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Article

Aerosol Optical Properties over South Asia from Ground-Based Observations and Remote Sensing: A Review

S. Ramachandran [1,*] and Sumita Kedia [2]

[1] Space and Atmospheric Sciences Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

[2] Computational Earth Sciences Group, Centre for Development of Advanced Computing, Pune 411007, India; E-Mail: sumitag@cdac.in

* Author to whom correspondence should be addressed; E-Mail: ram@prl.res.in; Tel.: +91-79-2631-4664; Fax: +91-79-2631-4659.

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Abstract: Seasonal and inter-annual variabilities in aerosol optical depth (AOD) and aerosol size distribution are investigated using ground-based measurements (sun photometers and sun/sky radiometers), and MODIS (MODerate Imaging Spectroradiometer) and MISR (Multiangle Imaging SpectroRadiometer) satellites over Ahmedabad, Gurushikhar, Karachi, Kanpur and Gandhi College in South Asia during 2006–2008. An analysis and a review on the comparison between aerosol optical depths measured from ground-based observations and remote sensing over South Asia is performed. Karachi and Ahmedabad AODs are two times higher than Gurushikhar, a high altitude remote site. AODs over Kanpur and Gandhi College in the Indo-Gangetic basin are higher than those measured over Ahmedabad, Gurushikhar and Karachi. Summer monsoon AODs are higher over Ahmedabad and Karachi, while winter AODs are higher over Kanpur and Gandhi College. AOD ratio, ratio of AODs obtained at 0.38 μm and 0.87 μm, is higher during postmonsoon and winter than premonsoon and monsoon suggesting the abundance of fine mode aerosols during postmonsoon and winter. Monsoon AOD ratios are lowest owing to the dominance of coarse mode (mainly sea salt) particles. Ångström wavelength exponent (α) during postmonsoon and winter are higher than that of premonsoon and monsoon values. Lower α values over Gurushikhar and Karachi indicate the dominance of coarse mode aerosols (dust in Gurushikhar, and dust and sea salt in Karachi). Dominance of fine mode aerosols due to anthropogenic activities give rise to higher α values over urban locations (e.g., Ahmedabad and Kanpur). Comparison between ground-based and MODIS (Terra and

Aqua) retrieved AODs show that aerosol optical depths do not change significantly in an hour and much of the diurnal AOD variation is captured well by the two MODIS instruments. The temporal difference (about an hour) between the ground-based and remote sensing measurements contributes negligibly to the observed differences in AODs. The differences between ground-based and remote sensing (MODIS and MISR) AODs vary on spatial scales. During the study period (2006–2008) MODIS underestimates AODs over western India by about 0.04, while over the Indo-Gangetic Plain MODIS overestimates AOD by 0.06 in (Kanpur) and underestimates by 0.07 (Gandhi College) with respect to AODs measured by hand held sun photometer and Microtops sun photometer (Ahmedabad and Gurushikhar), and AERONET sun/sky radiometers (Karachi, Kanpur and Gandhi College) respectively. During the same period MISR underestimates AODs in the range of 0.02–0.17 over Ahmedabad, Gurushikhar, Karachi and Kanpur, while in Gandhi College MISR overestimates AOD by 0.2 when compared to ground-based AODs. Results on spatial, seasonal and inter-annual variations in aerosol characteristics will be useful in improving the aerosol retrieval algorithms in remote sensing, and in regional and global estimates of aerosol radiative forcing.

Keywords: aerosols; optical properties; observations; remote sensing; South Asia; review

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1. Introduction

Atmospheric aerosols influence the global energy balance by scattering and absorbing both solar and terrestrial radiation (direct effect), as well as by acting as cloud condensation nuclei and altering the cloud microphysical properties (indirect effect) [1]. Aerosols are produced in the atmosphere through various natural and anthropogenic processes, and they get dispersed horizontally and vertically through prevailing atmospheric circulation. Aerosols are short lived with a residence time of about a week in the lower troposphere. Due to their short lifetimes and widely distributed sources, aerosols exhibit large spatial and temporal variabilities. In recent years, there has been a substantial increase in the interest in studying natural and anthropogenic aerosols because of their influence on climate through direct and indirect radiative effects [1]. Despite this, aerosols are still a major source of uncertainty in the prediction of climate change due to inadequate information on the variabilities of aerosol characteristics on regional and temporal scales [1].

In this regard, aerosol characteristics retrieved from MODerate Imaging Spectroradiometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR) on board Terra and Aqua satellites can provide a detailed knowledge over a larger spatial range. MODIS (Terra, Aqua) provides near-global daily observations of the Earth in a wide spectral range which are used to derive aerosol optical properties over land and ocean [2]. MISR observes the Earth's environment globally and makes near simultaneous measurements at nine view angles to provide greater sensitivity while deriving aerosol optical depths, however, the frequency of global coverage is lower (9 days) when compared to MODIS [3,4]. Validation of satellite derived data through collocated ground-based direct measurement is very essential [2,5], as the satellite retrieval involves *apriori* assumptions including the atmospheric composition over different regions across the globe. Furthermore, satellite retrievals are based on the radiant energy reflected and emitted by the Earth [2]. In contrast, to determine aerosol optical depths ground-based instruments [6] rely on the measurements of attenuation of solar radiation reaching the surface. Aerosol optical depth (AOD) retrieved from ground-based measurements, is considered the most reliable because of lower uncertainties as compared to satellite retrievals. In addition, ground-based measurements can reliably be used to obtain continuous data on a variety of aerosol characteristics over a particular location [7]. Several recent studies are based on the comparison between independent aerosol retrieval both from satellite and ground-based measurements over different regions [2,4,8–14].

A seven year (2000–2006) analysis of global aerosol climatology obtained using MODIS AODs revealed that on annual mean scale AODs over South Asia were the highest ([2], Table 2) when compared to the rest of the world. South Asia comprises India, Pakistan, Nepal, Bhutan, Bangladesh and Sri Lanka. It is densely populated as more than one-fifth of the world population lives in this region, and faces serious environmental threats in terms of air pollution, monsoon floods, droughts and associated climate change. Increases in aerosol loading due to growing population and industrialization in recent decades have resulted in an increase in health-related problems, and impacted air quality, agriculture and water resources in Asia [1,15]. Anthropogenic aerosols over South and East Asia can significantly change the energy balance of the Earth-atmosphere system on regional scales [1,15,16]. A climatology of aerosol optical and microphysical properties over the Indian subcontinent using 9 years of MISR data indicated that the winter to premonsoon changes in aerosol properties are not dominated by dust, but also by an increase in anthropogenic components, particularly biomass burning [17]. Aerosol properties over the The Indian subcontinent were found to display strong seasonal and spatial heterogeneity. It was reported that both natural and anthropogenic aerosols decrease over large areas of the landmass in winter compared to postmonsoon, and in postmonsoon when compared to monsoon. It was shown that AODs are high over the densely populated rural areas, thus, emphasizing that aerosols over rural areas in India need to investigated. Many regional hot spots (mainly urban centers and densely populated rural areas) over India exhibit statistically significant seasonal linear trends in AOD, with an increase of about 0.1–0.4 in the last decade [18].

In this context, it is important to examine aerosol characteristics over a regional aerosol hot spot which can be helpful not only in regional scale, but also in global air quality and climate. Earlier studies on the comparison of ground-based and satellite (mainly MODIS) retrieved AODs over the South Asian region were mostly over India and in particular over Kanpur, an AERONET (Aerosol Robotic Network [6]) location; to name a few [19–23]. All the above mentioned studies used the monthly mean MODIS and AERONET AODs. The absolute difference between MODIS and AERONET AODs during January-May and August-December for a 5-year period (2001–2005) over Kanpur was 0.08 ± 0.07, while during June-July the absolute difference in the 5-year period was estimated to be 0.24 ± 0.10 [21]. These differences were within the expected error bounds of MODIS AOD retrievals over land [2]. Results on validation of MODIS and MISR AODs using the AERONET AODs over Kanpur during winter and summer seasons showed that MISR performs better than MODIS during both the seasons [20]. This better performance by MISR was attributed to its design in terms of viewing and spectral capability.

MODIS was found to overestimate AODs during summer where as both the sensors were found to underestimate AOD during winter [20].

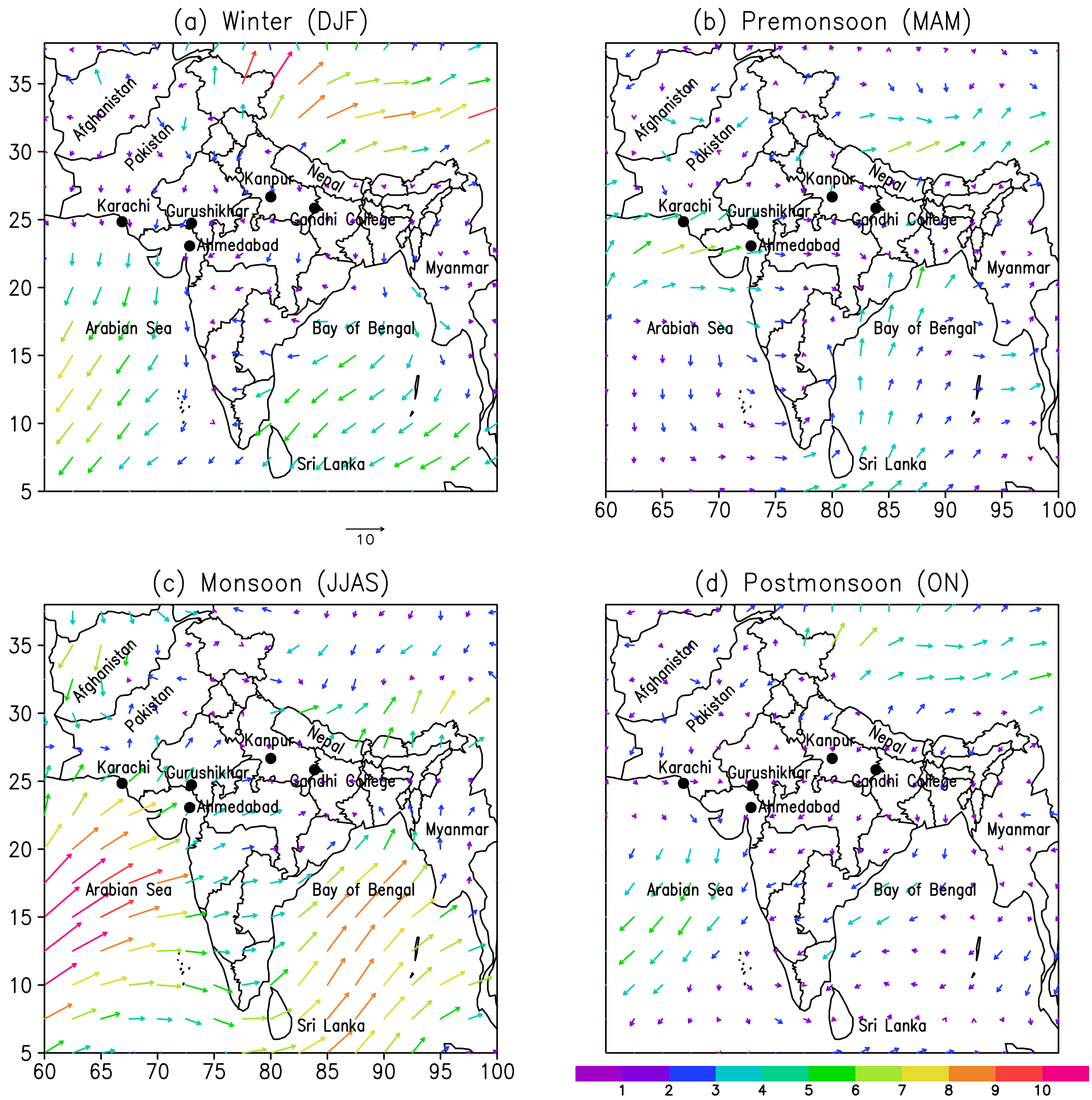
Over the South Asian region, analysis and validation of aerosol optical properties have been conducted over a particular location as was seen above. In the present study, for the first time we analyze aerosol characteristics from five locations spread over a large region in South Asia during different seasons with an aim to examine the space-time variation in aerosol characteristics, and the effect of long range transport. AODs obtained from ground-based measurements over these locations are compared with AODs retrieved from two satellites (MODIS and MISR) during 2006–2008. To get further insight into the aerosol size distribution Ångström wavelength exponent (α) is retrieved from the spectral AODs. Daily measurements of aerosol optical depths in the 0.38–0.87 µm wavelength region made during 2006–2008 over Ahmedabad, Gurushikhar, Karachi, Kanpur and Gandhi College are used in the study. Daily mean AODs measured in situ are compared with daily mean MODIS and MISR AODs over each location and inferences are drawn. An analysis and documentation on the spatial and seasonal variabilities in aerosol optical characteristics over South Asia, attain significance in the context of air quality, air pollution and regional and global climate. The results obtained on the inter-comparison between ground-based and remote sensing AODs will be useful to improve the retrieval algorithms and the trend analysis of AODs.

2. Topography of Study Locations

The South Asian region is a land of many contrasts. Its landscape varies from the mighty peaks of Himalayas in the north, through vast plain and arid desert, to tropical forest and coastal regions in the south. The South Asian region experiences tropical and subtropical climatic conditions resulting in extreme temperatures, rainfall and relative humidity which introduces large spatial and temporal variability in aerosol characteristics over this region. The region is a potential source for many types of both natural and anthropogenic aerosols such as mineral dust, sea salt, black carbon, sulfate, nitrates, and other organic water soluble substances. This region, in general, and India, in particular, due to rapidly growing industrialization and expanding urbanization in recent years has become a major regional aerosol hot spot.

The present study is conducted over five different locations in South Asia, namely, Ahmedabad (23.03°N, 72.55°E, 55 m above mean sea level (AMSL)), Gurushikhar (24.65°N, 72.78°E, 1,680 m AMSL), Karachi (24.87°N, 67.03°E, 49 m AMSL), Kanpur (26.51°N, 80.23°E, 123 m AMSL), and Gandhi College (25.87°N, 84.13°E, 60 m AMSL) (Figure 1). Ahmedabad is an industrialized urban location in western India with several small and large scale industries including two power plants [24]. The city has a population of $\sim$5.8 million and is located in the southeast direction of Thar desert. Gurushikhar, Mount Abu is a relatively pristine site situated at a height of about 1.7 km above the mean sea level and is $\sim$300 km northeast of the That desert. The site is situated at the highest peak of Aravalli range of mountains in western India with a cleaner and stable atmosphere where the effect of local pollution is minimum. During winter Gurushikhar exhibits free tropospheric characteristics as the boundary layer height is lower than the altitude of Gurushikhar; while during summer Gurushikhar lies within the boundary layer. Karachi, an urban, coastal city located in the southeastern part of Pakistan on the Arabian Sea experiences scanty rainfall and subtropical climate [25,26]. Karachi has a large industrial base which includes oil-fired power plants, cement factories, steel mill, textile plants, heavy petrochemical industries, and several small industries. Karachi is densely populated (population of ∼14 million) [26]. Kanpur and Gandhi College are situated in the Indo-Gangetic basin which is one of the largest river basins in the world, and is one of the densely populated and highly polluted regions in India. This region is bordered by the Himalayas to the north and Vindhyan Satpura ranges to the south. Kanpur is an urban, industrial city with a population of more than four million [27], while Gandhi College is a rural village location in Ganga basin.

Figure 1. Synoptic surface level wind speed (ms^{-1}) over South Asia during (**a**) winter (DJF); (**b**) premonsoon (MAM); (**c**) monsoon (JJAS); and (**d**) postmonsoon (ON). Study locations—Ahmedabad, Gurushikhar, Karachi, Kanpur, and Gandhi College are marked in the figure.



3. Wind Patterns and Meteorological Conditions

Surface level daily mean temperature, relative humidity (RH), wind speed and wind direction data during 2006–2008 are obtained from National Center for Environmental Prediction (NCEP) reanalysis. NCEP reanalysis data is available at $2.5^\circ \times 2.5^\circ$ latitude–longitude resolution. To examine the spatial variation in synoptic winds (Figure 1) the NCEP data over the study domain are utilized. However, temperature, winds and relative humidity for each study location (data for Figures 2–6) are obtained at the respective latitude–longitude of each location. Since the objective of the study is to examine the seasonal and spatial variations in aerosol characteristics, the coarse resolution meteorological data used in the study is not expected to alter the inferences and overall conclusions. The daily mean temperature, RH and wind speed are further used to calculate the monthly mean value and standard deviation. Daily rainfall corresponding to each location are obtained from Tropical Rainfall Measuring Mission (TRMM) satellite $1^\circ \times 1^\circ$ latitude-longitude rainfall data, from which monthly accumulated rainfall are calculated. Surface level synoptic winds over the study region during winter (December-January-February, DJF) are calm, north/northeasterly and are from the polluted northern hemisphere (Figure 1(a)); temperatures are colder and the atmosphere is dry (low RH). In premonsoon (March–April–May, MAM) winds originate and travel from/through a less polluted west (arid/marine) (Figure 1(b)); temperatures increase slightly and RH is lower than winter. In this season mineral dust gets transported from adjacent Thar desert and the Middle East to western India [24]. During monsoon (June-July-August-September, JJAS) the winds (NCEP reanalysis) are stronger, moist and are from the marine and western regions (Figure 1(c)); both temperature and RH are high during this season. During postmonsoon (October-November, ON) wind patterns start shifting in direction from southwest to northeast (Figure 1(d)); temperature and RH reduce. On the basis of meteorology, the aerosol data are grouped into four major seasons of winter, premonsoon, monsoon, and postmonsoon, and discussed. Seasonal variation in meteorological parameters during 2006–2008 for each location are drawn subsequently in Figures 2–6.

The sources of aerosols which include natural and anthropogenic vary on regional basis. Ahmedabad, Karachi and Kanpur are urban centers, industrialized and have large number of automobiles. The gas to particle reaction products of the exhausts from the industry and automobiles can contribute to the fine mode aerosols in these locations, while during monsoon and favorable wind conditions sea salt and dust particles in the coarse mode (Figures 2–6) can be present in these locations. Gurushikhar, a remote, high altitude site is observed to be influenced by long range transport of aerosols. Gandhi College, a rural site located downwind of major urban centers, namely, Delhi, Lucknow, Kanpur, *etc.* in the Indo-Gangetic basin will have a mix of rural and urban aerosol emissions. Over the west (Karachi, Ahmedabad and Gurushikhar) the meteorological features are similar between Ahmedabad and Gurushikhar, while they are different in Karachi. The seasonal rainfall, for example, is much lower over Karachi when compared to Ahmedabad and Gurushikhar (Figures 2–4). Kanpur and Gandhi College in the north exhibit similar meteorological features; however, there exist differences in winds and rainfall (Figures 5 and 6). The variation in the local sources of aerosols, long range transport, in addition to meteorology and atmospheric dynamics can influence and modulate the spatiotemporal variabilities in aerosol characteristics over a region which are investigated in detail.

Figure 2. Monthly mean (**a**) temperature (°C); (**b**) relative humidity (%); (**c**) rainfall (mm); and daily average wind speed and wind direction in (**d**) winter; (**e**) premonsoon; (**f**) monsoon; and (**g**) postmonsoon over Ahmedabad during 2008. Vertical bars indicate $\pm 1\sigma$ variation from the mean. The wind speeds are shown as function of its magnitude varying from <1 to >8 ms^{-1} at an interval of 1 ms^{-1}.

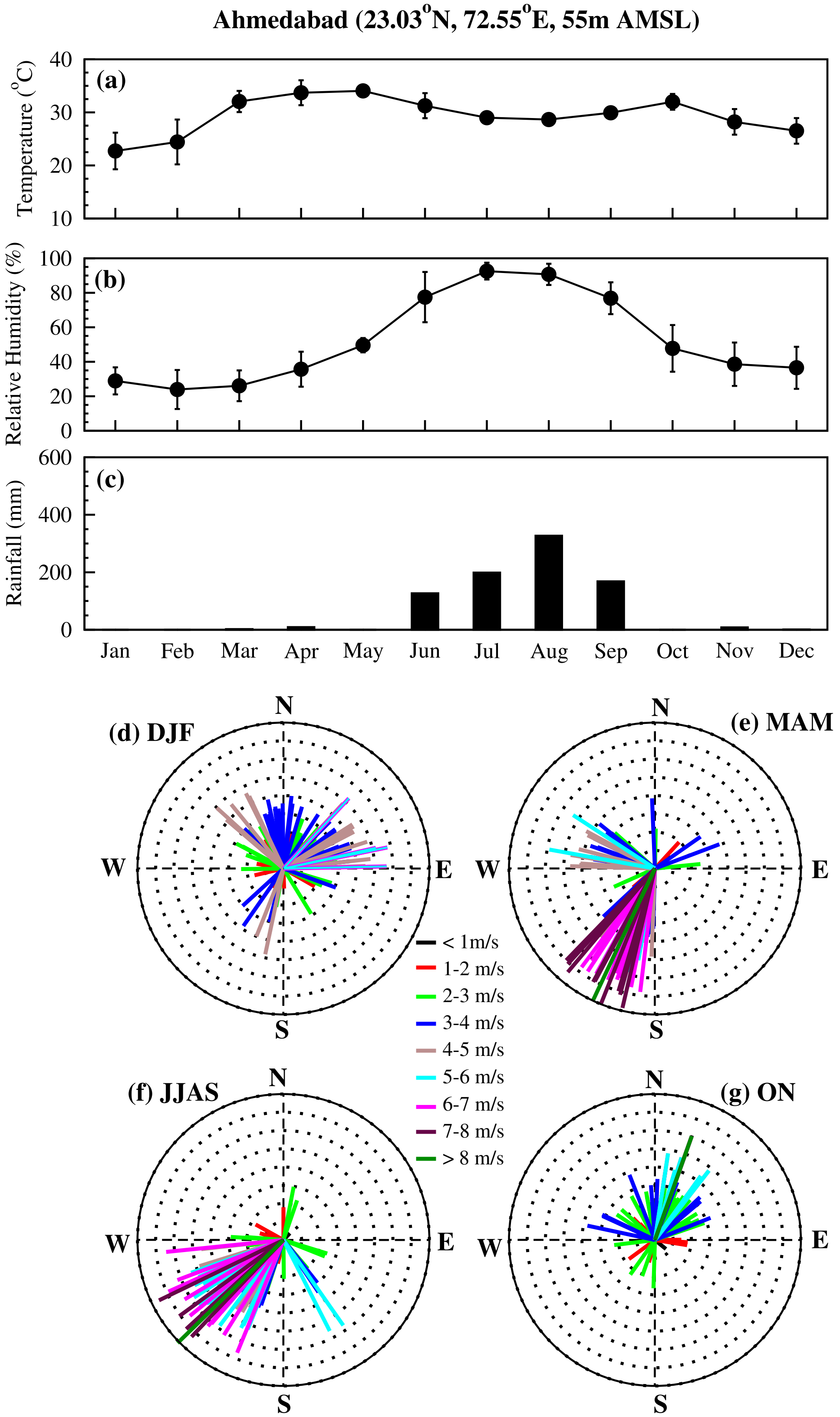


Figure 3. Monthly mean (**a**) temperature (°C); (**b**) relative humidity (%); (**c**) rainfall (mm); and daily mean wind speed and wind direction during (**d**) winter; (**e**) premonsoon; (**f**) monsoon; and (**g**) postmonsoon over Gurushikhar in 2008. Vertical bars denote $\pm 1\sigma$ variation from the mean.

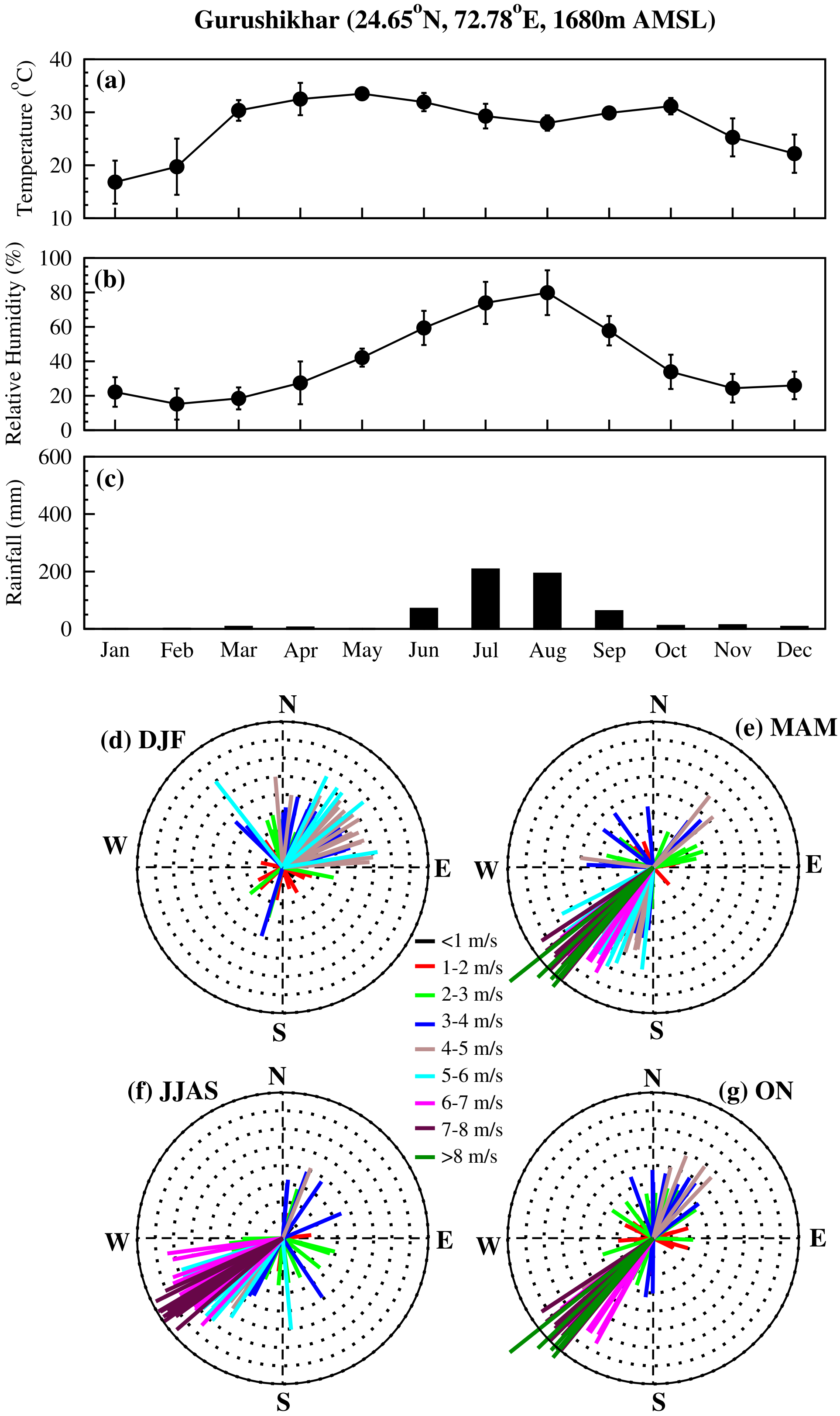


Figure 4. Monthly mean (**a**) temperature (°C); (**b**) relative humidity (%); (**c**) rainfall (mm); and daily average wind speed and wind direction corresponding to (**d**) winter; (**e**) premonsoon; (**f**) monsoon; and (**g**) postmonsoon over Karachi in 2008. Vertical bars represent $\pm 1\sigma$ variation from the mean.

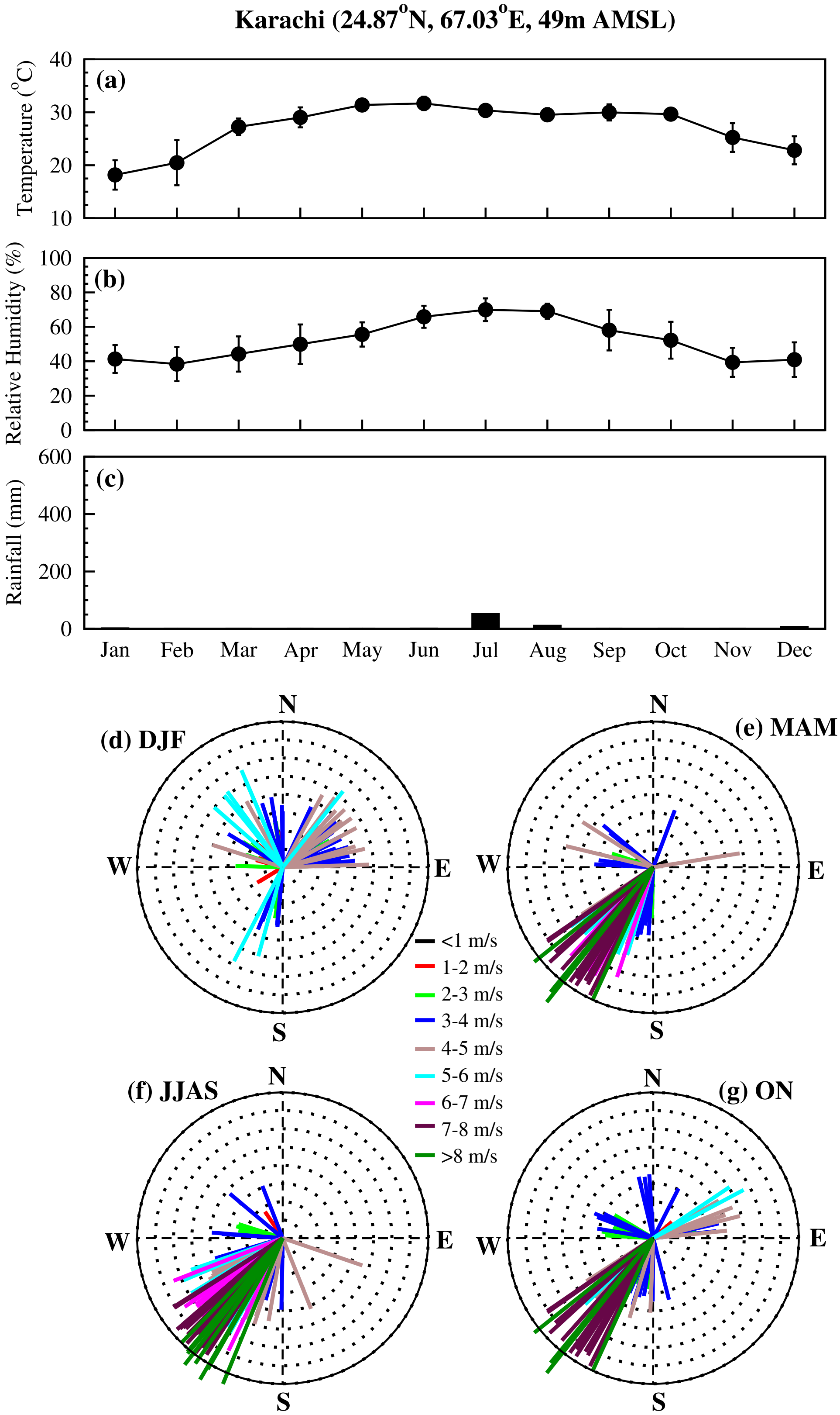


Figure 5. Monthly mean (**a**) temperature (°C); (**b**) relative humidity (%); (**c**) rainfall (mm); and daily mean wind speed and wind direction in (**d**) winter; (**e**) premonsoon; (**f**) monsoon; and (**g**) postmonsoon over Kanpur during 2008. Vertical bars indicate $\pm 1\sigma$ variation from the mean.

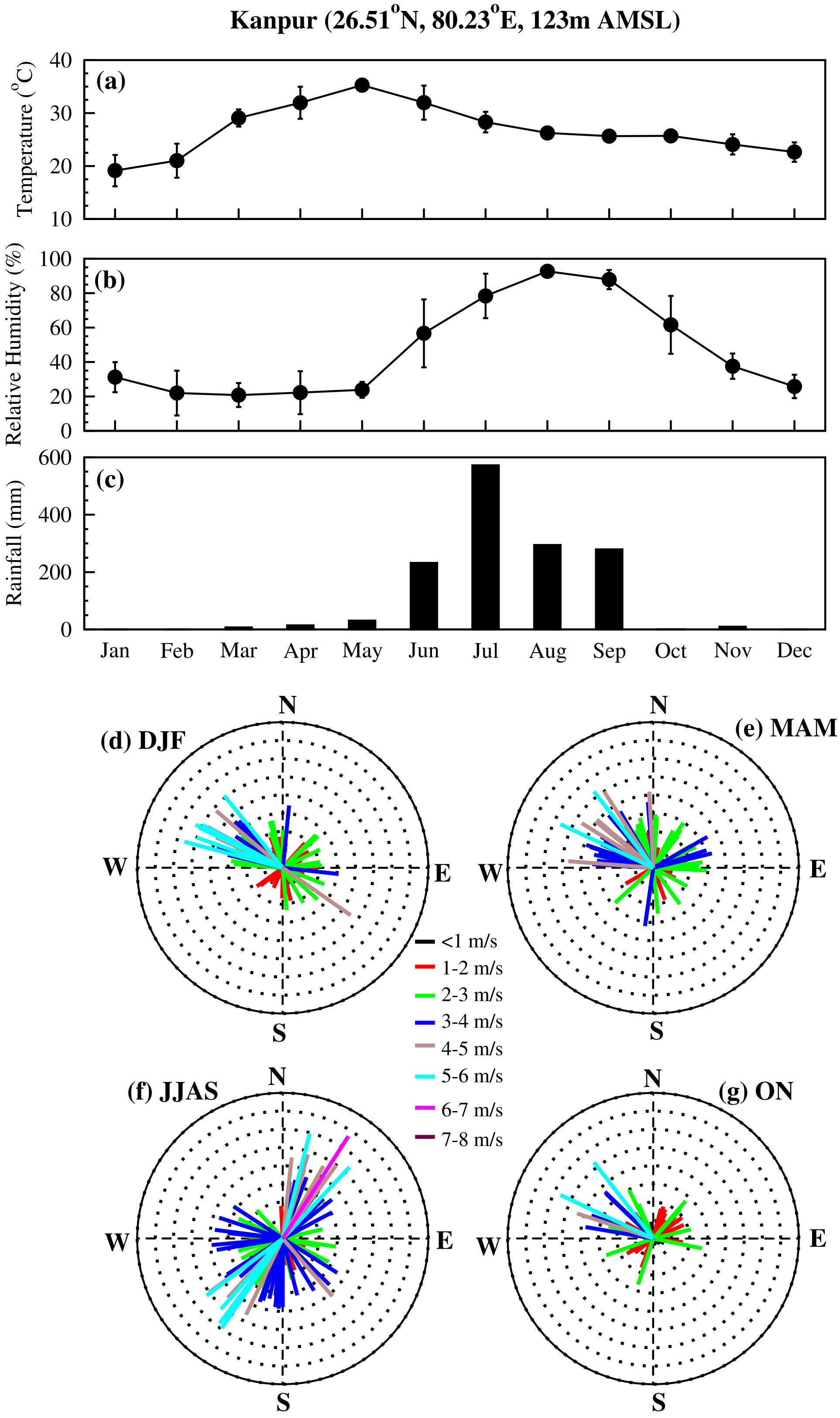
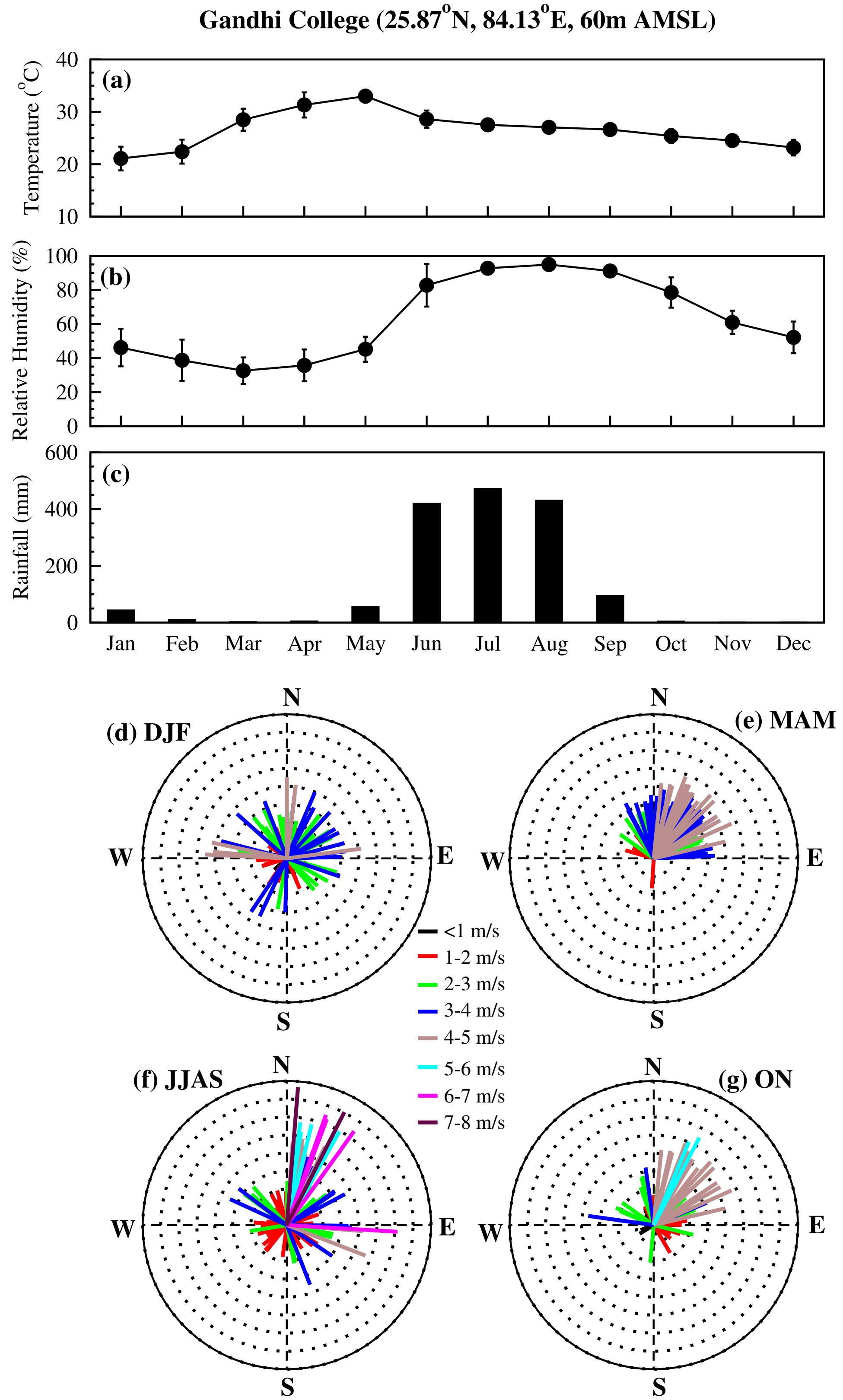


Figure 6. Monthly mean (**a**) temperature (°C); (**b**) relative humidity (%); (**c**) rainfall (mm); and daily average wind speed and wind direction corresponding to (**d**) winter; (**e**) premonsoon; (**f**) monsoon; and (**g**) postmonsoon over Gandhi College in 2008. Vertical bars correspond to $\pm 1\sigma$ variation from the mean.



4. Measurements, Data, and Analysis

4.1. Aerosol Optical Depths

4.1.1. Sun Photometers: Hand Held and Microtops II

Measurements of direct solar radiation intensities reaching the surface are conducted using two kinds of sun photometers—(i) a hand held sun photometer (October 2006–December 2007); and (ii) a set of Microtops-II sun photometers (January 2008–December 2008) over Ahmedabad and Gurushikhar. These measurements were conducted everyday at 1-hour time interval from 09:00 Local Standard Time (LST) to 17:00 LST under only clear sky conditions. The indigenously built hand held sun photometer consists of an interference filter, photo diode and necessary electronics. The sun photometer measures the solar intensity at five different wavelength bands centered at 0.38, 0.50, 0.65, 0.75 and 0.87 µm. The bandwidths of the filters used for the measurement in the present study are about 0.01 µm and the field of view of the sun photometer is about 4°. The indigenously built hand held sun photometer has been used extensively and successfully in several studies over oceans and continental locations [28].

The governing equation of sun photometry measurements follows Beer-Lambert's law, which can be written as

$$\tau = \frac{-1}{\mathrm{m}}\left[\ln\left(\frac{\mathrm{I}}{\mathrm{I_o}}\right) - 2\ln\left(\frac{\mathrm{r_o}}{\mathrm{r}}\right)\right] \tag{1}$$

where τ is the total integrated columnar optical depth of the atmosphere, I is the instantaneous solar radiation intensity measured by the photometer and I_o is the solar radiation intensity obtained from Langley plot for zero air mass, m is the atmospheric air mass, r is the instantaneous value of the Sun-Earth distance and r_o is the Sun-Earth distance when I_o values are obtained. The total integrated columnar optical depth of the atmosphere comprises

$$\tau = \tau_{rs} + \tau_{aerosol} + \tau_{ma} \tag{2}$$

where τ_{rs} is the Rayleigh scattering optical depth (scattering due to air molecules), τ_{aerosol} is the aerosol optical depth (AOD) and τ_{ma} is the optical depth due to molecular absorptions such as ozone, water vapor or nitrogen dioxide.

$I_o(\lambda)$ values are obtained using Langley plot technique. In this technique, the natural logarithm of the photometer outputs measured for various solar zenith angles are plotted with respect to air mass. Through the experimentally observed points a least square fitted straight line is drawn and is extrapolated to meet zero air mass in the abscissa. The intercept gives $I_o(\lambda)$ of a particular wavelength. Similarly, Langley plots are made to obtain $I_o(\lambda)$ for all wavelengths. The voltage $I_o(\lambda)$ obtained for zero air mass is a constant in time for a particular wavelength, if the response of the instrument is constant and if the value is corrected for the mean solar distance.

To draw Langley plots observations are to be taken in a cleaner and stable atmosphere where the effects of local pollutants are minimum. These conditions are best met at high altitude mountain sites. In the present case observations are taken from sunrise to sunset, at Gurushikhar in Mt. Abu, at a height of about 1,680 meters above the mean sea level. From the total columnar optical depths (Equation (1)), contribution due to Rayleigh scattering and absorption due to ozone and water vapor at the respective wavelengths are subtracted to calculate aerosol optical depths (AODs) (Equation (2)). An air column density of 2.16×10^{25} molecules per cm^2 appropriate for the tropical region is used in the estimation of Rayleigh scattering contribution. Monthly mean columnar concentrations of ozone and water vapor over the tropics are used to estimate ozone and water vapor optical depths [28]. Water vapor contributes much less than 0.1% to the total optical depth in the wavelength range of 0.38–0.87 μm. Therefore, even during the wet season water vapor does not give rise to additional uncertainty in AODs. Contribution due to nitrogen dioxide is less than 0.5% in this wavelength region and is not considered in the present study. The uncertainties in the aerosol optical depth measurements arise from (i) instrumental error due to bias and precision; and (ii) ignoring the forward scattering contribution to the measured irradiance. The solar radiation intensities are measured with an accuracy better than 1%. The uncertainty in aerosol optical depths retrieved using hand held sun photometer is <15% [28].

The hand held Microtops II sun photometer (Solar Light Company, Glenside, PA, USA) can measure AODs at five wavelength bands centered around 0.38, 0.44, 0.50, 0.675 and 0.87 μm [29]. Field of view of Microtops instrument is 2.5° and the band width of each filter is about 0.01 μm. The indigenous hand held sun photometer and the Microtops sun photometer were periodically calibrated (3–6 month intervals) during 2006–2008 at Gurushikhar and the corresponding calibration constants obtained from Langley plot analysis have been used for the subsequent period. The calibration constants (I_o) in the 0.38–0.87 μm wavelength range varied <2% during the study period. Aerosol optical depths from Microtops are derived following the same procedure outlined earlier for the sun photometer. The absolute uncertainty in AODs retrieved from Microtops measurements is 2%–5% in the 0.38–0.87 μm range. AODs measured using the hand held sun photometer and Microtops were found to show a good agreement ($R^2 \geq 0.94$) in the 0.38–0.87 μm wavelength range.

4.1.2. AERONET

Aerosol Robotic Network (AERONET) is a ground-based Sun/sky radiometer which measures the total ambient aerosol characteristics at different wavelengths. AERONET derives the total column aerosol properties from the measurements of solar radiance. The field of view of the instrument is about 1.2° and the instrument makes direct Sun measurements at every 15 min [6]. AERONET Level 2, cloud screened and quality assured AOD data [30], at the wavelength bands of 0.38, 0.44, 0.5, 0.675 and 0.87 μm at Kanpur, Karachi and Gandhi College during 2006–2008 are used. The uncertainty in the calculation of AERONET AODs is estimated to be $< \pm 0.01$ for wavelengths >0.44 μm and $< \pm 0.02$ for ultraviolet wavelengths [31].

4.1.3. MODIS Terra/Aqua Satellites

The MODerate resolution Imaging Spectroradiometer (MODIS) is a remote sensor on board the two Earth Observing System (EOS) Terra and Aqua satellites. Terra and Aqua satellites operate at an altitude of 705 km with Terra spacecraft crossing the equator at about 10:30 LST (local standard time) (ascending northward) while Aqua spacecraft crosses the equator at around 13:30 LST (descending southward) [2]. In the present study, Level 3 MODIS Collection 5.1 atmosphere daily global aerosol optical depth at $1^\circ \times 1^\circ$ grid resolution are utilized. MODIS Terra and Aqua derived aerosol products over land and oceans are tested, validated, compared, and are being extensively used to investigate spatiotemporal variations in aerosol optical characteristics [2,32]. The algorithms developed to retrieve AODs from MODIS Terra and Aqua were tested and validated with data obtained from airborne imagers [2]. The results of these field tests combined with sensitivity studies suggested that 1σ (standard deviation) of AOD retrievals from MODIS would fall within $\pm$(0.05 + 0.15AOD) over land [5]. These error bounds are referred to as expected error. A global evaluation of collection 5 MODIS AODs over land revealed that >66% (one standard deviation) of MODIS-retrieved aerosol optical depth (AOD) values compare to AERONET observed values within an expected error envelope of (0.05 + 15%), with a high correlation of 0.9 [5].

Daily aerosol optical depth at 0.55 μm from both Terra and Aqua satellites from January 2006–December 2008 are obtained over each location, and daily mean (Terra + Aqua) AODs are calculated. The daily mean AODs are further used to calculate the seasonal mean AODs for all the five locations during 2006–2008. The LST 10:30 and 13:30 of MODIS Terra and Aqua are the local times at the equatorial crossing point of the sub-satellite track. The local time at any other observation location can differ by as much as about $\pm$42 min depending on the longitudinal distance from the sub-satellite track. An additional correction which arises due to the latitude of the observation point, is small in case of MODIS, as its orbit is nearly polar [33].

For the day to day intercomparison of MODIS and sun photometer AODs, in this study, the sun photometer measured AODs between 09:48 and 11:12 LST (corresponding to Terra), and 12:48 and 14:12 LST (corresponding to Aqua) taking into account the longitudinal dependence, are averaged and plotted. Since, MODIS Terra and Aqua AODs are available only twice a day it may not be able to adequately represent the daily mean over many places. In this study, we use the ground based sun photometer AOD data to characterize the diurnal cycle seasonally and examine how the diurnal variation is captured by the two MODIS overpass times during the day. The results (discussed later) suggest clearly that the AODs obtained at two times are able to capture the diurnal cycle seasonally in all the study locations adequately well. Details on the absolute differences between sun photometer and Terra, and sun photometer and Aqua, and their mean are discussed in Section 5.3.

4.1.4. MISR

Multiangle Imaging SpectroRadiometer (MISR) was launched into polar Earth orbit aboard the Terra spacecraft in December 1999 [34]. MISR images the Earth at nine discrete view angles ranging from 70° aftward to 70° forward, and at four different wavelengths (0.443, 0.555, 0.670 and 0.865 μm). Daily MISR Level-3 0.555 μm AOD data at 17.6 km resolution are obtained for all the five study locations during 2006–2008 and the seasonal means are estimated by averaging all the available AODs. Comparison between daily MISR AODs with ground-based AODs is discussed in Section 5.3. A comparison between AODs from MISR and MODIS retrievals over collocated AERONET sites in land showed that MODIS AODs at 0.47 and 0.66 μm are larger than those obtained from MISR by about 35% and 10% on an average, when all land surface types are considered [10]. MISR was found to show a good agreement with AERONET within the maximum of $\pm$0.05 or $\pm$0.2AOD over land [10]. A global assessment of comparison between MISR and AERONET AODs showed that about 70% to

75% of MISR AOD retrievals are within 0.05% or 20% AOD of the paired validation data [14]. When AERONET AOD was ≥0.4, the MISR retrieved AOD was frequently underestimated over land [14].

4.2. Ångström Exponent (α)

Analysis of the spectral variation of aerosol optical depths can provide information on aerosol size distribution. The spectral variation of aerosol optical depth can be represented by Ångström power law, which is expressed as

$$\tau = \beta\lambda^{-\alpha} \tag{3}$$

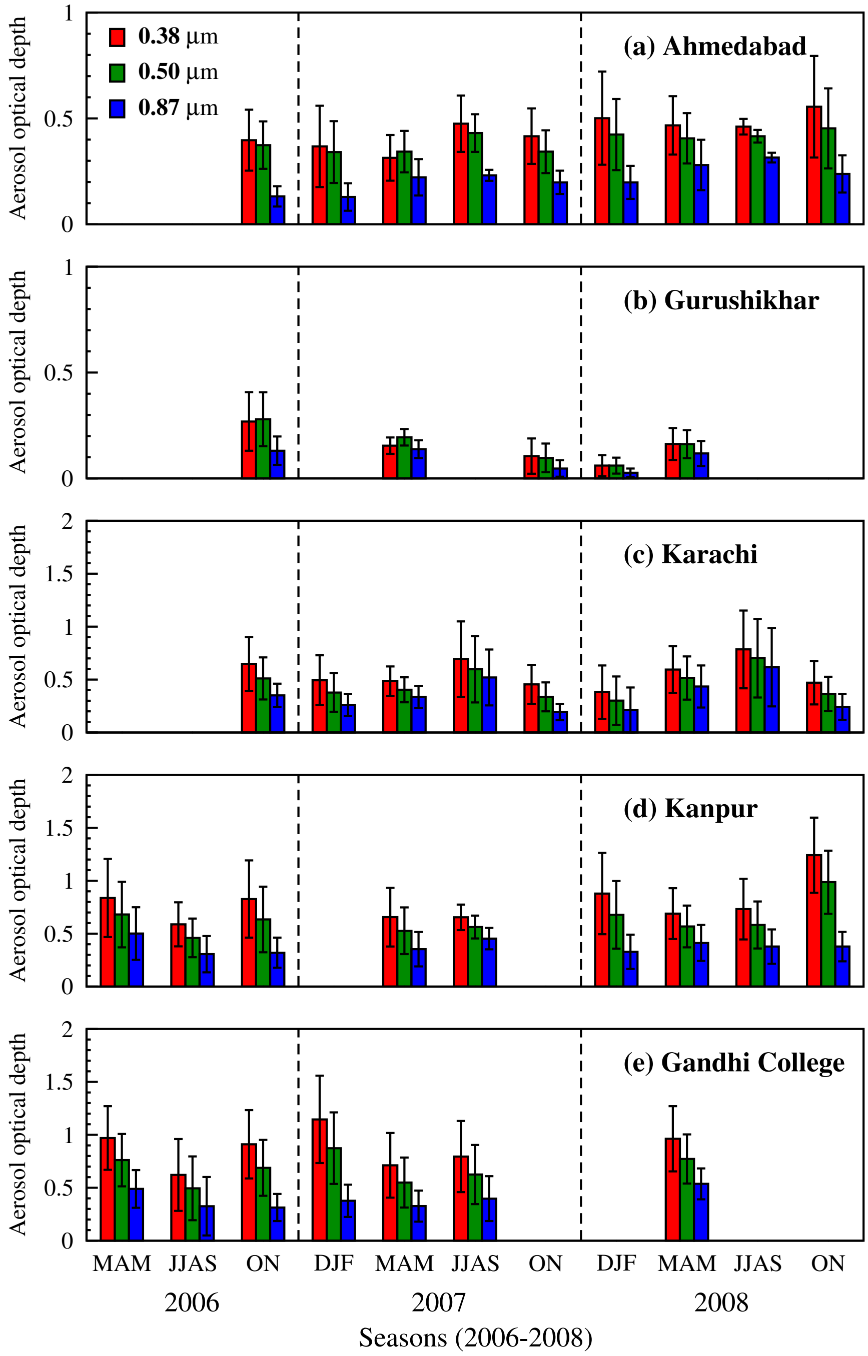
where λ is the wavelength in µm, α and β are Ångström parameters. The value of α depends on the ratio of concentration of larger to smaller aerosols in the aerosol size distribution and β represents the columnar aerosol loading in the atmosphere. The Ångström power law is a useful tool for extrapolating AOD throughout the shortwave spectral region. The value of the Ångström exponent qualitatively indicates the aerosol particle size. Values of $\alpha \leq 1$ indicate size distributions that are dominated by coarse mode aerosols such as dust and sea salt, and values of $\alpha \geq 2$ indicate size distributions dominated by fine mode aerosols typically produced by urban pollution and biomass burning [31,35]. Such characterization is useful in the retrieval of aerosol parameters and applying correction factors in remote sensing, and in modeling the radiative effects of aerosols [35]. The α values are estimated for an individual data set of AODs by least square fitting AODs against the respective wavelength on a log-log scale for all the five locations during 2006–2008, and seasonal means are calculated.

5. Results and Discussion

5.1. Aerosol Optical Depths: Ground-Based Sun Photometer, Microtops and AERONET

Seasonal mean AODs measured at 0.38, 0.50 and 0.87 µm using hand held sun photometer, Microtops sun photometer, AERONET sun/sky radiometers during 2006–2008 are shown over the five study locations (Figure 7). The 0.38, 0.50 µm AODs represent the short wavelength region and are expected to be dominated by fine mode particles, while 0.87 µm AODs represent the long wavelength region and will be influenced by coarse mode particles. At the outset, AODs exhibit strong seasonal and wavelength dependence. AODs during winter and premonsoon are lower than that of monsoon season. AODs decrease gradually as wavelength increases (Figure 7); the gradient in AODs is steeper in Kanpur and Gandhi College. 0.38 and 0.50 µm AODs are higher than that of 0.87 µm AODs during the entire study period (Figure 7) at all the locations except Gurushikhar. AODs in Ahmedabad are about a factor of two higher than Gurushikhar. AODs in the Indo-Gangetic Plain are higher than that of Ahmedabad, while Karachi AODs are comparable. Higher AODs at lower wavelengths indicate the abundance of smaller size particles. During postmonsoon and winter the boundary layer is shallow and holds the pollutants in a smaller volume near the Earth's surface when compared to summer. Over the Indian subcontinent the dust activity is found to peak in the spring (March-May) which decreases in summer with the onset of southwest monsoon [36]. The increase in dust activity accompanied with southwesterly winds contributes to the increase in AODs during premonsoon over Ahmedabad (Figure 7(a)). Wet deposition by precipitation or wet removal is one of the main mechanisms for removal of aerosols from the atmosphere. Though wet removal is most effective in reducing the near surface aerosol concentration, it has been shown that AOD increases significantly when RH increases mainly due to the hygroscopic growth of water soluble aerosols [37]. This increase in AOD due to the hygroscopic growth was found to overwhelm the removal of aerosols and addition of sea salt aerosols in the atmosphere during summer monsoon.

Figure 7. Seasonal mean aerosol optical depths at 0.38, 0.50 and 0.87 μm during 2006–2008 over (**a**) Ahmedabad; (**b**) Gurushikhar; (**c**) Karachi; (**d**) Kanpur and (**e**) Gandhi College. Gaps in the figure denote the absence or non availability of sun photometer, Microtops and AERONET sun/sky radiometer aerosol optical depth data. Vertical bars indicate $\pm 1\sigma$ deviation from the seasonal mean.



In contrast over Gurushikhar, the difference in AODs at shorter and longer wavelengths is not significant, suggesting lower concentration of fine mode aerosols. AODs could not be measured over Gurushikhar due to cloudy, overcast conditions during monsoon. AODs in the visible wavelength region are more influenced by fine mode aerosols, while when coarse mode aerosols are dominant AODs in the longer wavelength are affected. AODs over Gurushikhar are lowest during winter season as the measurement site remains above the boundary layer. Highest value of AODs are observed during premonsoon, when the measurement site is affected by long range transport of dust particles.

Over Karachi winter, premonsoon and postmonsoon AODs at 0.38 and 0.50 μm are more or less the same in 2007, while in 2008 winter AODs are lower than premonsoon and postmonsoon AODs. AODs during monsoon are higher by about 1.5 times over Karachi (Figure 7(c)). Seasonal and inter-annual variation is similar in short and long wavelength regions in Karachi which indicates that the abundance of fine and coarse mode particles showed similar variabilities. Higher AODs during premonsoon and monsoon occur due to winds coming from the southwest with higher speed (Figure 4(e),(f)) which increases the concentration of dust and sea salt in the atmosphere respectively. The seasonal cycle in AODs is consistent with aerosol sources and transport effects over Karachi. Over Afghanistan, Iran, Pakistan and China, which are mountainous regions dust sources are found in closed intermountain basins [36]. The dust activity starts in April–May, becomes strong in June–July, and weakens considerably by September over Pakistan basin [36]. Karachi, located on the coast of Arabian Sea, witnesses considerable dust activity during premonsoon and monsoon seasons. In addition, during the monsoon season (Figure 1(a)) winds transport sea salt aerosols over Karachi.

Unlike the other three locations seasonal variation in Kanpur AODs are not so strong while there exists a large inter-annual variability. AERONET AODs during 2001–2003 also showed distinct inter-annual variations over Kanpur [27] as seen here. Gandhi College being a rural, downwind location south of Kanpur exhibits similar features as that of Kanpur. Higher AODs during postmonsoon and winter is a characteristic feature of the locations in Indo-Gangetic basin. Over much of northern India the temperatures are colder in the winter. During postmonsoon and winter the boundary layer is shallow and holds the pollutants in a smaller volume, when compared to summer, which results in confinement of aerosols. The colder temperatures along with the trapping of pollutants give rise to hazy and foggy conditions over Indo-Gangetic basin [4,21]. In addition, the dense population in this region contributes to large aerosol sources (due to fossil fuel consumption and bio fuels used for domestic purposes) which produce higher AODs.

Ahmedabad, Gurushikhar and Karachi situated in the western region of South Asia are governed by more or less similar meteorological conditions except for rainfall over Karachi (a factor of ten less when compared to the other two locations), but are distinct in terms of the environment (urban, remote and high altitude, urban/coastal respectively) and therefore are influenced by different types of aerosols and sources. Over this region highest AODs are observed over Karachi; while the lowest AODs are obtained over Gurushikhar. AODs over Ahmedabad and Karachi are at least a factor of two higher than the AODs measured over Gurushikhar. This is due to the fact that Gurushikhar, being a high altitude remote location is dominated by coarse mode aerosols from natural sources (mainly mineral dust) in the atmosphere (Table 1); while both Ahmedabad and Karachi are densely populated and highly industrialized areas. Among the urban locations, Karachi AODs are higher in all the seasons during

2006–2008 when compared to Ahmedabad. Highest AODs over Karachi could be because of much higher population (∼14 million, when compared to about 5.8 million over Ahmedabad, and about 50,000 in Gurushikhar), industrialization, and in addition, being a coastal station the contribution of sea salt cannot be excluded. Kanpur and Gandhi College in northern India situated in one of the the most polluted and densely populated regions, namely the Indo-Gangetic basin, are influenced by similar meteorological conditions. Kanpur is an urban, industrial city while Gandhi College is a rural location. AODs over the Indo-Gangetic basin are higher than those measured in the western region of South Asia. 0.38 and 0.50 μm AODs over Gandhi College are about 20% higher than Kanpur; while 0.87 μm AODs nearly the same for all the seasons over both the locations. This suggests that though both Kanpur and Gandhi College are located in the Indo-Gangetic basin, Gandhi College AODs can be higher as it is located downwind of major urban centers; also being a rural location the local production due to biomass emissions over Gandhi College could be contributing to the higher AODs.

Table 1. Seasonal mean 0.5 μm aerosol optical depths (along with $\pm 1\sigma$ standard deviation) measured using hand held sun photometer and Microtops over Ahmedabad and Gurushikhar, and from AERONET over Karachi, Kanpur and Gandhi College during 2006–2008. Seasonal mean AODs correspond to year 2007 unless otherwise mentioned.

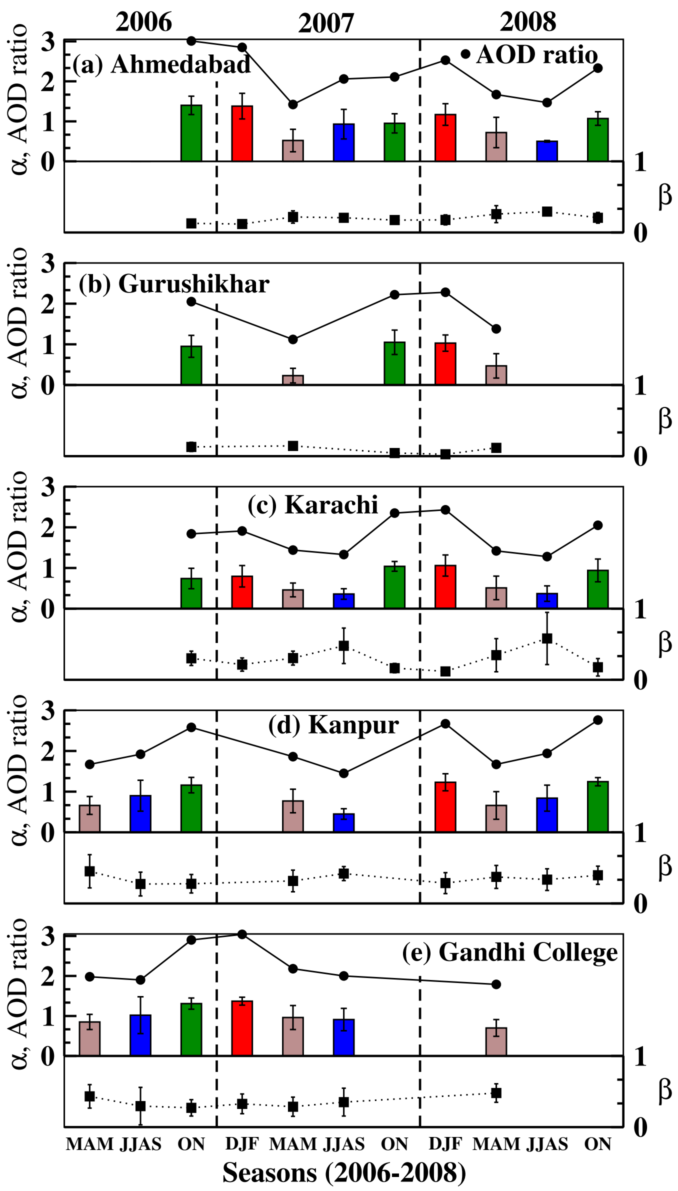
Seasons	Ahmedabad	Gurushikhar	Karachi	Kanpur	Gandhi College
Winter	0.37 ± 0.15	0.06 ± 0.03 ^{a}	0.38 ± 0.18	0.88 ± 0.32 ^{b}	0.87 ± 0.34
Premonsoon	0.31 ± 0.10	0.19 ± 0.04	0.40 ± 0.12	0.66 ± 0.22	0.55 ± 0.24
Monsoon	0.46 ± 0.09		0.60 ± 0.31	0.65 ± 0.11	0.63 ± 0.29
Postmonsoon	0.42 ± 0.07	0.10 ± 0.06	0.34 ± 0.14	0.83 ± 0.31 ^{c}	0.69 ± 0.26 ^{d}

^{a,b} 2008, and ^{c,d} 2006.

5.2. Ångström Coefficients and AOD Ratio

The α (estimated from the AODs in the 0.38–0.87 μm wavelength range) is found to show strong seasonal, inter-annual as well as spatial variability similar to AODs. Over Ahmedabad, α is found to be high during postmonsoon and winter season; while during premonsoon and monsoon α value is lower (Figure 8(a)) for all the three years. This feature of lower α value is consistent with the presence of mineral dust and hygroscopically grown water soluble aerosols, which are in the coarse mode, during premonsoon and monsoon respectively. Over Gurushikhar α is found to be lower than that of Ahmedabad throughout the study period indicating a higher concentration of coarse mode aerosols (Figure 8(b)). The intra seasonal variation in α is quite significant over Gurushikhar; premonsoon α is at least a factor of three lower when compared to postmonsoon and winter. The lower α during premonsoon highlights the dominance of long range transported dust particles in the atmosphere, while during postmonsoon and winter AODs are lower and fine mode aerosols are present giving rise to higher α values. α values over Karachi, an urban, coastal station are lower than those obtained over Ahmedabad (Figure 8(c)) suggesting the presence of coarse mode (sea salt) aerosols. The α values over Gurushikhar are significantly lower during premonsoon (Figure 8(b)), due to the abundance of coarse mode dust particles. In Karachi, the α values during monsoon are lower during premonsoon and monsoon than during winter and postmonsoon. The monsoon α values are lower than even premonsoon because in addition to the dust particles that are present during monsoon, sea salt particles get transported (Figure 1). Thereby, coarse mode particles become more abundant during monsoon in Karachi and give rise to further lower values of α. Over the Indo-Gangetic basin (Kanpur and Gandhi College) α value is found to increase from premonsoon to winter (Figure 8(d,e)). Seasonal differences in the magnitudes of α over the Indo-Gangetic basin are not quite strong as compared to the other three locations in the west. Higher α during postmonsoon and winter over the Indo-Gangetic basin arise due to the increase in the abundance of fine mode aerosols contributed mainly by anthropogenic activities, and atmospheric dynamics (shallow boundary layer and colder temperatures help trap the aerosols).

Figure 8. Ångström coefficients α and β (Equation (3)) derived from the aerosol optical depths measured in the 0.38–0.87 µm wavelength region over (**a**) Ahmedabad; and (**b**) Gurushikhar; (**c**) Karachi; (**d**) Kanpur; and (**e**) Gandhi College during 2006–2008 for different seasons. Vertical bars indicate $\pm 1\sigma$ deviation from the seasonal mean. Seasonal mean AOD ratio (=0.38 µm AOD/0.87 µm AOD) is also plotted.



The α values during postmonsoon and winter are higher than those obtained during premonsoon and monsoon in all the locations during 2006–2008 (Table 2). However, the magnitude of seasonal differences exhibit spatial variation. The higher α values ($\geq$1) suggest the dominance of fine mode aerosols, mainly from anthropogenic activities (fossil and bio fuel emissions); α values lower than 1 indicate the dominance and/or contribution of coarse mode particles from natural sources (dust and sea salt) [35]. While higher α values in the study locations can be attributed to the dominance of fine mode aerosols over urban areas (Ahmedabad and Kanpur), dust and sea salt aerosols also contribute and dominate (Gurushikhar, Kanpur and Karachi). The β is anti-correlated with α over Karachi; β decreases during post-monsoon and winter while α increases. This feature is seen in all the study locations, but this anti-correlation feature is more evident and significant over Karachi.

Table 2. Ångström exponent (α) and $\pm 1\sigma$ standard deviation derived from spectral aerosol optical depths measured in the 0.38–0.87 µm wavelength region over Ahmedabad, Gurushikhar, Karachi, Kanpur and Gandhi College. α values correspond to 2007 unless otherwise stated.

Seasons	**Ahmedabad**	**Gurushikhar**	**Karachi**	**Kanpur**	**Gandhi College**
Winter	1.38 ± 0.32	1.03 ± 0.20 [a]	0.80 ± 0.26	1.23 ± 0.21 [b]	1.37 ± 0.10
Premonsoon	0.52 ± 0.28	0.23 ± 0.18	0.46 ± 0.17	0.77 ± 0.29	0.96 ± 0.30
Monsoon	0.93 ± 0.37		0.36 ± 0.13	0.45 ± 0.13	0.91 ± 0.28
Postmonsoon	0.95 ± 0.24	1.05 ± 0.30	1.04 ± 0.12	1.16 ± 0.19 [c]	1.31 ± 0.14 [d]

[a,b] 2008, and [c,d] 2006.

AOD ratio, indicative of the dominance of fine or coarse mode aerosols, is found to show seasonal and spatial variations corroborating the results obtained on AODs (Table 3). A higher AOD ratio over Ahmedabad when compared to Gurushikhar indicates that fine mode aerosols are less abundant over Gurushikhar. Postmonsoon and winter AOD ratios in the study locations are higher than those obtained during premonsoon and monsoon suggesting the abundance of fine mode aerosols during postmonsoon and winter. Monsoon AOD ratios are the lowest in all the locations corroborating the increase and the dominance of coarse mode aerosols (Table 3). The magnitudes of AOD ratios exhibit spatial differences indicating that the source strengths of fine and/or coarse mode aerosols over these locations vary (higher or lower) during the year (Table 3). For example, AOD ratios over Gandhi College are higher than Kanpur throughout the year indicating a higher amount of fine mode aerosols in Gandhi College, which is corroborated by higher α (Table 2) values. These results from the detailed analysis of spatial, seasonal and inter annual variations in aerosol characteristics (Tables 1–3) over five locations in South Asia highlight the spatial and seasonal variabilities in the contribution of fine and coarse mode particles from different aerosol sources, and the influence of meteorology including the effect of long range transport.

Table 3. Seasonal mean aerosol optical depth (AOD) ratio (=0.38 µm AOD/0.87 µm AOD) determined from aerosol optical depths measured using hand held sun photometer and Microtops over Ahmedabad and Gurushikhar, and from AERONET over Karachi, Kanpur and Gandhi College during 2006–2008. Seasonal mean AODs correspond to year 2007 unless otherwise mentioned.

Seasons	Ahmedabad	Gurushikhar	Karachi	Kanpur	Gandhi College
Winter	2.9	2.3 [a]	1.9	2.7 [b]	3.0
Premonsoon	1.7	1.1	1.4	1.9	2.2
Monsoon	1.5		1.3	1.4	2.0
Postmonsoon	2.1	2.2	2.4	2.6 [c]	2.9 [d]

[a,b] 2008, and [c,d] 2006.

5.3. Comparison of Ground-Based and Satellite AODs

Daily values of ground-based sun photometer AODs are compared with MODIS Terra and Aqua AODs in Figures 9 and 10. Since the availability of ground-based AODs at the exact time of Terra and Aqua overpasses which are 10:30 and 13:30 LST respectively is, difficult ground-based sun photometer AODs available within ± 5 min of the satellite overpass are used. In Figures 11 and 12 ground-based sun photometer AODs averaged during the ± 42 min time frame of Terra and Aqua overpasses are compared with Terra and Aqua AODs as a function of season. At the outset, there are no visible differences in seasonal variations in the comparison figures between ground-based AODs measured within ± 5 min interval and those that are averaged within the ± 42 min with respect to Terra and Aqua AODs (Figures 9–12, Table 4). This analysis confirms that (i) aerosol optical characteristics do not change significantly within an hour over the observation site (variation within an hour is quite less); (ii) much of the diurnal AOD variation is captured well by the two MODIS instruments during their overpass times and (iii) the temporal difference between the ground-based and remote sensing measurements contributes negligibly to the observed variations/differences in aerosol optical characteristics. The results show that mean of Terra + Aqua AOD may adequately represent the daily mean (Figure 13). Differences in MODIS Terra and Aqua, and MISR AOD values with respect to those obtained from the ground-based measurements are given in Tables 4 and 5. Over Ahmedabad Terra, Aqua and MISR underestimate the AODs ($\sim$0.05) (Table 5); and the underestimation ($\sim$0.10) is more on seasonal time scales (Table 4). On an annual mean (2006–2008) scale, MODIS and MISR underestimate over Gurushikhar, a high altitude site (Table 5), while on a seasonal mean basis MODIS Terra underestimates, while Aqua overestimates during winter (Table 4). In Karachi, MODIS overestimates in different seasons (Table 4) and on annual mean basis by about 0.14, while MISR underestimates by about 0.06 (Table 5). In Kanpur and Gandhi College, located in the Indo-Gangetic Plain, the features differ; MODIS overestimates by about 0.06, while MISR underestimates by 0.17 (Table 5). In contrast, over Gandhi College, MODIS underestimates AOD by about 0.07, while MISR overestimates by about 0.2. The mean AODs over Kanpur and Gandhi College are $>$0.6, and the $\pm 1\sigma$ variation is about 20%. These results quantitatively document the differences between ground-based AOD measurements and remote sensing (MODIS and MISR) over distinctly different environments on a variety of temporal scales.

Figure 9. Aerosol optical depths measured using ground-based sun photometers compared with MODIS Terra retrieved AODs corresponding to 10:30 LST. AODs are measured using indigenously developed hand held sun photometer and Microtops sun photometer over (**a**) Ahmedabad and (**b**) Gurushikhar, while (**c**) Karachi, (**d**) Kanpur and (**e**) Gandhi College AODs are measured using AERONET sun/sky radiometers. For comparison AOD data measured within ±5 min of 10:30 LST are used.

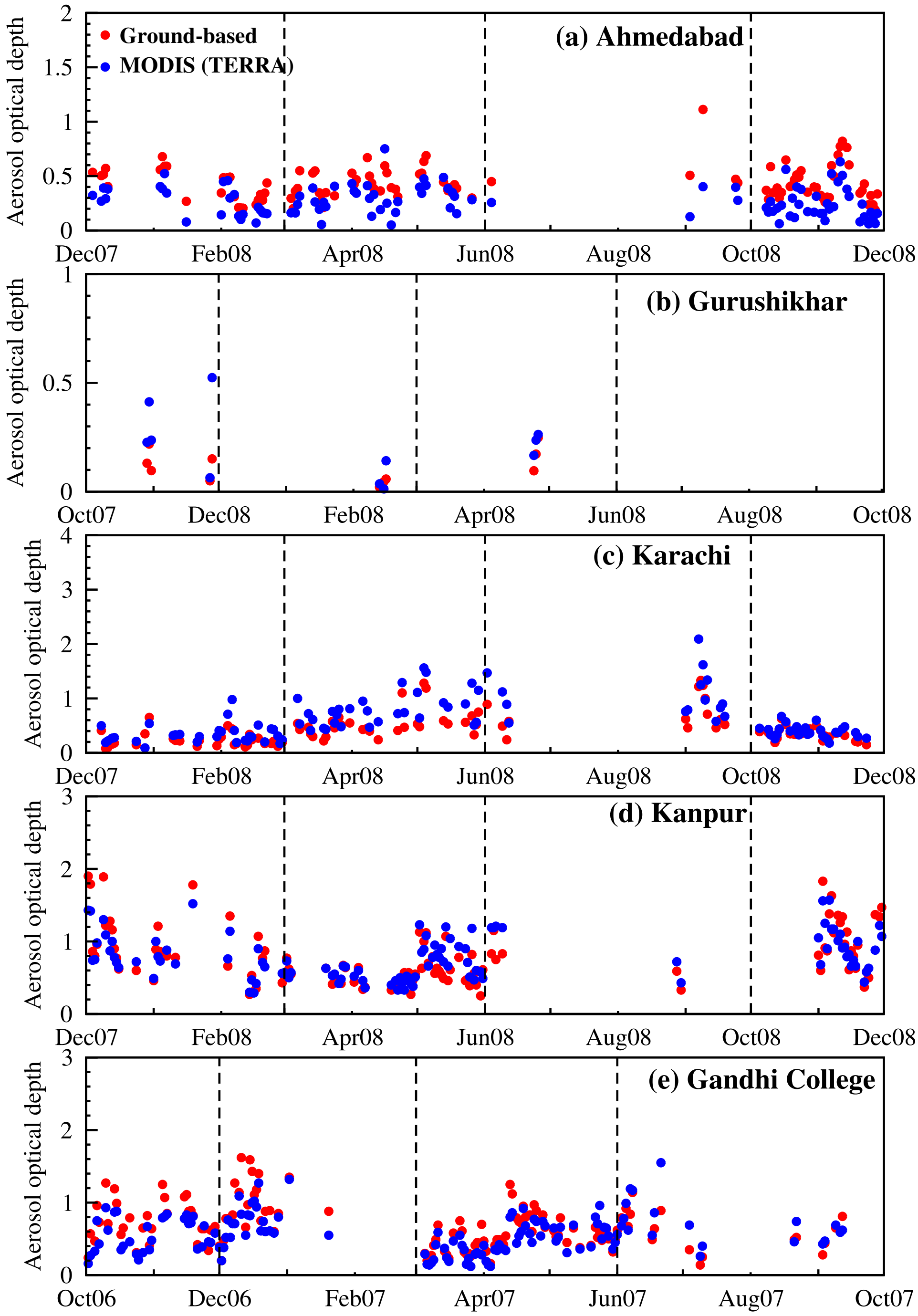


Figure 10. Aerosol optical depths measured using ground-based sun photometers compared with AODs retrieved from MODIS Aqua corresponding to 13:30 LST. AODs are measured using indigenously developed hand held sun photometer and Microtops sun photometer over (**a**) Ahmedabad and (**b**) Gurushikhar; while (**c**) Karachi, (**d**) Kanpur and (**e**) Gandhi College AODs are measured using AERONET sun/sky radiometers. For comparison AOD data measured within ±5 min of 13:30 LST are used.

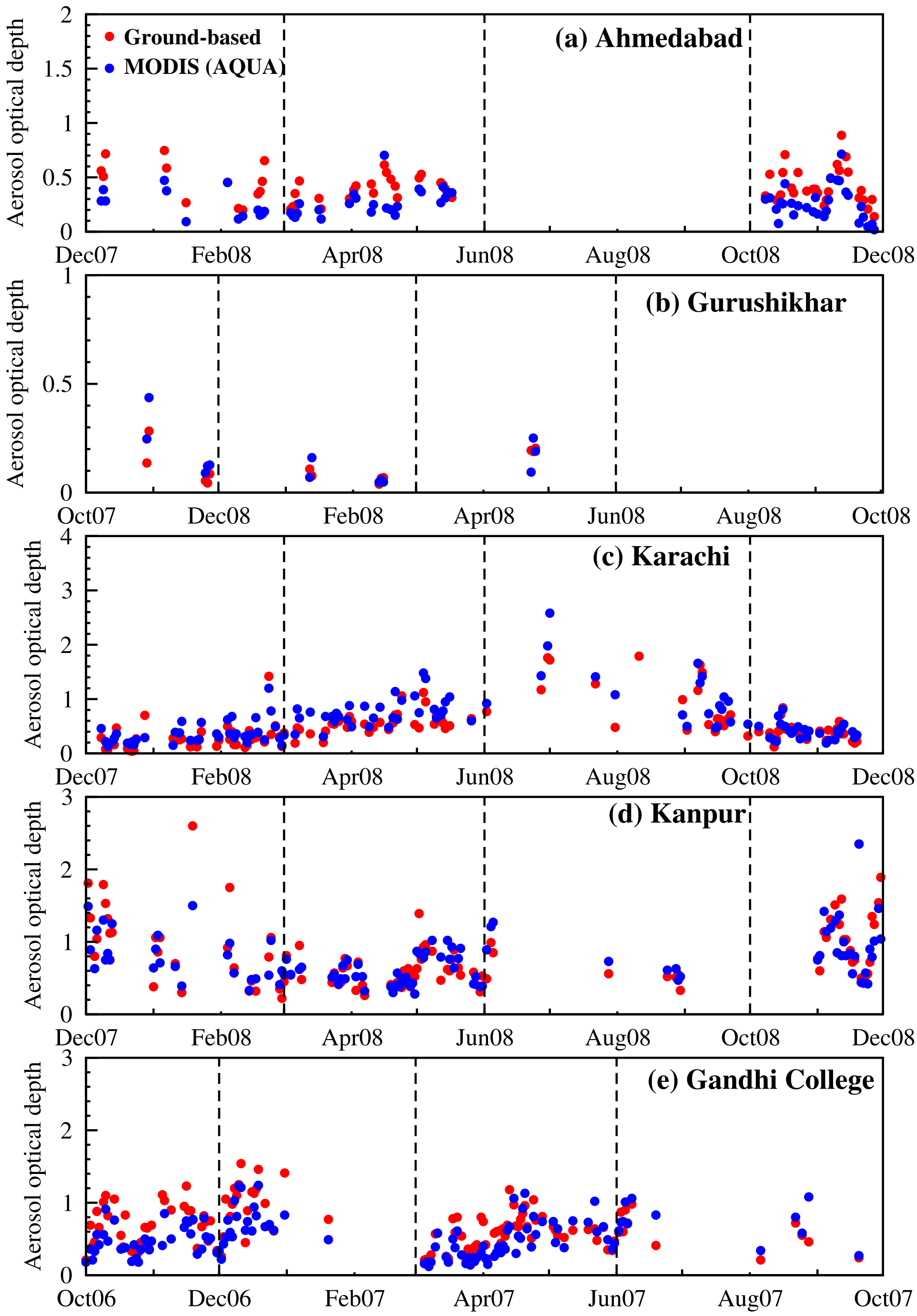


Figure 11. Daily aerosol optical depths measured using ground-based sun photometers compared with MODIS Terra AODs at each study location. AODs are measured using indigenously developed hand held sun photometer and Microtops sun photometer over (**a**) Ahmedabad and (**b**) Gurushikhar, while (**c**) Karachi, (**d**) Kanpur and (**e**) Gandhi College AODs are measured using AERONET sun/sky radiometers. For the intercomparison of MODIS and sun photometer AODs the ground based AODs measured between 09:48 and 11:12 LST (corresponding to Terra) taking into account the longitudinal dependence are averaged and drawn.

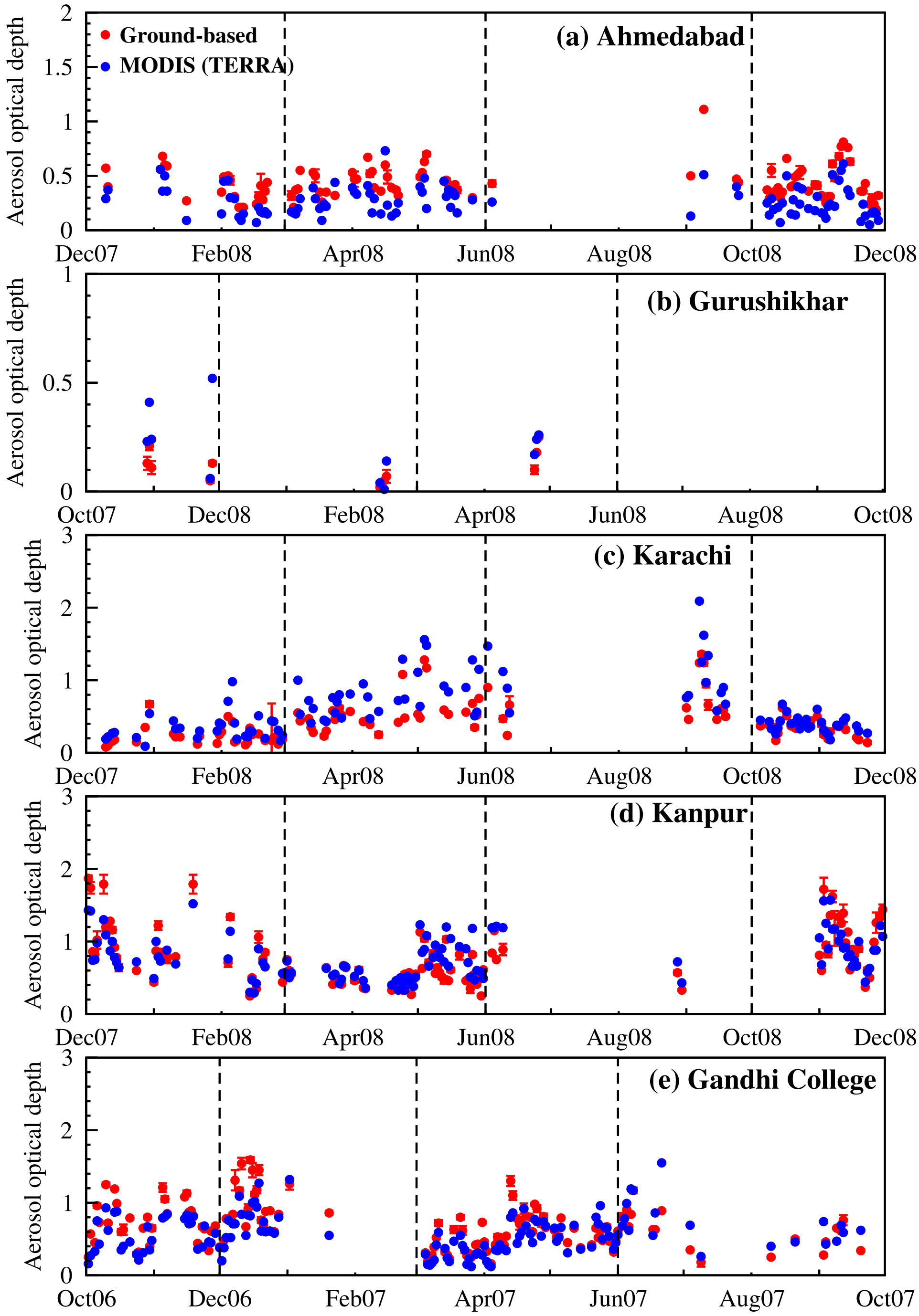


Figure 12. Daily aerosol optical depths measured using ground-based sun photometers compared with MODIS Aqua AODs at each study location. AODs are measured using indigenously developed hand held sun photometer and Microtops sun photometer over (**a**) Ahmedabad and (**b**) Gurushikhar, while (**c**) Karachi, (**d**) Kanpur and (**e**) Gandhi College AODs are measured using AERONET sun/sky radiometers. For the intercomparison of MODIS and sun photometer AODs the ground based AODs measured between 12:48 and 14:12 LST (corresponding to Aqua) taking into account the longitudinal dependence are averaged and drawn.

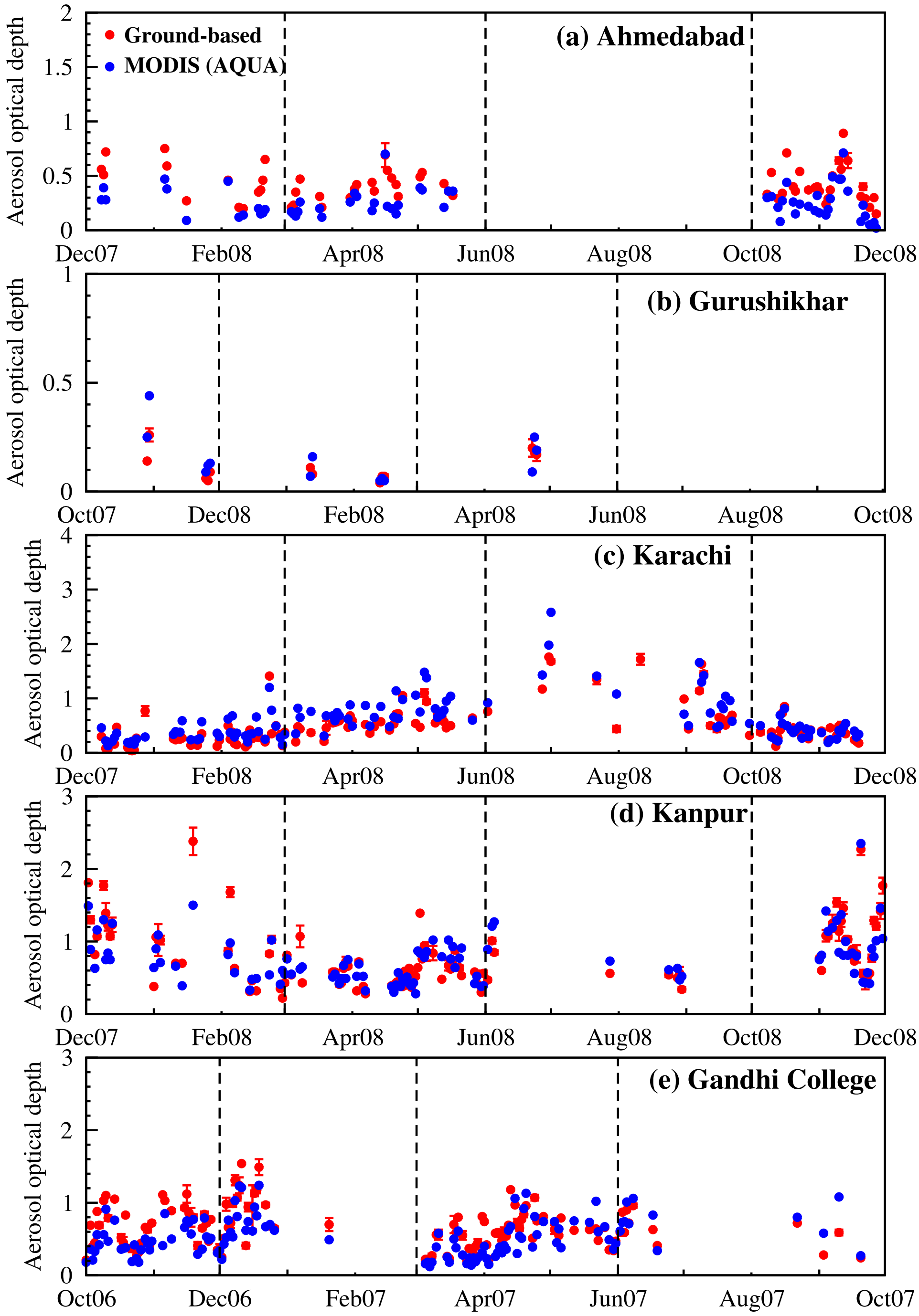


Table 4. Comparison of seasonal mean AODs in 2006–2008 obtained from ground-based measurements with AODs retrieved from MODIS Terra and Aqua. Ground-based AODs corresponding to within ±5 min of Terra and Aqua overpass times of 10:30 and 13:30 LST, and after averaging the measurements made during ±42 min corresponding to Terra and Aqua satellite pass tracks.

Source	**Ahmedabad**			
	DJF 2007–2008	MAM 2008	JJAS 2008	ON 2008
Ground-based (10:30 ± 5 min)	0.41	0.43	0.47	0.43
Ground-based (10:30 ± 42 min avg)	0.41	0.43	0.46	0.43
MODIS (Terra)	0.27	0.30	0.33	0.30
Ground-based (13:30 ± 5 min)	0.47	0.39		0.42
Ground-based (13:30 ± 42 min avg)	0.47	0.40		0.41
MODIS (Aqua)	0.27	0.27		0.28
	Gurushikhar			
	DJF 2008	MAM 2008	JJAS 2008	ON 2007
Ground-based (10:30 ± 5 min)	0.23	0.17		0.13
Ground-based (10:30 ± 42 min avg)	0.23	0.17		0.13
MODIS (Terra)	0.10	0.22		0.29
Ground-based (13:30 ± 5 min)	0.08	0.20		0.12
Ground-based (13:30 ± 42 min avg)	0.08	0.18		0.12
MODIS (Aqua)	0.08	0.18		0.20
	Karachi			
	DJF 2007–2008	MAM 2008	JJAS 2008	ON 2008
Ground-based (10:30 ± 5 min)	0.22	0.54	0.73	0.35
Ground-based (10:30 ± 42 min avg)	0.23	0.54	0.73	0.35
MODIS (Terra)	0.34	0.80	1.03	0.39
Ground-based (13:30 ± 5 min)	0.30	0.56	0.93	0.39
Ground-based (13:30 ± 42 min avg)	0.27	0.56	0.93	0.39
MODIS (Aqua)	0.37	0.75	1.21	0.40
	Kanpur			
	DJF 2007–2008	MAM 2008	JJAS 2008	ON 2008
Ground-based (10:30 ± 5 min)	0.79	0.57	0.75	1.03
Ground-based (10:30 ± 42 min avg)	0.81	0.57	0.76	1.02
MODIS (Terra)	0.82	0.65	0.99	0.95
Ground-based (13:30 ± 5 min)	0.81	0.59	0.60	1.09
Ground-based (13:30 ± 42 min avg)	0.83	0.59	0.62	1.06
MODIS (Aqua)	0.82	0.60	0.78	0.96
	Gandhi College			
	DJF 2006–2007	MAM 2007	JJAS 2007	ON 2006
Ground-based (10:30 ± 5 min)	0.94	0.54	0.61	0.74
Ground-based (10:30 ± 42 min avg)	0.94	0.55	0.61	0.74
MODIS (Terra)	0.73	0.46	0.71	0.56
Ground-based (13:30 ± 5 min)	0.92	0.56	0.60	0.68
Ground-based (13:30 ± 42 min avg)	0.89	0.56	0.62	0.68
MODIS (Aqua)	0.72	0.46	0.73	0.47

Figure 13. Diurnal mean aerosol optical depths measured using ground-based sun photometers compared with MODIS Terra and Aqua mean AODs at each study location. AODs are measured using indigenously developed hand held sun photometer and Microtops sun photometer over (**a**) Ahmedabad and (**b**) Gurushikhar, while (**c**) Karachi, (**d**) Kanpur and (**e**) Gandhi College AODs are measured using AERONET sun/sky radiometers. For the day to day intercomparison of MODIS and sun photometer AODs the ground based AODs measured between 09:48 and 11:12 LST (corresponding to Terra), and 12:48 and 14:12 LST (corresponding to Aqua) taking into account the longitudinal dependence are averaged and drawn.

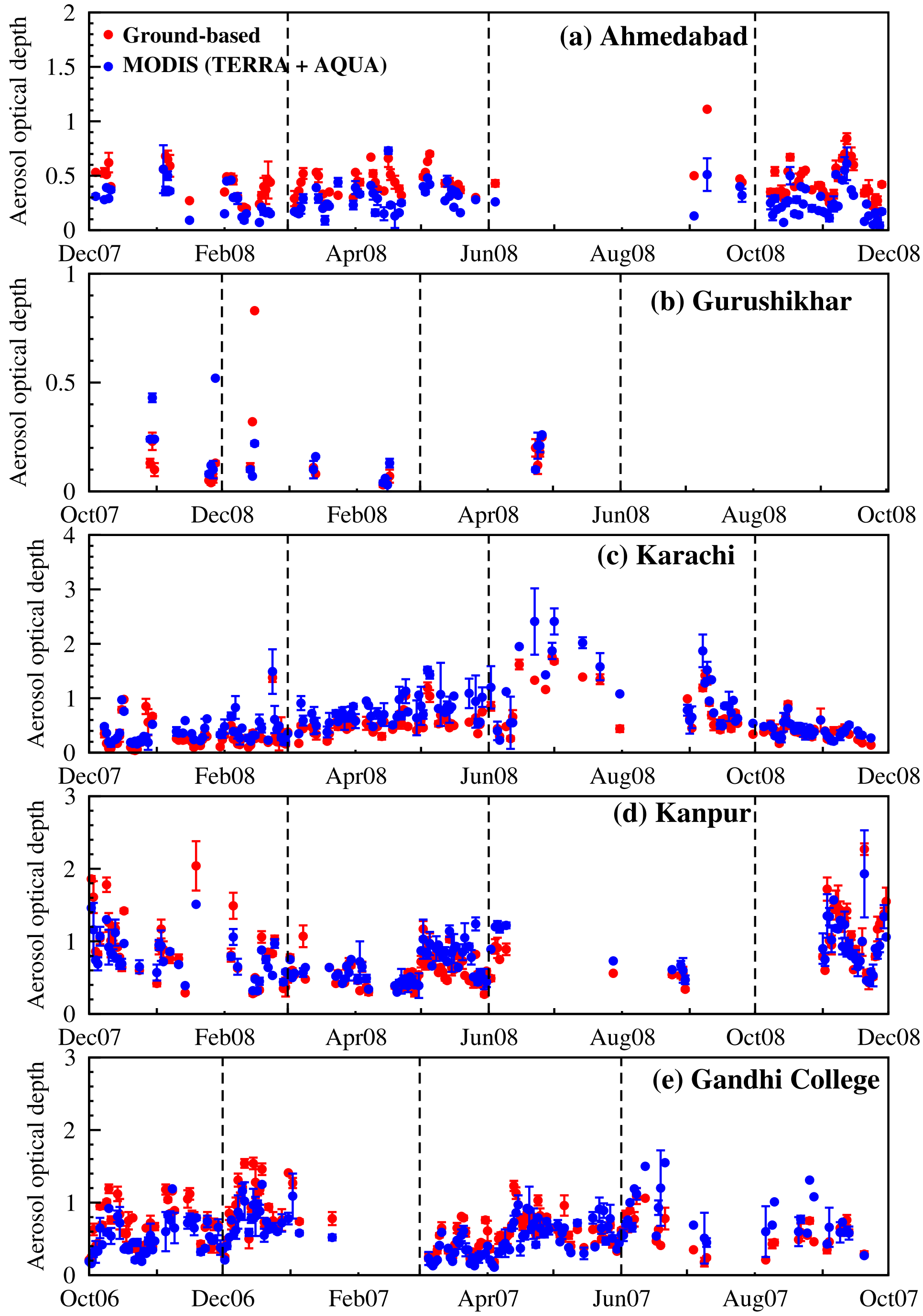


Table 5. Comparison of average (2006–2008) AODs obtained from ground-based measurements with AODs retrieved from MODIS Terra, Aqua, their mean (Terra + Aqua) and MISR. Mean AODs from ground-based measurements corresponding to Terra and Aqua satellite passing times, and the overall mean for 2006–2008 are given. AODs obtained from ground-based measurements are subtracted from MODIS and MISR (2006–2008) mean AODs. A positive value indicates overestimate of AOD by that amount by MODIS/MISR with respect to the ground-based measurement, while a negative value indicates an underestimate.

Source	Ahmedabad	Gurushikhar	Karachi	Kanpur	Gandhi College
Ground-based (09:42-11:12 h mean)	0.44	0.18	0.41	0.78	0.67
MODIS (Terra)	−0.08	+0.01	+0.16	0.00	−0.10
Ground-based (12:48-14:12 h mean)	0.44	0.12	0.52	0.80	0.66
MODIS (Aqua)	−0.08	+0.03	+0.14	−0.05	−0.13
Ground-based (Mean)	0.39 ± 0.04	0.16 ± 0.08	0.46 ± 0.13	0.63 ± 0.15	0.68 ± 0.13
MODIS (Terra + Aqua)	−0.07	−0.04	+0.13	+0.06	−0.07
MISR	−0.05	−0.02	−0.06	−0.17	+0.20

In Figure 14 seasonal means of sun photometer, Microtops and AERONET measured 0.5 μm AODs are compared with MODIS and MISR retrieved AODs at 0.55 μm and 0.555 μm respectively, over Ahmedabad, Gurushikhar, Karachi, Kanpur and Gandhi College. During the entire study period and for all the study locations MODIS and MISR AODs are broadly able to capture the seasonal variations (Figure 14), for example, the winter and postmonsoon low in AODs and the premonsoon and monsoon high in AODs. However, the magnitude of AODs are found to exhibit distinct behavior. MODIS underestimates AODs in Ahmedabad, Gurushikhar and Gandhi College by at least 0.04 in absolute magnitude, while it overestimates by about 0.06 in Kanpur and by 0.13 in Karachi. On the other hand, MISR underestimates AODs at all the locations except Gandhi College (Table 5). Over Kanpur and Gandhi College, separated by about 200-300 km, MODIS overestimates while MISR underestimates in Kanpur; MODIS underestimates while MISR overestimates over Gandhi College. Interestingly the over or underestimation in AODs by the two satellites over this region is almost the same in terms of the amount (Table 5).

Figure 14. Comparison of seasonal mean aerosol optical depths obtained from ground-based (sun photometer, Microtops and AERONET sun/sky radiometers), and satellites (MODIS and MISR) during 2006–2008 over (**a**) Ahmedabad; (**b**) Gurushikhar; (**c**) Karachi; (**d**) Kanpur; and (**e**) Gandhi College. Ground based aerosol optical depths correspond to 0.5 μm, while MODIS and MISR retrieved aerosol optical depths are at 0.55 and 0.555 μm respectively. Vertical bars denote $\pm 1\sigma$ deviation from the seasonal mean.

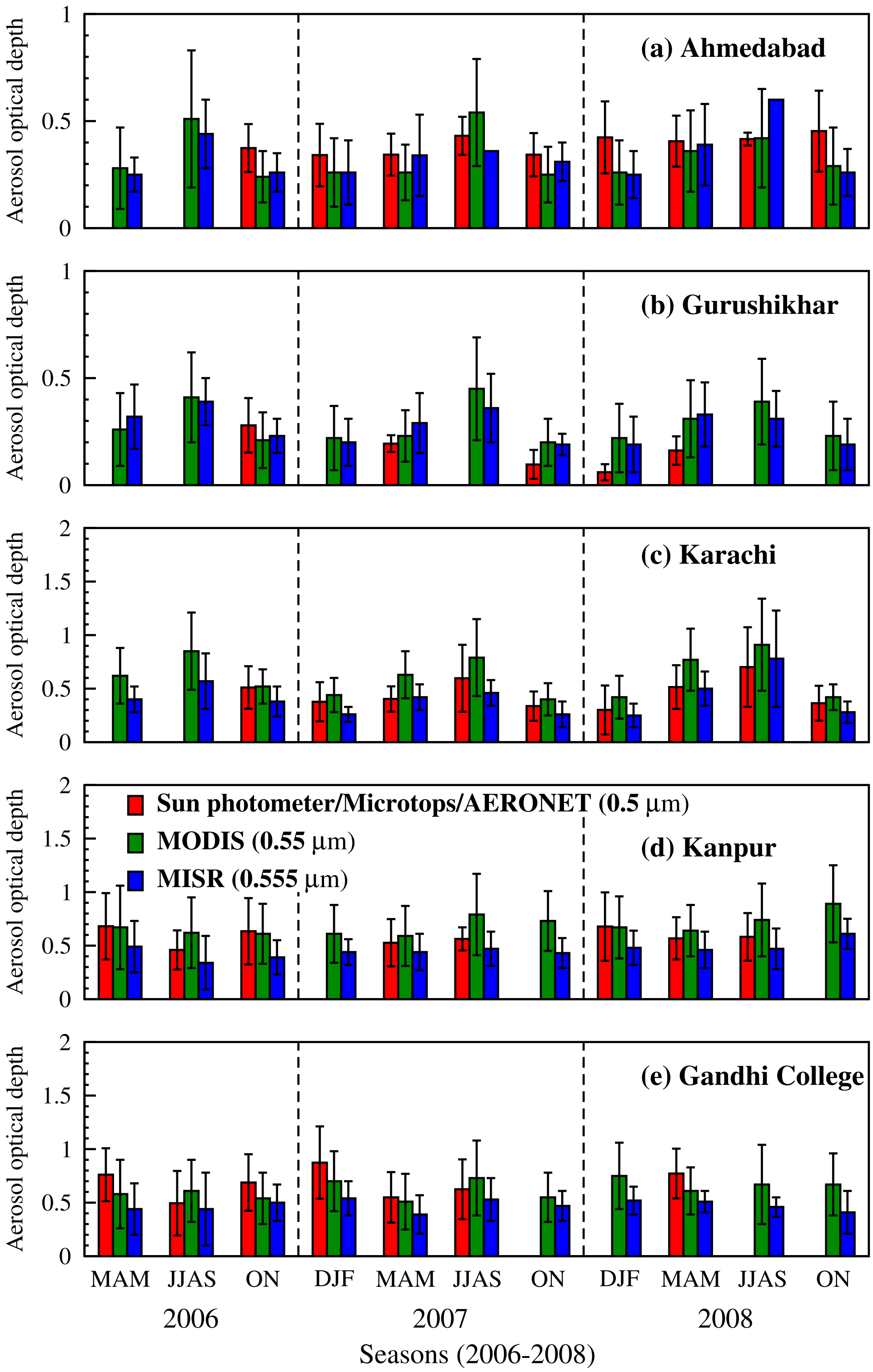
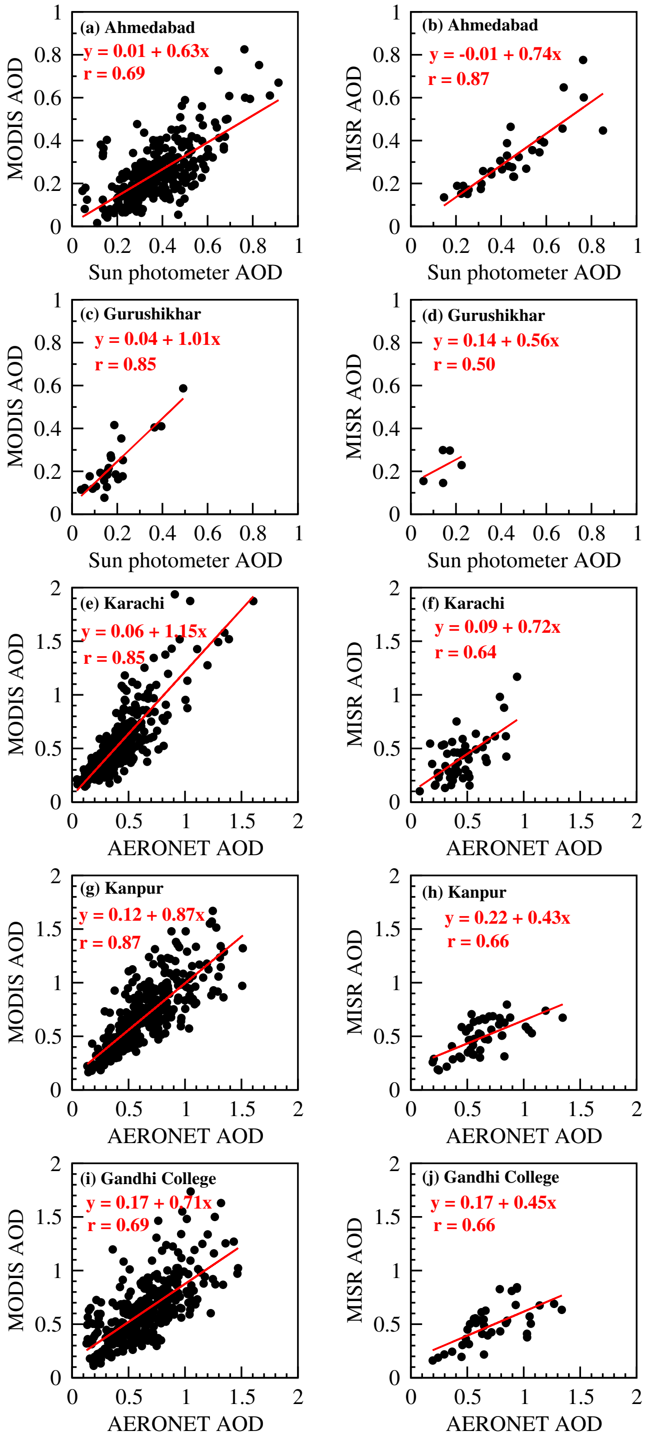


Figure 15. Correlation between ground-based sun photometer, Microtops and AERONET sun/sky radiometers measured AODs and satellite (MODIS and MISR) retrieved AODs during 2006–2008 over Ahmedabad (**a**,**b**); Gurushikhar (**c**,**d**); Karachi (**e**,**f**); Kanpur (**g**,**h**); and Gandhi College (**i**,**j**). Ground-based AODs correspond to 0.5 µm, while MODIS and MISR retrieved AODs are at 0.55 and 0.555 µm respectively.



A one-on-one correlation between the collocated daily mean AODs obtained over each study location from ground-based (sun photometer, Microtops, and sun/sky radiometers) and satellite (MODIS and MISR) measurements (Figure 15) is shown. Correlation coefficients lie in the range of 0.50–0.87 in the study locations (Figure 15). The correlations are not so strong due to the differences between the AODs retrieved from MODIS, MISR and ground-based instruments. The plausible causes that could contribute to the differences between ground-based and satellite retrieved AODs include: (1) spatial difference between the two measurements (point, *vs.* grid); (2) uncertainties associated in deriving AODs from both ground-based and satellite retrievals; and (3) differences in the wavelengths (0.50 μm in case of sun photometer/Microtops/sun/sky radiometers, 0.55 μm from MODIS, and 0.555 μm from MISR) [2,28]. It should be noted that while MODIS provides a near global coverage daily [38], MISR can provide the global coverage once in 9 days, which reduces the number of days on which AODs can be compared (Figure 15). A comparison of coincident MODIS, MISR and AERONET AODs revealed that instrument sampling, sampling differences, assumptions made in the MODIS and MISR standard algorithms about boundary conditions, missing particle property or mixing options, reflectances used in the retrievals, in addition to cloud screening could be contributing to differences in AODs between the ground-based and satellite measurements [39]. For example, it has been found that the dust models used in MISR retrievals are too absorbing, therefore, revised dust models including a wider range of bimodal, non-absorbing mixtures are being considered [40]. The analysis on the correlation between ground-based and remote sensing suggests that improvements to be made in retrievals including the surface reflectance and aerosol properties will enhance the correlation between ground-based and satellite retrieved AODs. The results on the spatio-temporal variations in aerosol optical characteristics over five locations governed by different sources, and the comparison between ground-based and remote sensing AODs will be useful in remote sensing to improve the retrieval algorithms, and in assessing the aerosol impact on climate.

6. Summary and Conclusions

Seasonal and inter annual variabilities in aerosol optical depth (AOD) and size distribution are examined over five locations in South Asia during 2006–2008. Ahmedabad, Gurushikhar and Karachi in the West of South Asia are in the semi arid/arid region. Ahmedabad and Karachi are urban and industrialized locations. Karachi in addition is a coastal station. Gurushikhar, a remote, high altitude site is more influenced by long range transport of aerosols. Kanpur and Gandhi College in the Indo-Gangetic basin are urban, industrial city and a rural location respectively. AODs retrieved from hand held sun photometer and Microtops measurements in Ahmedabad and Gurushikhar, and from AERONET sun/sky radiometer measurements over Karachi, Kanpur and Gandhi College are utilized in the study. Ångström wavelength exponent (α) is determined from spectral AODs obtained in the wavelength region of 0.38–0.87 μm over Ahmedabad, Gurushikhar in western India, Karachi, Kanpur and Gandhi College in the Indo-Gangetic Plain. AODs obtained from the ground-based measurements (sun photometers and sun/sky radiometers) have been compared with satellite (MODIS and MISR) retrieved AODs during 2006–2008.

The major findings of the study are:

(1) Highest AODs are observed over Karachi; while the lowest AODs are obtained over Gurushikhar. AODs over Ahmedabad and Karachi are at least a factor of two higher than the AODs measured over Gurushikhar. AODs over the locations (Kanpur and Gandhi College) in the Indo-Gangetic basin are

higher than those measured in the western region of South Asia. AODs in short wavelength (0.38 μm) over Gandhi College are about 20% higher than Kanpur; while AODs at 0.87 μm are nearly the same for all the seasons over both the locations. Higher AODs over Gandhi College occur as the location is downwind of major urban centers in the Indo-Gangetic basin, and being a rural location the local production from biomass emissions could contribute additionally to the increase in AODs.

(2) Over the study locations in west of South Asia, an increase in AODs is observed during monsoon because of higher wind speeds, relative humidity, hygroscopic growth of water soluble aerosols, and deeper boundary layer. Winter AODs are higher in the Indo-Gangetic basin, due to shallow boundary layer, increase in fossil fuel and bio fuel emissions which give rise to hazy and foggy conditions, and therefore higher AODs.

(3) AOD ratio, ratio of AODs at 0.38 μm and 0.87 μm, an indicator of whether sub-micron or super-micron aerosols dominate the aerosol size distribution, is found to show seasonal and spatial variations consistent with AOD variations. Postmonsoon and winter AOD ratios in the study locations are higher ($\geq$2) than those obtained during premonsoon and monsoon suggesting the abundance of fine mode aerosols during postmonsoon and winter. Monsoon AOD ratios are the lowest because of the dominance of coarse mode (mainly sea salt) particles.

(4) Ångström wavelength exponent (α) is found to exhibit large spatial, seasonal, and inter annual variations during 2006–2008. α values during postmonsoon and winter are higher than that of premonsoon and monsoon values in all the locations. α values are lower over Gurushikhar and Karachi indicating the dominance of coarse mode aerosols (dust in Gurushikhar, and sea salt in Karachi). Higher α values over the study locations can be attributed to the dominance of fine mode aerosols over urban locations (e.g., Ahmedabad and Kanpur).

(5) Comparison between ground-based and MODIS (Terra and Aqua) retrieved AODs show that aerosol optical characteristics do not change significantly in an hour and much of the diurnal AOD variation is captured well by the two MODIS instruments. The temporal difference (about an hour) between the ground-based and remote sensing measurements contributes negligibly to the observed differences in AODs. The differences between ground-based and remote sensing AODs vary on spatial scales. During the study period (2006–2008) MODIS underestimates AODs over western India by about 0.04, while over the Indo-Gangetic Plain MODIS overestimates AOD by 0.06 in (Kanpur) and underestimates by 0.07 (Gandhi College) when compared to AODs measured by hand held sun photometer and Microtops sun photometer (Ahmedabad and Gurushikhar), and AERONET sun/sky radiometers (Karachi, Kanpur and Gandhi College) respectively. During the same period MISR underestimates AODs in the range of 0.02–0.17 over Ahmedabad, Gurushikhar, Karachi and Kanpur, while in Gandhi College MISR overestimates AOD by 0.2 when compared to ground-based AODs.

(6) The aerosol characterization and the knowledge obtained on the correlation and the differences on different temporal scales between ground-based and remote sensing AODs over five different environments can serve as inputs to improve the remote sensing retrieval algorithms. The spatial, seasonal and inter-annual variations in aerosol characteristics over South Asia will be useful in aerosol radiative forcing estimates on regional scale, and regional/global climate impact studies.

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Conflicts of Interest

The authors declare no conflict of interest.

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