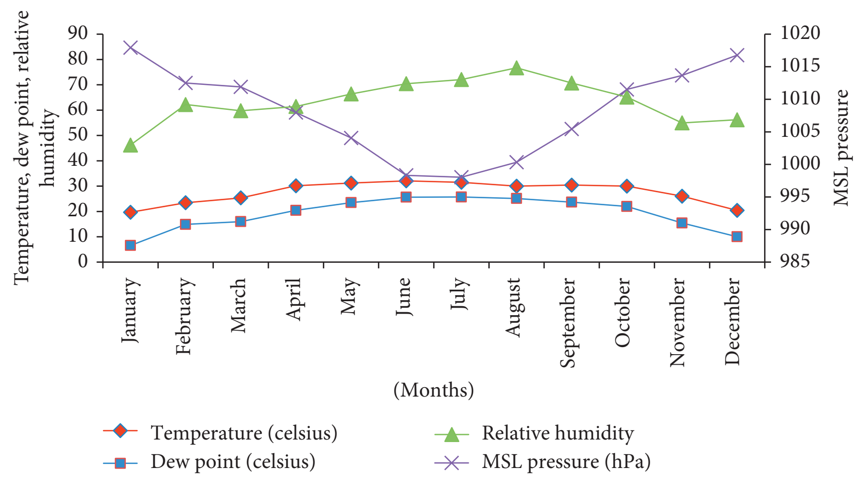
The inversion algorithm developed by Dubovik and King [15] is used to retrieve single-scattering albedo (SSA), refractive index (RI), asymmetry parameter, and size distributions of aerosols. The retrieval error in SSA is estimated to be in the range of 0.03–0.05. The uncertainty in the size distribution of aerosols within the radius of 0.1–7 μm lies in the range 15–35%, while for very small aerosols (0.05–0.1 μm) and very large aerosols (7–15 μm) it goes down considerably (greater than 35%) due to very low sensitivity of little sensitivity of aerosol scattering at AERONET wavelengths [5, 6].

Detailed description of retrieval errors of the CIMEL sky radiometer is given by Dubovik and King [15] and Smirnov et al. [16]. In the current study, we have used level 2.0 (quality assured) AOD at 500 nm, fine/coarse AOD, fine-mode fraction and AE data from direct sun algorithm, and absorption AE, extinction AE, SSA, RI, asymmetry parameter, and size distribution data from inversion algorithm. The data can be obtained via the NASA website at http://aeronet.gsfc.nasa.gov/.

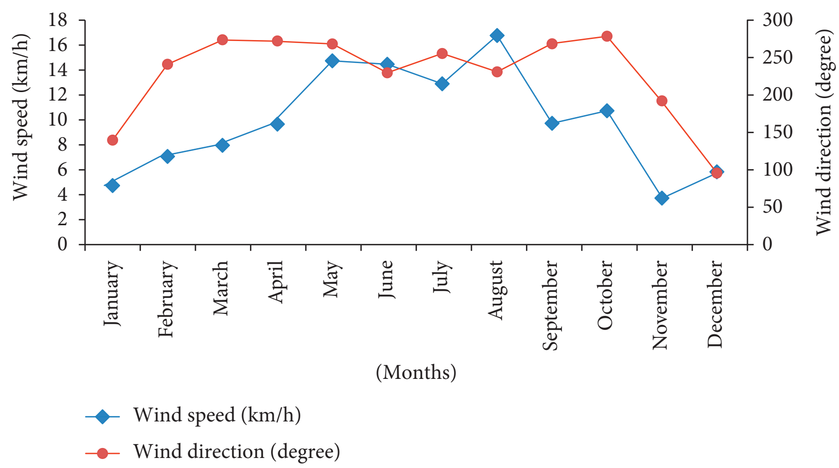
3. Results and Discussion

3.1. Variability in AOD and AE. The intensity of radiation, while travelling through Earth's atmosphere is attenuated by aerosols and gases. The AOD is a measure of extinction by the aerosols in the intensity of solar radiation during traversing through the terrestrial atmosphere. It is the most important parameter that represents the atmospheric aerosol burden. It is also significant for the identification of aerosol source regions and aerosol evaluation [17]. The AOD and AE are generally used to describe the atmospheric aerosol burden and the aerosol size distribution [18]. AE provides fundamental information about the aerosol size, and it is computed by spectral variation of AOD. Singh et al. [19], while analyzing variation of AE over central India, showed that coarse-mode and fine-mode aerosols are approximately equal in the regions where AE is close to 1. They further reported that the value of AE steadily grows as the fine-mode aerosol contribution increases.

Figure 3(a) shows the time series and trend of monthly mean values of AOD at 500 nm over Karachi for the period September 2006–August 2014. We observe a strong seasonality in AOD variations which is the specific feature of IGB that observes four distinct seasons during the year. The average values of AOD over Karachi are generally higher during spring and summer than autumn and winter. The slope and y-intercept of the linear trend line are found to be 0.0002 and 0.474, respectively. Figure 3(b) shows the histogram of AOD at 500 nm over Karachi during the study

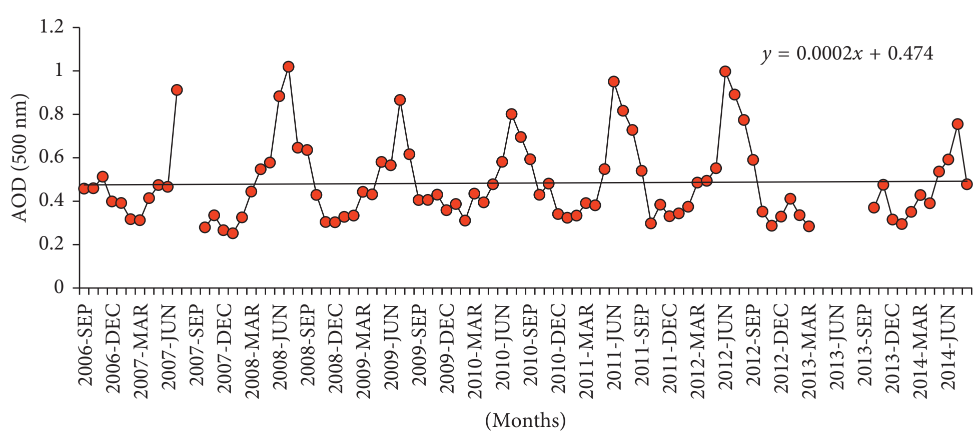


(a)



(b)

FIGURE 2: Variability of monthly average (a) temperature, dew point, relative humidity, and mean sea level (MSL) pressure, and (b) wind speed and wind direction over Karachi during the study period.



(a)

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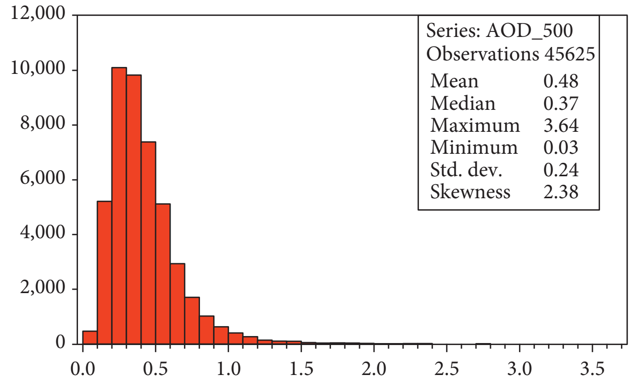
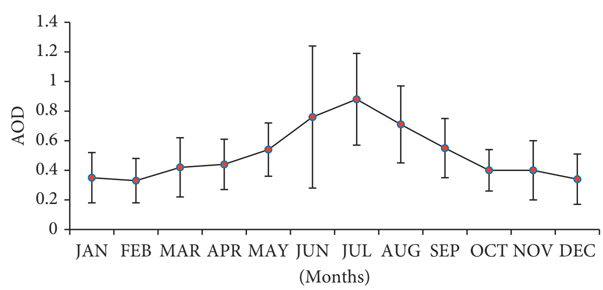


(b)

FIGURE 3: (a) Time series and linear trend of monthly mean AOD over Karachi during September 2006–August 2014. Broken line means no data. (b) All points AOD data at 500 nm over Karachi during September 2006–August 2014.

TABLE 1: Descriptive statistics of monthly average AOD, fine-mode AOD, coarse-mode AOD, and fine-mode fraction at 500 nm over Karachi during September 2006–August 2014.

	AOD	Fine-mode AOD	Coarse-mode AOD	Fine-mode fraction
Mean	0.48	0.18	0.30	0.42
Standard error	0.02	0.01	0.02	0.02
Median	0.42	0.17	0.24	0.39
Standard deviation	0.20	0.05	0.20	0.16
Range	0.86	0.28	0.88	0.59
Minimum	0.25	0.10	0.04	0.19
Maximum	1.11	0.37	0.91	0.79



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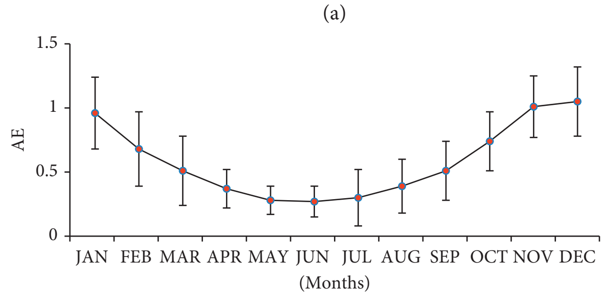

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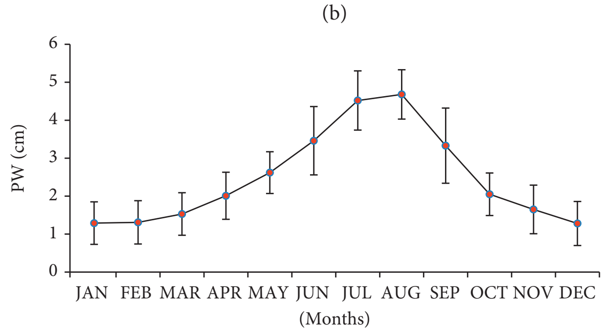

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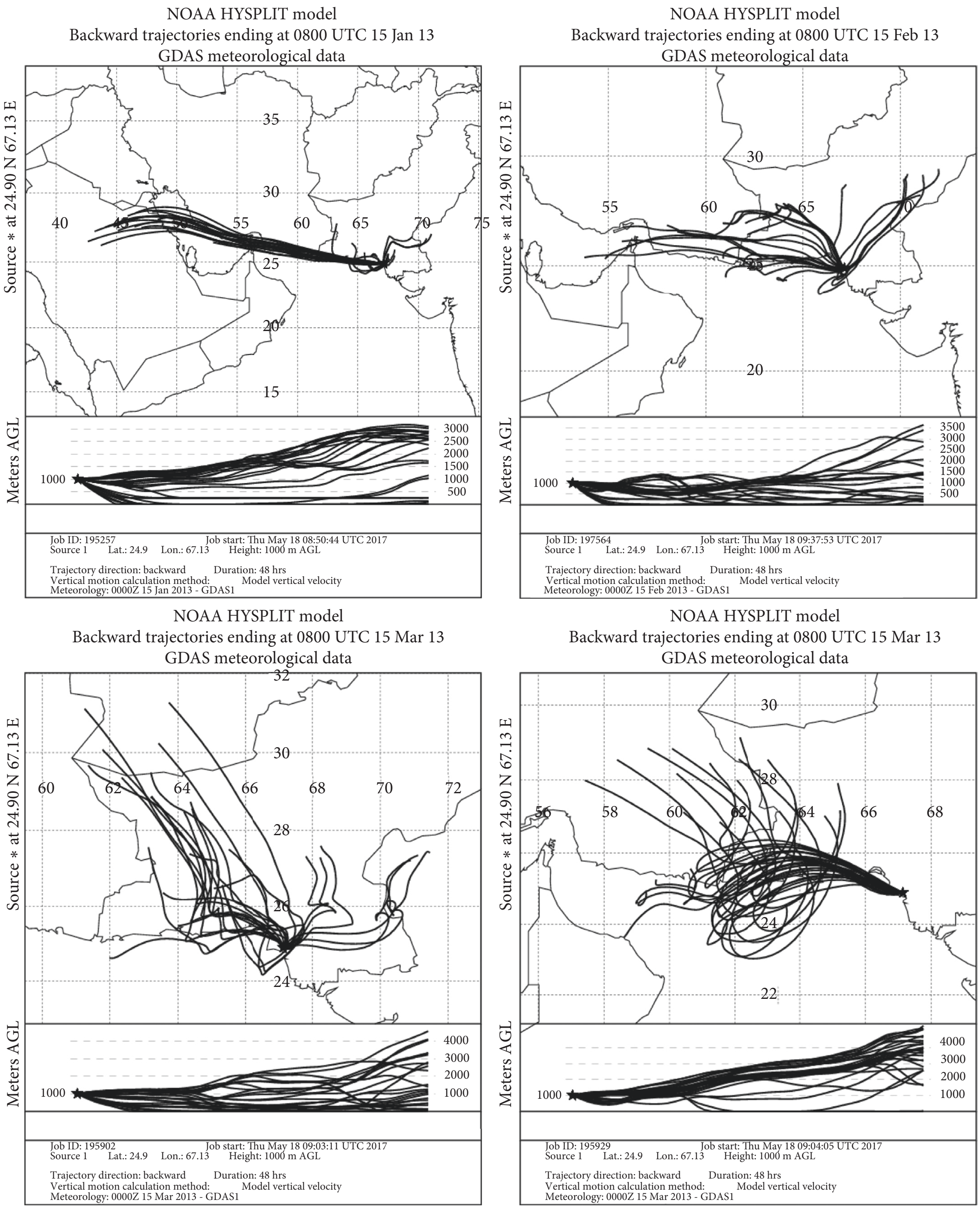

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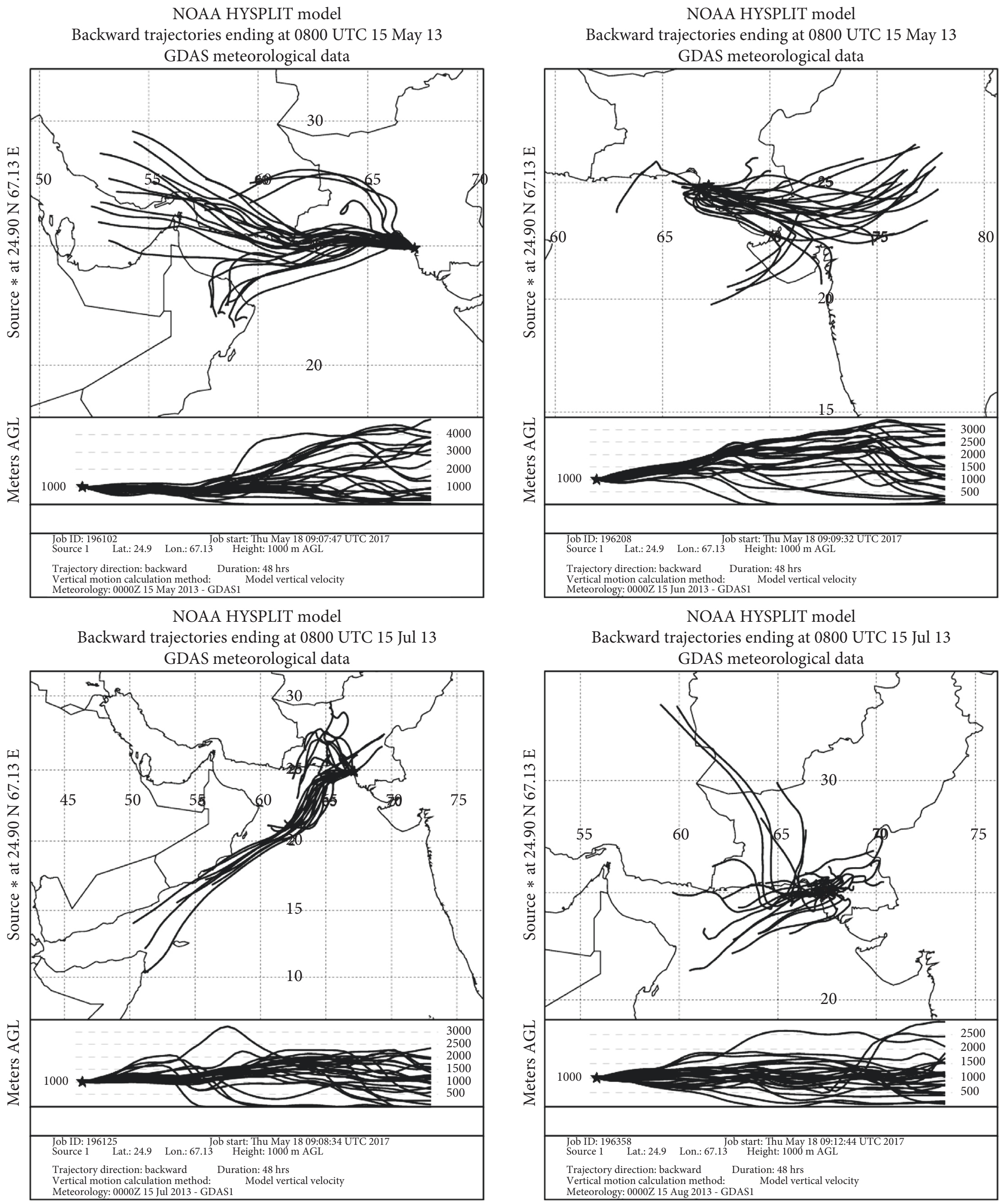

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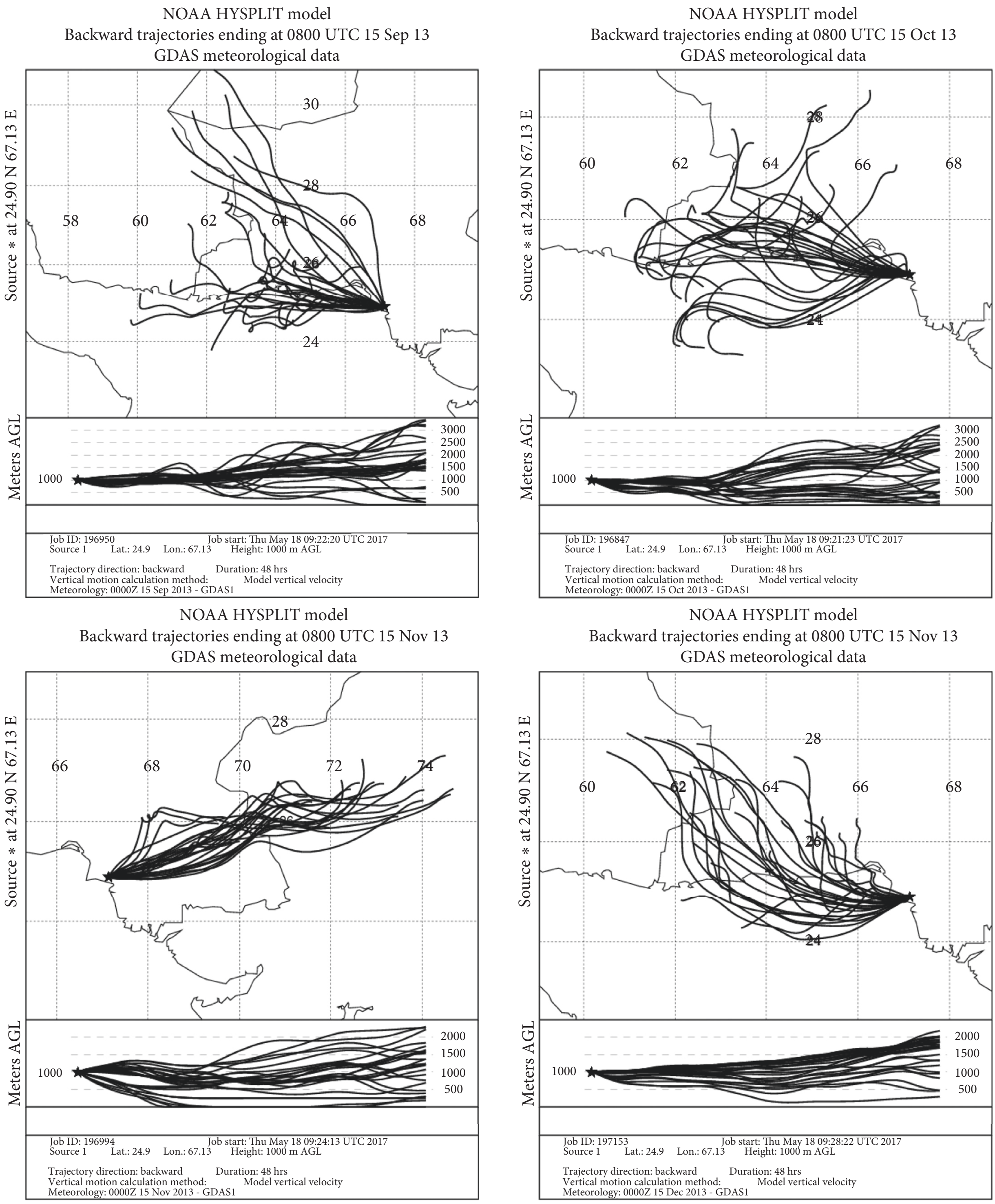

(d)

Figure 4: Monthly average variations in the (a) AOD (500 nm), (b) AE (440/870 nm), and (c) PW over Lahore during September 2006–August 2014 along with the standard deviations. (d) HYSPLIT model backward trajectories during year 2013.

period. It can be observed that highest frequency is observed at a value of 0.3.

Descriptive statistics of monthly average AOD, fine-mode AOD, coarse-mode AOD, and fine-mode fraction at 500 nm over Karachi during September 2006–August 2014 have been presented in Table 1. The mean monthly AOD is found to be 0.48 ± 0.20 during the study period. It can be further observed from Table 1 that the monthly mean value (0.30) of coarse-mode AOD is greater than the monthly mean value (0.18) of fine-mode AOD. The coarse-mode AOD is observed to have the highest range (0.88). Figures 4(a)–4(c) show the monthly average AOD (at 500 nm), AE, and precipitable water (PW) along with their standard deviations over Karachi during the period September 2006–August 2014. The error bars show the corresponding standard deviations of each monthly mean value. In order to understand the movement of air masses over Karachi, HYSPLIT model backward trajectories have been computed (Figure 4(d)). We note that, in spite of natural changes or fluctuations in the meteorological conditions and aerosol transport, the variations in the three parameters (i.e., AOD, AE, and PW) over Karachi are almost gradual and steady. We also find strong seasonal variabilities in all the three parameters. The average values of AOD are, in general, higher during spring and summer than those during autumn and winter. A similar trend has been found by Ali et al. [20], while analyzing the AERONET data over Lahore. However, a comparison of monthly average AOD values over Karachi (present study) and Lahore [20] reveals that Karachi carries only about 80% aerosol burden than that of Lahore.

Furthermore, we notice that the highest value of monthly mean AOD (0.88 ± 0.31) is recorded in July along with the AE value of 0.30 ± 0.22, indicating the dominance of coarse particles. Ali et al. [20], while studying aerosol properties over Lahore, also found the highest value of monthly mean AOD (1.02 ± 0.41) in July with the AE value of 0.84 ± 0.28. Thus, the peak AOD and the corresponding AE values observed over Karachi are found to be smaller than those measured over Lahore. This difference suggests that the atmosphere over Karachi is less polluted as compared to Lahore, while it contains comparatively elevated amount of coarse-mode particles. These particles basically originate from Thar, Sistan, and Sahara regions. We observe the lowest monthly mean AOD (0.33 ± 0.15) in February along with the AE value of 0.68 ± 0.29, representing that Karachi has the lowest aerosols burden during this month. In an earlier study over Karachi, Alam et al. [5] found the maximum average AOD value of 0.92 ± 0.28 in July, whereas the minimum monthly average AOD value was recorded to be 0.31 ± 0.11 in February. These differences arise probably because Alam et al. [5] utilized data for only one year, that is, August 2006–July 2007. In another study, Alam et al. [6] tried to analyze the AERONET data over Karachi and Lahore for a period of only six months (April–June 2010 and December 2010–February 2011). However, in terms of climatic effects, we need long-term data to analyze the situation reliably.

Alam et al. [5] also analyzed aerosol optical properties such as AOD and AE over Karachi by using AERONET data. We note some differences in AOD and AE values found in the present study and that of Alam et al. [5]. The differences have been calculated by subtracting the AOD and AE values found by Alam et al. [5] from AOD and AE values found in the present study, respectively. We observe notable differences in AOD values such as 0.3, −0.12, 0.11, and 0.1 in June, November, March, and September, respectively. As far as AE is concerned, we observe differences of 0.35, 0.24, 0.16, and 0.14 in January, November, October, and February, respectively. The inconsistencies in the results are possibly due to the fact that Alam et al. [5] utilized the data of just twelve months (August 2006–July 2007), while in present study, we have used long-term data of more than seven years (September 2006–August 2014).

Figure 4(c) shows notable variations in mean monthly PW over Karachi during the study period. It can be noted from Figure 4(c) that PW starts to increase from January (1.29 cm) and becomes maximum in August (4.68 cm) and then decreases afterwards. The occurrence of the highest value of PW in August is attributed to the high amounts of rainfall received by Karachi during the monsoon season. An overall mean value of PW is observed to be 2.48 ± 1.24 cm. Due to high values of PW, water is attracted by hygroscopic particles such as ammonium sulfate, ammonium nitrate, and sodium chloride leading to increased size of aerosol particles. During pollution episodes, high values of PW further worsen the situation by reducing the visibility. Furthermore, in the presence of aerosol and gaseous pollution, high PW is responsible for increase in the speed of process of smog formation. The scattering and absorption of light by aerosols in the lower atmosphere deteriorate the visibility [21]. In particular, fine-mode aerosols are recognized as the main cause of poor visibility [22]. Temperature inversion and low wind speeds limit the dispersion of aerosol pollution and result in low visibility. High water vapor content further reduces the visibility due to hygroscopic growth of aerosols. High hygroscopic growth increases the particulate matter concentration and scattering ability of aerosols [23].

3.2. Identification of Aerosol Types. Optical and physical properties of aerosols are dependent upon their origins. A number of methodologies have been used for the classification of aerosols. Kaskaoutis et al. [24], Sharma et al. [25], and Tariq et al. [13] used correlation of AOD and AE, while Russell et al. [26] and Giles et al. [27] used correlation between absorption and extinction AE to discriminate aerosol types. Russell et al. [26] used absorption Ångström exponent (440–870) (AAE) and extinction Ångström exponent (440–870) (EAE) from AERONET to classify dominant aerosol types. The cluster analysis using the scatter plot of AAE and EAE reduces the ambiguities in aerosol classification [26]. Different threshold values of aerosol properties are considered for aerosol subtype classification. The selection of threshold values is dependent upon location, range of AOD, and aerosol characteristics [28].

In this study, we have used the scatter plot of AAE and EAE to categorize dominant aerosol types over Karachi. We have considered $\mathrm{EAE} < 1.0$ and $0.7 < \mathrm{AAE} < 1.3$, $\mathrm{EAE} > 0.8$ and $\mathrm{AAE} > 1.3$, and $\mathrm{EAE} > 1$ and $\mathrm{AAE} > 1.2$ to represent urban/industrial aerosols, desert dust aerosols, and biomass burning aerosols, respectively [7, 29]. The remaining cases that do not belong to any of the aforementioned groups are referred to as mixed type of aerosols. Seasonal classification of different aerosol types using the scatter plot between daily mean AAE and EAE values over Karachi during the study period has been shown in Figure 5. It can be observed from Figure 5 that desert dust aerosols remained present in the atmosphere of Karachi during all the seasons, but they are more dominating in the seasons of spring and summer. Figure 5(b) exhibits dust storm

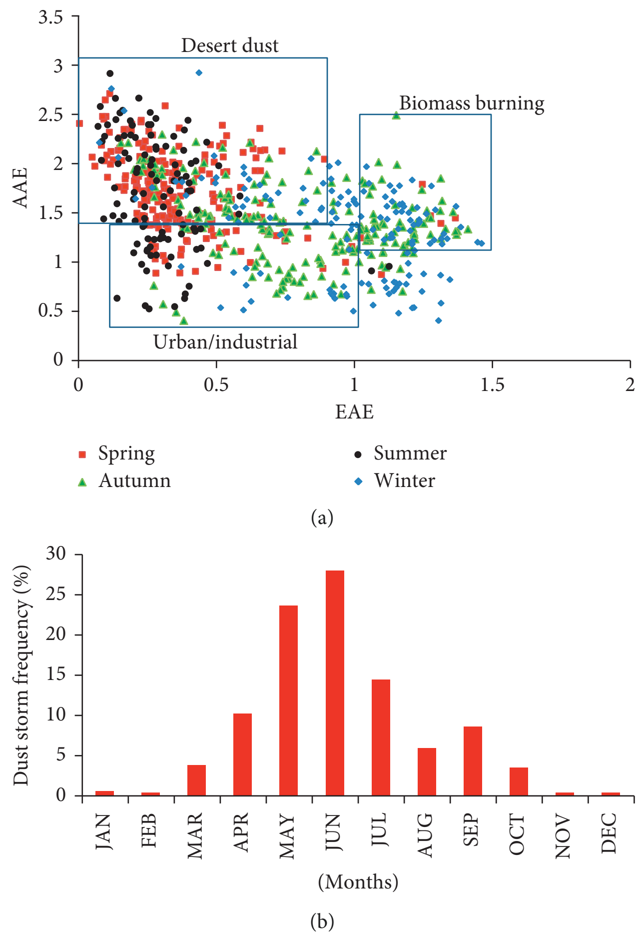

Figure 5: (a) Classification of aerosols during seasons of spring (MAM), summer (JJA), autumn (SON), and winter (DJF) using the scatter plot of daily average absorption Ångström exponent (440–870) (AAE) versus extinction Ångström exponent (440–870) (EAE) over Karachi and (b) dust storm frequency over central region of Pakistan during the study period.

frequency over the central region of Pakistan during the study period. It can be noted from the figure that higher (greater than 10%) dust storm frequencies were observed during April–July. Urban/industrial aerosols are also observed to contribute to aerosol pollution over Karachi during all the seasons. It can further be noted that during winter and autumn, biomass burning aerosols also contribute to total aerosol burden over Karachi.

3.3. Size Distribution. Size distribution of aerosols is retrieved from the inversion algorithm [15] in the range 0.05–15 μm. Figure 6 shows the aerosol volume size distribution over Karachi during different seasons. A bimodal size distribution of aerosols is observed over Karachi (Figure 6). The two-mode distribution of aerosols is caused by various factors such as combination of two air masses carrying diverse types of aerosols. The maximum volume concentration of fine-mode aerosols is found to occur at a radius of ~0.15 μm in winter and autumn and, at a radius of ~0.11 μm, in summer and spring seasons. The highest value

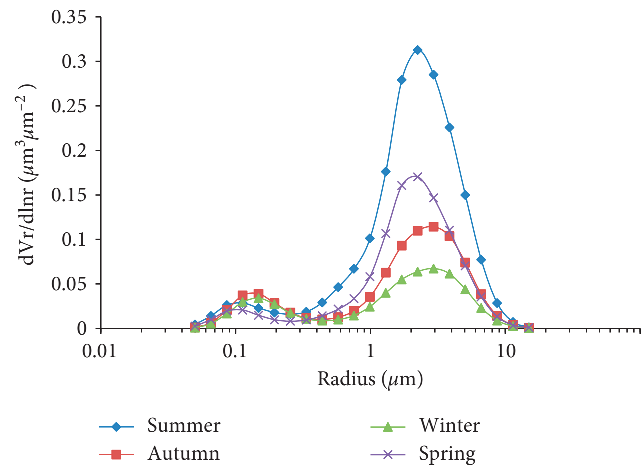

Figure 6: Seasonal averaged volume size distribution over Karachi during the study period.

of volume concentration of fine-mode aerosols is observed during autumn and lowest during spring. The high fine-mode volume concentration in autumn is attributed to increased emissions from biomass burning activities. The peak value of fine-mode volume concentration is observed to be 0.039, 0.034, 0.037, and 0.021 during autumn, winter, summer, and spring, respectively. We find the highest coarse-mode volume concentration in summer and lowest during winter season. The coarse-mode volume concentration in summer is seen to be about five times greater than that of winter. This difference in concentration is attributed to the high temperatures and wind speeds which eject dust aerosols from the surface. For coarse aerosols, the peak volume concentration is found to be 0.313, 0.171, 0.114, and 0.067 in summer, spring, autumn, and winter, respectively.

3.4. Single Scattering Albedo. Single-scattering albedo (SSA) is one of the key parameters that explain the contribution of aerosols towards radiative forcing. Increasing trend of SSA with wavelength represents the presence of desert dust aerosols, while its decreasing trend indicates the presence of urban/industrial and biomass burning aerosols [30]. Seasonal variations in average SSA with respect to wavelength (440 nm–1020 nm) over Karachi are shown in Figure 7.

It can be noted that SSA increases with wavelength during all the seasons, but it shows a maximum increase during spring season. Yu et al. [28] also reported an increase in SSA values caused by dust aerosols in spring season. This indicates that dust aerosols are consistently present in the atmosphere of Karachi during all the seasons, but they became more dominating in spring. The SSA increased in the range 0.897–0.960, 0.925–0.968, 0.897–0.930, and 0.900–0.914 during spring, summer, autumn, and winter, respectively. SSA values during the summer season are found to be the highest at all the wavelengths. Additionally, during summer, hygroscopic growth of aerosols causes SSA values to increase [9]. The mean SSA values are found to be 0.905, 0.929, 0.938, and 0.942 at the wavelength of 440 nm, 675 nm, 870 nm, and 1020 nm, respectively.

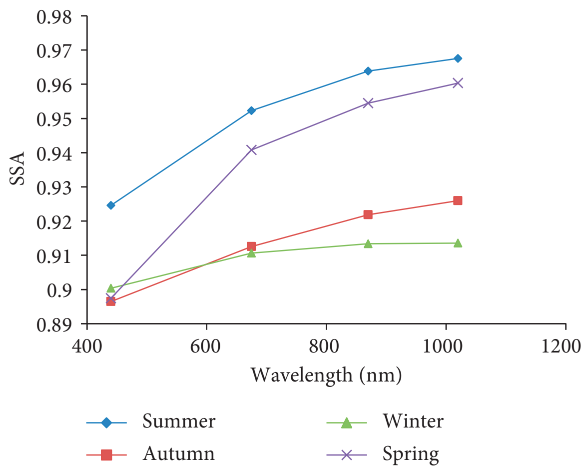

Figure 7: Variations in seasonal averaged SSA with respect to wavelength over Karachi during September 2006–August 2014.

3.5. Refractive Index. The refractive index (RI) of aerosols is an important optical property that depends on chemical composition and SSA of aerosol particles [30, 32]. The RI being a complex quantity has real and imaginary parts. The real part of the RI exhibits elevated values for high scattering, while the imaginary part increases with absorption [3]. Numerous studies have been reported that the RI to be 1.53 for dust aerosols [33–35], but uncertainty of ±0.05 in this value exists due to different methods of measurements and chemical composition of dust [36, 37].

Cheng et al. [38, 39] and Alam et al. [6] showed that the real part of the RI is larger at higher wavelengths because of high absorption due to coarse-mode aerosols.

Seasonal variations of real and imaginary parts of the RI in the wavelength range of 440–1020 nm over Karachi during September 2006–August 2014 have been shown in Figure 8. It can be observed in Figure 8(a) that during autumn and winter seasons, the real part of the RI shows considerable increasing trend in the wavelength range of 440–870 nm. During spring, the real part of the RI is found to be consistently high (>1.52) at all the wavelengths indicating the dominance of desert dust aerosols. Yu et al. [3] also presented a similar result over Beijing.

It can be seen in Figure 8(b) that the imaginary part of the RI shows a declining trend in the range 440 nm–675 nm, and then, it becomes almost stable in the range 675 nm–1020 nm. Yu et al. [3] also found low wavelength dependence of the imaginary part of the RI over Beijing. The high value of the imaginary part of the RI at each wavelength during winter indicates the dominance of absorbing aerosols in the atmosphere over Karachi. During summer, decreased values of the imaginary part of the RI at each wavelength represent the dominance of nonabsorbing aerosols. The hygroscopic growth of aerosols during summer season also leads to lower values of the imaginary part of the RI [40]. The maximum value of the imaginary part of the RI is found in winter (0.0803) and minimum in summer (0.0243). During spring and autumn, moderate mean values of 0.0643 and 0.0333 of the imaginary part of the RI, respectively, show the nearly equal amounts of different types of aerosols over Karachi.

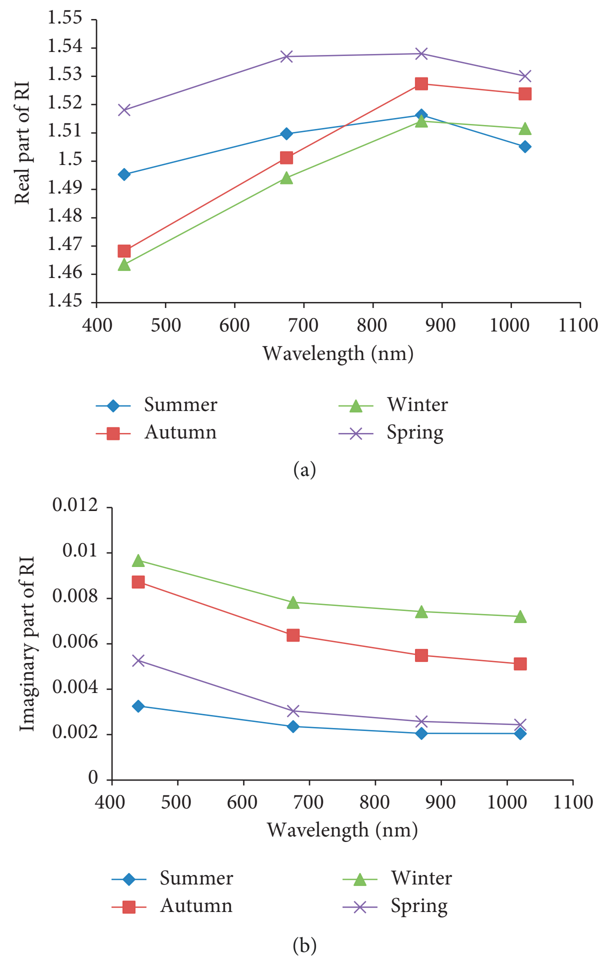

Figure 8: Seasonal variations in (a) real part and (b) imaginary part of the RI (refractive index) over Karachi during September 2006–August 2014.

3.6. Asymmetry Parameter. The asymmetry parameter is frequently used to illustrate the angular distribution of scattered light in various radiative transfer models. The asymmetry parameter and SSA are reported to have positive correlation likely due to the scavenging of aerosol particles by clouds [41]. So far, there is no direct method for the measurement of the asymmetry parameter, but several methods are used to retrieve the asymmetry parameter from aerosol and radiation measurements. The asymmetry parameter reports the direction of light after scattering by aerosol particles and hence calculated by taking cosine of the scattering direction weighted by the phase function. It ranges from +1 for complete forward scattering to −1 for complete backward scattering. For a symmetric scattering, its value is zero. Zege et al. [42] showed that the asymmetry parameter ranges from ~0.1 to ~0.75 for very clean atmospheres to heavily polluted conditions.

Figure 9 shows the variations in the spectral asymmetry parameter in different seasons over Karachi during September 2006–August 2014. It can be seen in Figure 9 that the asymmetry parameter remains higher at all the wavelengths during summer as compared to other seasons.

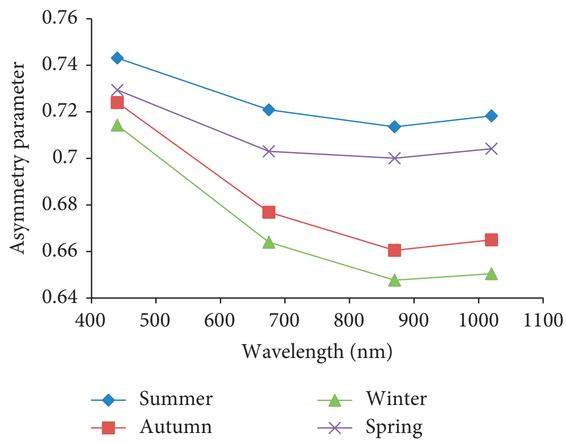

Figure 9: Variations in the seasonal averaged asymmetry parameter over Karachi during September 2006–August 2014.

It can be further noted that the asymmetry parameter shows a decreasing trend in the wavelength range 440–870 nm during each season and then depicts a little increase in the range 870–1020 nm. The seasonal mean values of the asymmetry parameter are found to be 0.724, 0.709, 0.669, and 0.682 during summer, spring, winter, and autumn, respectively [43].

4. Conclusions

In this study, we analyzed relatively long-term data of aerosol properties such as AOD, AE, size distribution, and SSA over Karachi using Aerosol Robotic Network (AERONET) ranging from September 2006 to August 2014. The mean annual AOD and AE are found to be 0.50 ± 0.21 and 0.59 ± 0.29, respectively. We noticed that the highest value of monthly mean AOD (0.88 ± 0.31) is recorded in the month of July and the minimum value of AOD (0.33 ± 0.15) in February. Precipitable water (PW) increases from January (1.29 cm) and becomes maximum in August (4.68 cm) and then decreases afterwards. The cluster analysis using the scatter plot between absorption AE and extinction AE reveals that desert dust prevails in the atmosphere over Karachi in spring and summer, while biomass burning aerosols dominate in autumn and winter. The peak value of fine-mode volume concentration is found to be 0.039, 0.034, 0.037, and 0.021 during autumn, winter, summer, and spring, respectively. For coarse aerosols, the peak volume concentration is found to be 0.313, 0.171, 0.114, and 0.067 in summer, spring, autumn, and winter, respectively. The SSA increases in the range 0.897–0.960, 0.925–0.968, 0.897–0.930, and 0.900–0.914 during spring, summer, autumn, and winter, respectively. The real part of the refractive index (RI) is found to be highest during spring (1.53) and lowest during winter (1.50). The imaginary part of the RI is observed to be consistently elevating during winter and lower during spring in the range 440–1020 nm. The seasonal mean values of the asymmetry parameter are found to be 0.724, 0.709, 0.669, and 0.682 during summer, spring, winter, and autumn, respectively.

Additional Points

(i) The mean annual AOD and AE were found to be 0.48 ± 0.20 and 0.59 ± 0.29, respectively. (ii) Cluster analysis revealed that desert dust prevails over coastal megacity Karachi in spring and summer. (iii) The highest volume concentration of coarse-mode aerosols was observed in summer.

Conflicts of Interest

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

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