Atmospheric Pollution Research 6 (2015) 254-266

Atmospheric Pollution Research

www.atmospolres.com

Spatio–temporal distribution of absorbing aerosols over Pakistan retrieved from OMI onboard Aura satellite

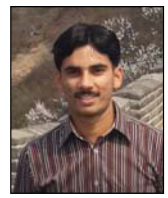
Salman Tariq, Muhammad Ali

Remote Sensing and GIS Group, Department of Space Science, University of the Punjab, New Campus, Lahore–54590, Pakistan

ABSTRACT

The observations of aerosol index (AI) deduced from Ozone Monitoring Instrument (OMI) with spatial resolution of 0.25°×0.25° have been analyzed over Pakistan from December 2004 to November 2008. Significant spatio–temporal variabilities in AI values were observed with higher values in southern parts and lower values in northern parts of Pakistan. The mean annual AI in Southern and Northern Pakistan have been found to be 1.220±0.250 and 1.088±0.280, respectively with an overall mean of 1.155±0.257 over the entire country. The monthly spatially averaged values of AI show a clear maximum in the month of May (1.539±0.499), one of the two months having highest dust storm activity in the region, and minimum value in the month of December (0.851±0.134), having lowest dust storm activity. We have also examined the effect of precipitation on AI values and have found that inverse correlation exists between AI and accumulated precipitation, particularly in the months of July, August and September with corresponding R^2 values of 0.24, 0.25 and 0.33 respectively.

Keywords: *Ozone Monitoring Instrument, aerosol index, Pakistan*



Corresponding Author:
Salman Tariq
☎ : +92-3008844797
✉ : salmantariq_pu@yahoo.com

Article History:
Received: 28 May 2014
Revised: 22 September 2014
Accepted: 23 September 2014

doi: 10.5094/APR.2015.030

1. Introduction

It has been recognized that atmospheric aerosols affect the energy balance, climate and hydrological cycle (IPCC, 2007). These particles interact with solar radiation by scattering and absorbing it in such a way that the aerosols absorbing the solar radiation warm the atmosphere, while reflecting aerosols have a cooling effect. Aerosol particles also act as cloud condensation nuclei and affect the microphysical properties and formation of clouds (Andreae and Rosenfeld, 2008). Thus the studies of aerosol properties and processes can lead to a better understanding about the factors involved in regional and global climate change. Because of limitations of ground based observations, satellite systems provide a unique opportunity to monitor and assess the air quality and thus help to improve our understanding of impact of aerosols on energy balance and climate. However, large uncertainties still exist in predicting and quantifying the influence of aerosols on climate (IPCC, 2001) and these uncertainties can be reduced by deeply studying the aerosol characteristics and their atmospheric effects.

During the last few decades, there has been a continuous increase in the use of satellite remote sensing (SRS) to investigate aerosol properties. In particular, the ultraviolet (UV) aerosol indices (AI) constitute a useful tool in SRS that yields information on absorbing aerosols. Because of low surface albedo of land within ultraviolet wavelengths, this range is regarded to be useful for the detection of aerosols over land (de Graaf et al., 2005). The spectral comparison between two ultraviolet wavelengths is used to calculate AI values. This spectral contrast appears because of difference in the behavior of absorbing aerosols and other phenomena such as surface reflection, Rayleigh scattering, gaseous absorption and cloud and aerosol scattering (Torres et al., 1998). Consequently the observations of AI have been used to identify the air pollution sources over the whole globe, to examine the transport of air pollutants across the continents, to model air quality and forecast, and to study radiation energy balance and climate forcing (Ahmad et al., 2006). The aerosol index represents the difference between measured and calculated spectral contrast at two near UV wavelengths (Herman and Celarier, 1997). The magnitude of AI depends upon aerosol optical depth, aerosol type (single scattering albedo), height of aerosol layer and viewing geometry (Torres et al., 2002). The absorbing aerosols such as smoke and desert dust are assigned positive values of AI while pure scatterers are assigned negative values (Torres et al., 1998). However, negative AI may also occur due to other features such as high altitude clouds and spectral slopes in the surface reflectance among the reference wavelengths (Baddock et al., 2009). Near zero values of AI represent the presence of clouds (Hsu et al., 1999), while aerosol index values greater than 1.0 correspond typically to absorbing aerosols such as soot particles or dust (Washington et al., 2003; Kubilay et al., 2005).

Recently Gupta et al. (2013) have analyzed the MODIS (Moderate Resolution Imaging Spectroradiometer) AOD retrievals over two mega cities (Karachi and Lahore) of Pakistan. The main objective of their study was to assess the standard of MODIS data for air quality and climate applications. By using ten years (2001–2010) of high quality satellite AOD data Gupta et al. (2013) have examined spatial and temporal trends of atmospheric aerosols. Their analysis shows a decreasing trend over Lahore during the studied period, though it may not necessarily represent actual mass concentrations over the surface. Habib et al. (2006) studied the spatial and temporal variability of TOMS (Total Ozone Mapping Spectrometer)–AI using long term (1981–2000) data over India. Their analysis shows that northwestern area of the studied region that includes central and southern parts of Pakistan is dominated by high desert dust loadings in conjunction with comparatively low rainfall during May and June. According to the findings of Habib et al. (2006) the seasonal variations in TOMS–AI were mainly related to the seasonal cycle in dust and biomass burning emissions and a large impact of rainfall in reducing the aerosol load through washout process. In order to assess the use of Aura–OMI–AI over Greece, Kaskaoutis et al. (2010) have studied the AI data derived from OMI observations. Their analysis shows a strong south to north gradient that varies seasonally, such that becoming more intense during spring and summer and minimizing during winter. In this paper we present a study of AI obtained from OMI measurements over Pakistan, a poorly studied area and having locations with a variety of aerosol loadings, aerosol types, anthropogenic activities, meteorological conditions and topographic patterns. The key objective of the present work is to analyze the regional spatio–temporal patterns of absorbing aerosols by exercising the use of Aura–OMI observations. To the best of our knowledge no such study has so far been conducted over Pakistan to analyze the variabililties of AI derived from OMI. However, OMI observations have recently been used to study the tropospheric NO_2 over Pakistan (ul–Haq et al., 2014). In order to investigate the effect of precipitation on variability of absorbing aerosol loading, we have also examined the data from Tropical Rainfall Measuring Mission (TRMM) over the study area and have tried to find its correlation with the OMI–AI measurements.

2. Methodology

2.1. Study area

Pakistan is a South Asian country having an area of about 796 100 km^2 and population of over 186 million. It shares its borders with People's Republic of China, India, Afghanistan and Iran and to the south there is a coastline of almost 1 046 km along the Arabian Sea and gulf of Oman (see Figure 1). Geographically, Pakistan can be divided into three main categories: the northern mountainous areas, the Indus River plain and the Baluchistan Plateau. Pakistan possesses highly variable altitudes ranging from sea level to the second highest peak of the world (8 611 m), situated in Himalayan region i.e. Mount Godwin Austin/K–2. These extreme topographic variations along with highly variable climatic conditions make Pakistan a unique territory for studying spatio–temporal patterns (Alam et al., 2011a).

Pakistan is a developing country facing problems such as rapid growth in its population density, environmental degradation and increasing pressures on its resources and infrastructure (Ali et al., 1996), and rapid urbanization and industrial expansion are considered to be among the major factors responsible for atmospheric pollution in this region. Prospero et al. (2002), while studying the global distribution of major atmospheric dust sources, have pointed out that TOMS data show high absorbing AI values over Northwest India and Pakistan, covering an area extending from the coast of Arabian Sea to the northern reaches of Pakistan. These high TOMS–AI values have been attributed to dust and large emissions of incomplete combusted fuels of different types, as well as heating and cooking fires and emissions from millions of motor–cycle and diesel engines (Prospero et al., 2002). Consequently, this region is considered to have the worst visibility in the world (Husar et al., 2000). As far as the sources of dust are concerned, the easterly movements of low pressure systems are usually related to the large dust storms in the area. Figure 2 shows the maps of surface temperatures, and specific humidity and wind speeds at 850 mb during all the four seasons (DJF, MAM, JJA and SON). NCEP–Reanalysis 2 data from NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, have been used to plot maps of surface temperature, specific humidity and wind speeds. We observe relatively higher temperatures in central and southeastern parts of Pakistan during all the seasons, with highest temperatures being observed during summer season (JJA). Winter season (DJF) is relatively dry while summer season has the highest specific humidity.

Figure 1. *Map of Pakistan showing major cities and neighboring countries.*

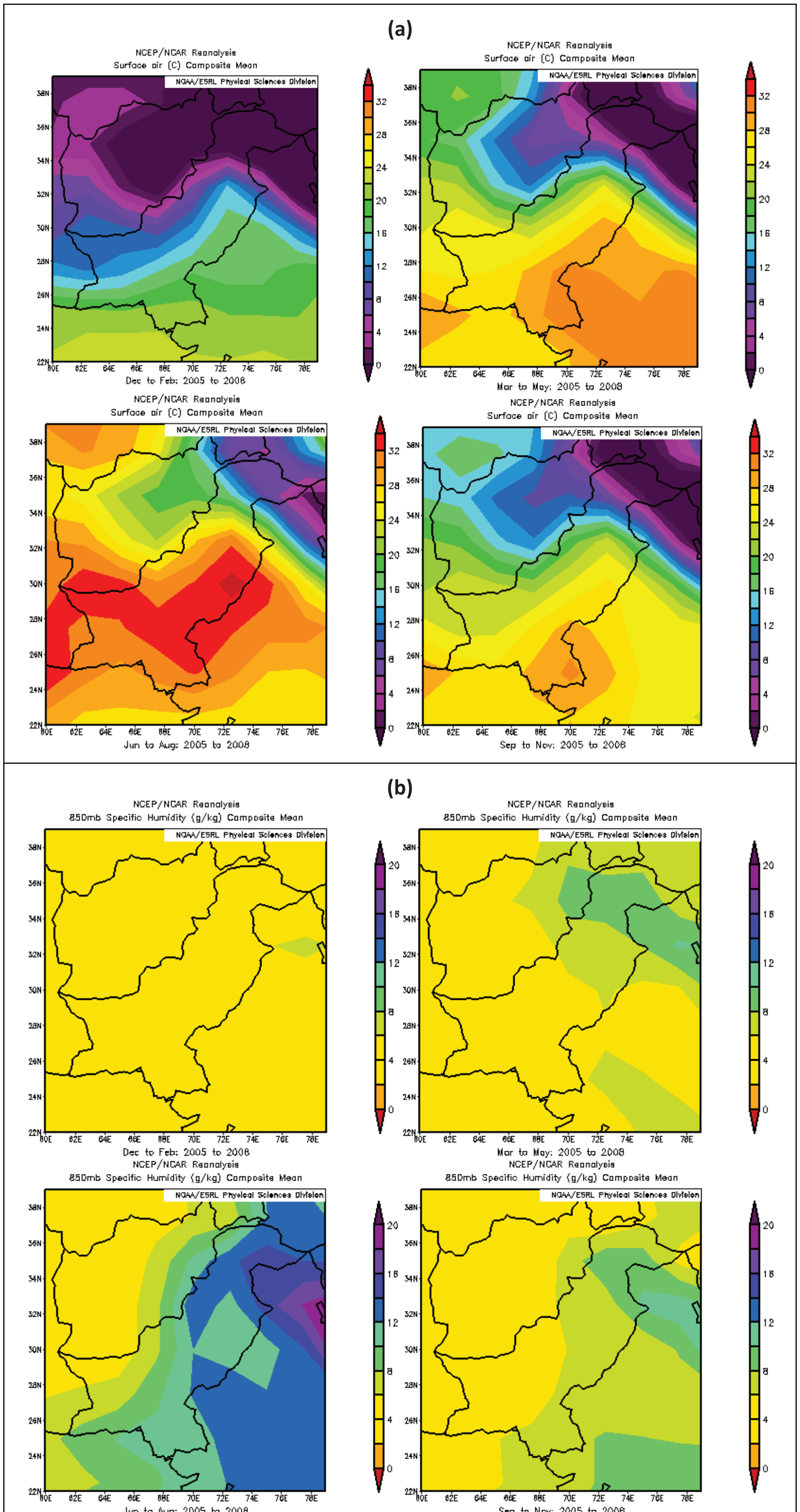


Figure 2. *Maps of surface temperature **(a)**, specific humidity at 850 mb **(b)**, and wind speeds at 850 mb **(c)**, for four major seasons (DJF, MAM, JJA, SON) over Pakistan during the study period.*

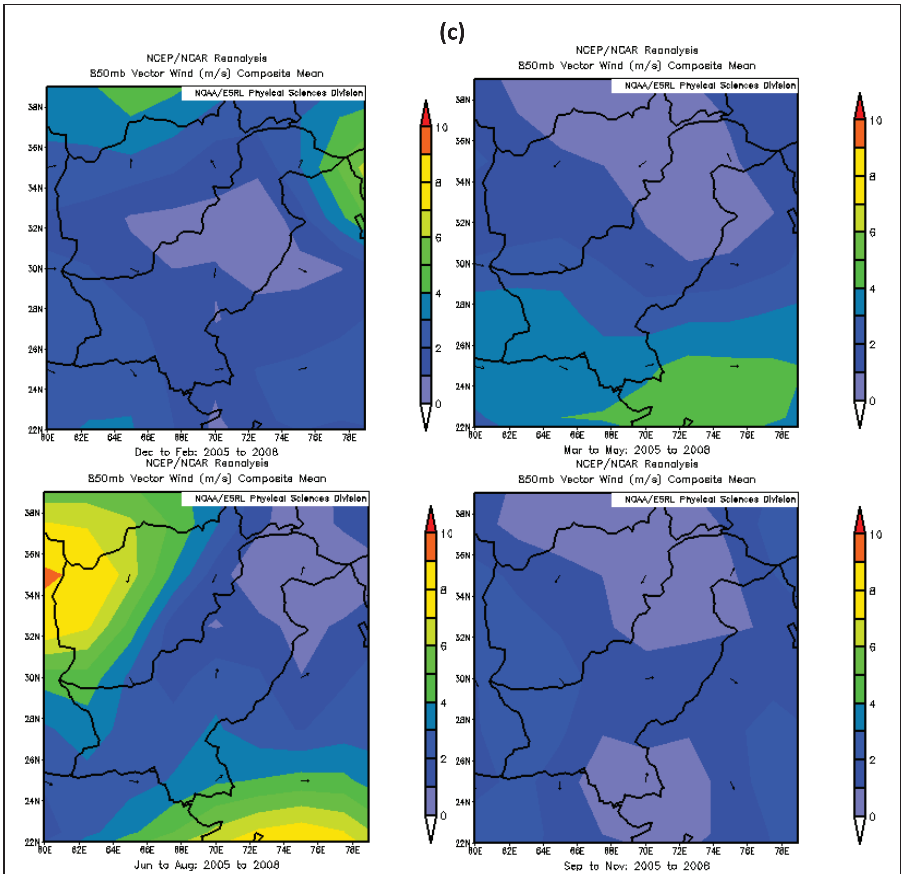


Figure 2. *(Continued).*

2.2. Datasets

The Total Ozone Mapping Spectrometer (TOMS) provided aerosol information starting from 1978 that has been continued by Ozone Monitoring Instrument (OMI) on board the Aura satellite that was launched in July 2004. OMI is an important instrument for monitoring the ozone layer and it can differentiate between various types of aerosols such as dust, smoke and sulfate. It measures the backscattered solar radiation from the atmosphere and surface of the Earth over the wavelength range from 270 nm to 500 nm, having a spectral resolution of about 0.5 nm. In addition to highly resolved spectral information, the main quality of OMI is its unprecedented spatial resolution along with daily global coverage (Levelt et al., 2006). Thus, far more cloud free scenes are obtained than the earlier backscatter spectrometer measurements. Its nadir pointing telescope has a wide field of view of 114°, which is used for swath registration, perpendicular to the flight direction of the satellite (Levelt et al., 2006). The reflectance measured at the top of the atmosphere (TOA) is used to retrieve several aerosol products including AI by using a multi–wavelength algorithm. The OMI algorithms rely heavily on experience gained from TOMS, GOME (Global Ozone Monitoring Experiment) and other instruments and are continued to be improved by science team members (Levelt et al., 2006). We have used the ultraviolet AI daily data produced by OMTO3G (Version 003) algorithm (available at http://disc.gsfc.nasa.gov/Aura/OMI/omto3g_v003.shtml) from the NASA Goddard Earth Sciences Data and Information Center (GES DISC, 2014). OMTO3G daily data products are created for each level–2 standard product by OMI science team. It contains data from fifteen level–2 data files (i.e. from 15 orbits) binned into 0.25×0.25 degree global grids (Ahmad et al., 2006). The information about time, latitude, longitude, view angles, quality flags of the pixels falling in the same grid is conserved. In our study, the data used are filtered by good quality as defined by science teams: viewing zenith angle and solar zenith angle ranges from 0° to 70°, radiative cloud fraction having values from 0.0 to 1.0, path length index from 3 to 7 and ocean glint angle +/–20° (Giovanni, 2014). Radiative cloud fraction provides the ability to filter clear sky (i.e. 0–30%) versus cloudy scenes. Monthly/seasonal means are calculated from daily data and standard deviation represents the deviation from mean monthly AI values. Missing values are not considered while calculating monthly/seasonal means and standard deviations.

It is difficult to interpret physically the concept of AI (de Graaf et al., 2005), which is a qualitative parameter representing the presence of absorbing aerosols. The ultraviolet AI from OMI instrument is basically a residual quantity obtained from the measured spectral contrast of radiances of two wavelengths (317.5 nm and 331.2 nm under most conditions, and 331.2 nm and 360 nm for high ozone and high solar zenith angle conditions), and the contrast calculated by modeling an atmosphere that is free from aerosols and clouds and is bounded by a Lambertian reflector with a certain albedo value. The albedo is so chosen that the modeled reflectance at a reference wavelength, say λ_0, matches with the measured reflectance at that wavelength (de Vries and Wagner, 2011). In the OMTO3 algorithm, the reference wavelength λ_0 is taken to be 331 nm while λ is taken as 360 nm. The ultraviolet AI is then given by the ratio between the measured and modeled reflectances at λ:

$$AI = -100 \log_{10} \frac{R_{meas}}{R_{model}} \qquad (1)$$

where, R_{meas} and R_{model} are the measured and modeled reflectances respectively at the wavelength λ. AI is sensitive to elevated absorbing layers such as dust and biomass burning aerosols (de Graaf et al., 2005). The positive values of ultraviolet AI are attributed to the absorbing aerosols, such as smoke and dust, while, for non–absorbing aerosols (e.g. sea salt and natural sulfate), we get negative values of AI (Torres et al., 1998). Near zero values of AI are associated with the presence of clouds in the region concerned. Thus the ultraviolet AI can be used to differentiate the absorbing aerosols from scattering ones and the near ultraviolet aerosol sensing technique is especially useful for tracking absorbing aerosol types over all terrestrial surfaces even when covered by ice or snow and above clouds (Ahn et al., 2008; Baddock et al., 2009).

In order to observe effect of precipitation in AI values, precipitation data from Tropical Rainfall Measuring Mission (TRMM) has been used. The TRMM is a US–Japanese mission launched in November 1997 that aimed to measure rainfall variability within tropical and subtropical regions of the world. The TRMM, in coordination with other satellites, provides useful rainfall information that helps to understand the interactions between water vapors, clouds and precipitation. The main rainfall instruments on TRMM are the Precipitation Radar (PR), the TRMM Microwave Imager (TMI), and the Visible and Infrared Radiometer System (VIRS). The details of radiometric characteristics, calibration procedures, scanning geometry and data products have been given by Kummerow et al. (1998). The space segment of TRMM is a satellite having 35° inclination angle in a 350 km circular orbit. In the present study we have used monthly TRMM 3B42 (V6) accumulated rainfall data having spatial resolution of 0.25°×0.25°.

3. Results and Discussion

3.1. Time series of monthly mean AI values

The time series of monthly mean AI values spatially averaged over Pakistan along with their standard deviations for the period December 2004 to November 2008 are shown in Figure 3a. The highest monthly value of AI has been observed to be 3.2 in June 2006 (27.625° N, 68.375° E), while the lowest value has been found to be 0.5 at multiple locations. The wide range of AI values in the time series occurs mainly due to high AI values observed over the south and southeastern parts of Pakistan during summer. This climatic region is arid with very hot summer and mild winter and the seasonal variations over this region result in substantial variations in AI values. Apart from the regional and sub–continental events originating from the Sahara Desert (El–Askary et al., 2006), the main contribution to the AI values comes from the dust particles originating within the local areas including the Thar Desert. We do not observe any negative AI value over Pakistan indicating the dominance of UV–absorbing aerosols throughout the year. Kaskaoutis et al. (2010), however, found negative values as well for AI over North Greece in summer season, suggesting dominance of non–absorbing particles (e.g. sulfate and sea salt).

The main feature of AI time series exhibited in Figure 3a is yearly cyclic variations in the AI values with highest values observed during the months May–July, while lowest values were recorded during November–January. An almost similar cyclic trend has been found by Ali et al. (2014) in the variability of AERONET based observations of aerosol optical depth (AOD) over Lahore, a central location in Pakistan. This similarity between cyclic variations of AI and AOD bears out a strong seasonality, which is a specific feature of this South Asian region. These seasonal variations in OMI–AI values have appeared mainly due to seasonal cycle of dust and crop residue burning emissions and a large impact of precipitation in modifying the aerosol concentrations. Moreover, the positive values of AI indicate the dominance of absorbing aerosols in the total aerosol burden. The gradual increase in OMI–AI from February to May/June is related to the typical pre–monsoon dust activity. The regular increase in temperatures, wind speeds and dust storm activities during these months is mainly responsible for the enhanced AI values. Higher aerosol layer increases AI and aerosols lower than about 1 000 meters are not likely to be observed (de Graaf et al., 2005). In summers, unstable atmosphere causes the uplift of aerosols to greater heights resulting in high AI values. However, during winters stable atmosphere trap the aerosols to lower heights causing AI values to be low. The AI can be uncertain due to the contrast between true and modeled reflectance of land, changes in aerosol layer height, changes in solar zenith angle and reflectivity and pressure of clouds. As the rainfall in the monsoon season starts, a gradual decrease in OMI–AI values is found. The observed cyclic variability in OMI–AI is associated mainly with the seasonal variation in the smoke and dust and reduction in the aerosol load by the washout process of rainfall activity. We further notice that, except for the year 2007, there is a gradual increase in the peak AI values from 2004 to 2008. While investigating the depletion in the peak AI values for the year 2007, we found that wet deposition, which is the most efficient process for reduction in aerosol load (Kaskaoutis et al., 2010) was the maximum during 2007. Figure 3b shows the mean monthly values of AI retrieved from OMI observations over Pakistan from December 2004 to November 2008. The error bars show the standard deviations. We notice a significant variation in monthly mean values of AI over Pakistan as compared to the variation observed by Kaskaoutis et al. (2010) over Greece. We find a computed mean value of AI to be 1.155±0.257 with monthly mean value ranging from 0.851±0.134 to 1.540±0.499. We notice that AI increases from January (0.855) to May (1.540) and then remains almost constant up to July (1.482) followed by a gradual decrease up to December (0.851). These temporal variations in OMI–AI over Pakistan can be well justified by considering the cyclic variations in meteorological conditions, anthropogenic activities and precipitation. Further, the results produced in the present study validate the earlier observations (e.g. Alam et al., 2011b) over this region.

Previous analyses over Pakistan (e.g. Alam et al., 2010; Alam et al. 2011b) have shown that, in general, the aerosol concentrations increase from north to south. Thus in order to produce a more meaningful analysis, we have divided the study area into two spatially equal regions: 24–30°N, 62–77°E, 30°–36°N, 62°–77°E. Approximately 65% of the total pixels are used to construct seasonal climatology during cold period and 90% of the total pixels are used for hot period climatology in the northern region of the study area. Figure 3c exhibits mean monthly AI values over Northern and Southern parts of Pakistan, with error bars indicating standard deviations from average values. From March to July the AI values are higher in the south as compared to the northern region. The reason is that the southern region is characterized by rapid urbanization, and proximity of desert lands that play a vital role during spring and pre–monsoon summer months. On the contrary, the agricultural land use dominates in the northern areas and the cities are usually semi–urban (Alam et al., 2011b). As far as the remaining months of the year are concerned (i.e. August–February) we get almost equal values of OMI–AI for both northern and southern regions. During winter months the weather is extremely cold in the upper parts of the northern region. Thus poorly combusted cooking and heating fires of wood, dung and other fuels contribute potentially to increase the absorbing aerosols in the atmosphere (Prospero et al., 2002). Hence in spite of much decreased dust particles, the AI in the northern region is almost equal to that in the southern part. However, in addition to dust particles, fine mode aerosols emitted primarily from crop residue burning/forest fires also contribute potentially to aerosol load over the studied region. These carbonaceous particles possess absorbing nature and dominate over the Indo–Gangetic Plain (IGP) during post–monsoon and winter seasons. A recent study over an Indian site, close to Delhi reveals that more than 70% aerosols belong to the category of urban–biomass aerosols (Sharma et al., 2014).

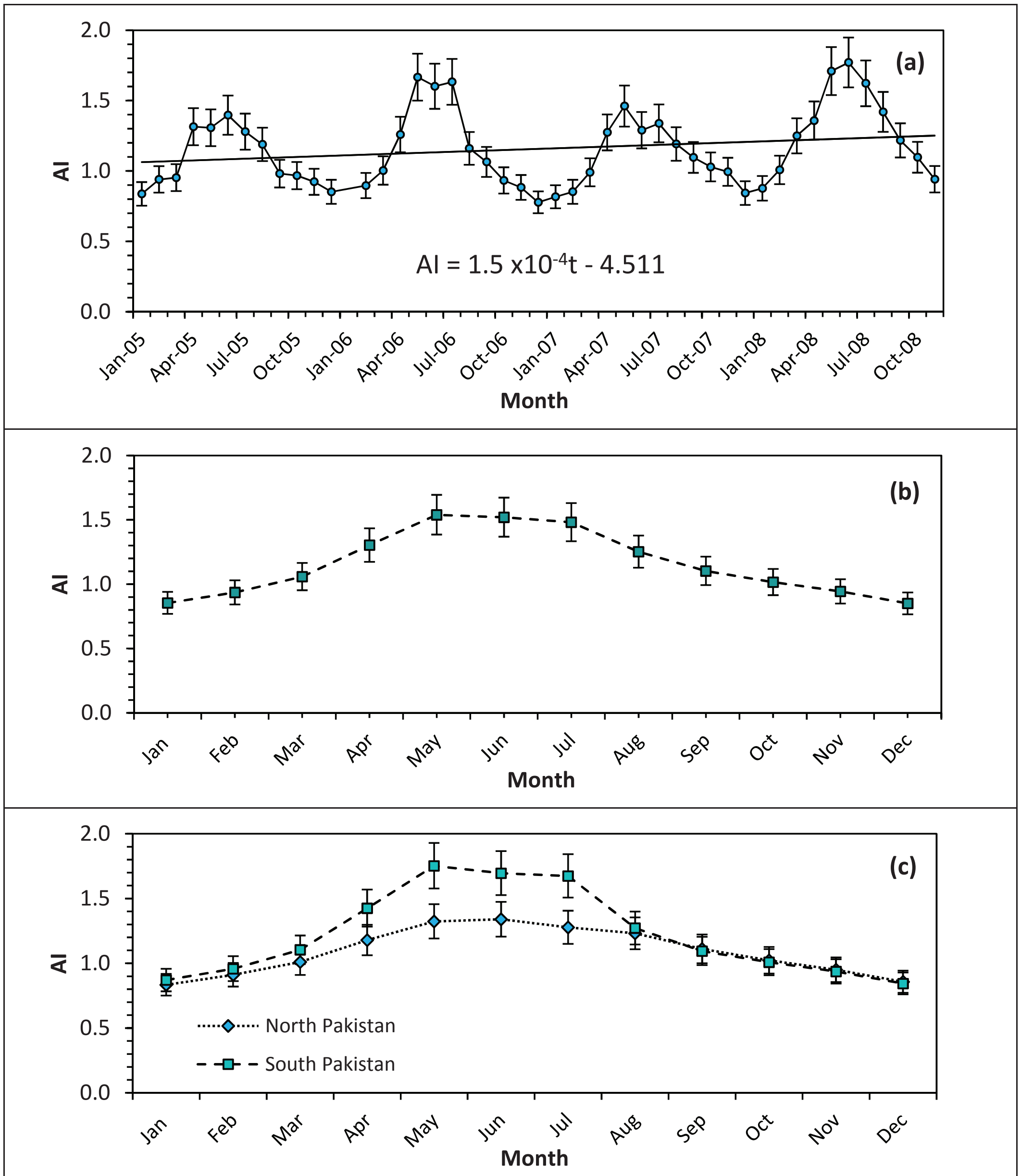


Figure 3. ***(a)*** *The time series of AI over Pakistan. The observed trend in AI values is shown by linear fit.* ***(b)*** *Variation in monthly average AI values over Pakistan.* ***(c)*** *Variability of monthly average AI values over Southern and Northern Pakistan (error bars show standard deviations from average values).*

Figure 4 shows yearly average AI data and corresponding rainfall measurements from the Tropical Rainfall Measuring Mission (TRMM) during the period December 2004 to November 2008. We find an overall increasing trend for AI over the studied region. Our results confirm the earlier observation of AI by Alam et al. (2011b) who also found an increasing trend in TOMS–AI values over the ten selected urban/industrial locations in Pakistan for the periods 1979 to 1992 (TOMS Nimbus–7) and 1997 to 2001 (TOMS Earth Probe). The gradual increase in aerosol loadings seems to be a common trend in the south Asian region, as some studies over neighboring India (e.g. Dey et al., 2005; Habib et al., 2006; Sarkar et al., 2006) have also pointed towards increasing tendencies in aerosol concentrations. It is pertinent to mention here that precipitation does have a great impact on aerosol burden but it is not the only parameter influencing the aerosol concentrations. Consider, as an example, the AI and precipitation data for the years 2005 and 2006 in Figure 4 that exhibits a positive correlation. In order to probe the discrepancy between AI–precipitation correlation for the years 2005 and 2006, we refer to Figure 5. This figure shows time series of three parameters (AI, precipitation and dust storm count) for the study period. We find that the dust storm counts during the year 2005 are only about 65% as compared to those for the year 2006. The dust storm data have been used for the mega city Lahore, a central location in Pakistan, which is influenced by major dust storm events in the region. Thus high AI values along with increased precipitation during 2006 (as compared to 2005) can be well justified by taking into account the dust storm data.

3.2. Spatial distribution of AI and its correlation with precipitation

Figure 6a exhibits the spatial variability of OMI–AI over Pakistan. It shows the mean annual spatial distributions for the period December 2004 to November 2008. A significant variability of AI values (0.6–2.0) has been observed among different parts of studied area. The major sources of aerosols in Pakistan are dust blowing from deserts either local or from neighboring countries like India, Iran and Afghanistan and biomass burning across the whole region. Local industries and other anthropogenic activities also affect the atmosphere over Pakistan. All these aerosol types have different physical and chemical properties. Non–absorbing aerosols include sulfate and sea spray aerosols, whereas smoke particles containing black carbon may have absorbing as well as non–absorbing character (Anderson et al., 1996; Torres et al., 1998). Mineral and desert dust particles, originated from Sahara Desert, exhibit absorbing characteristics, and hence the AI values are affected because their imaginary parts of refractive indices in the UV are wavelength dependent (Israelevich et al., 2002; Sinyuk et al., 2003; de Graaf et al., 2005). It is observed that Southern parts of Pakistan have comparatively high values of AI (greater than 1) because of the existence of dust particles in the air at the higher atmospheric levels (Figure 6a). Alam et al. (2011b) found that high AI values, especially over Southern Pakistan, were because of densely populated and industrialized mega city of Karachi (Qureshi, 2010). These high AI values over Karachi and Southern Pakistan are caused partially by the existence of local dust transported from the Thar Desert, and dust out breaks from Sahara (El–Askary et al., 2006; Alam et al., 2011b). In the Southern parts of Pakistan, the AI values are largely dependent upon dust aerosols, while in the northern region anthropogenic emissions also contribute substantially to the aerosol loading. In the calculated average annual value of AI over Pakistan (1.155±0.257), the high value of standard deviation indicates that absorbing aerosols are extremely variable in space and time.

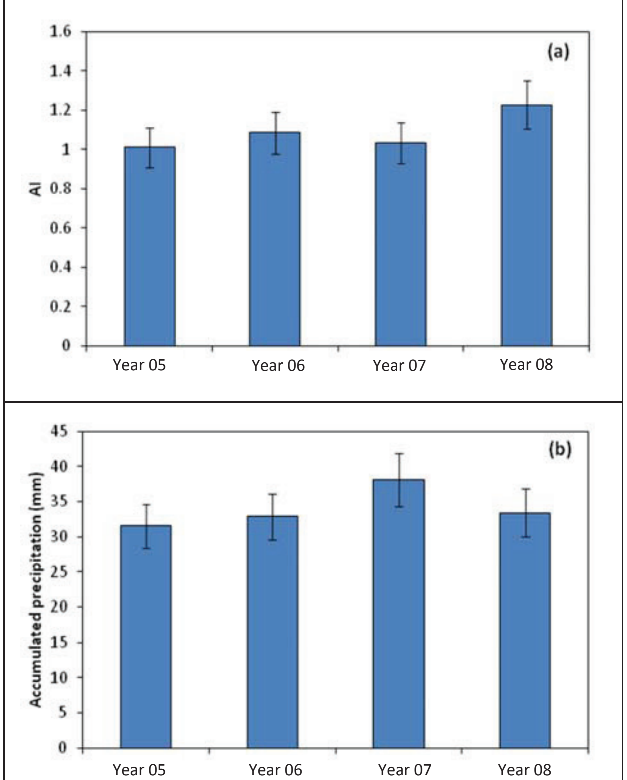


***Figure 4. (a)** Mean AI and **(b)** accumulated precipitation for the years 2005 to 2008.*

It is well known that wet deposition removes aerosols from the atmosphere. The effect of precipitation on monthly average AI values can be better understood with a linear equation of the form:

$$\text{Aerosol Index} = a \times (\text{Mean accumulated precipitation}) + b \qquad (2)$$

Table 1 presents the values of constants *a* and *b*, and square of the correlation coefficient R^2. From the table we notice that slope remains negative in every month indicative of the fact that precipitation decreases the AI through washout process. Also very low R^2 values in most of the months represent large scatter. We further notice that R^2 values greater than 0.2 are observed only in July, August and September, the months in which Monsoon winds bring rainfall in Pakistan. Highest rainfall amounts are received in Monsoon months and hence decreasing the AI. In the rest of the months very little or no rainfall causes R^2 to be very low. Habib et al. (2006) and Kaskaoutis et al. (2010) correlated precipitation with AI over India and Greece, respectively. They observed that generally rainfall is negatively correlated with AI. The average spatial distribution of AI and precipitation over Pakistan is given in Figures 6a and 6b. We notice that the rainfall distribution pattern follows Himalaya range; higher values are observed over Himalaya range and Northern Pakistan and lower values are found over its southern parts. A comparison of Figure 6a and 6b shows that larger AI values over Southern Pakistan are associated, in addition to other factors, with least precipitation. Thus, the spatial and temporal data of AI and precipitation indicate an inverse correlation between them. Figure 6c shows correlation as a scatter plot between average annual AI and accumulated precipitation over Pakistan. The computed AI–accumulated precipitation correlation is 0.3 due to large scatter but a decreasing trend exists in density maximum area. The decreasing trend is prominent in the areas receiving rainfall lesser than 30 mm. The spatio–temporal variability is smoothed out due to average annual values of AI and accumulated rainfall leading to lower correlation. Aerosol plumes such as biomass burning and dust out–breaks have a highly episodal nature (Kaskaoutis et al., 2010). Therefore, the correlations with precipitation are high, particularly in the months of July, August and September. Nevertheless, a detailed study of AI versus precipitation considering monthly and seasonal spatial distribution and correlations above various regions is beyond the scope of present study.

***Table 1.** Values of the a and b coefficients in the equation AI=a*(mean accumulated precipitation)+b applied to the monthly average values over Pakistan in the period December 2004–November 2008. All R^2 values are above 95% statistical significance level*

Month	a	b	R^2
Jan	–0.0004	0.86	0.003
Feb	–0.00073	0.96	0.011
Mar	–0.0027	1.1	0.109
Apr	–0.0048	1.4	0.092
May	–0.00058	1.6	0.001
Jun	–0.0011	1.6	0.014
Jul	–0.0024	1.7	0.241
Aug	–0.0019	1.4	0.249
Sep	–0.0039	1.2	0.334
Oct	–0.0018	1	0.005
Nov	–0.0013	0.95	0.005
Dec	–0.00013	0.85	0.000

The spatial distribution of AI and accumulated precipitation from October to March (cold period) and from the April to September (hot period) are shown in Figure 7a. The white areas correspond to missing data. The pockets of higher AI values in cold period are due to proximity of desert land masses and/or areas having minimum rainfall. We note that AI shows more intense pattern in the hot period than in the cold one. Comparing spatial distributions of AI and accumulated precipitation in cold and hot periods, it is worth observing that, in general, where the accumulated precipitation values are high, the AI values are low. This trend is particularly prominent in the hot period because of high rainfall amounts received in the northern parts of the country. Additionally, high AI values are associated with least precipitation over southern parts. Moreover, in the hot period spatial distribution of AI follows the pattern formed by Sulaiman–Kirthar range, which acts as a barrier for the winds transporting the dust particles originating from Thar, Thal and Cholistan Deserts.

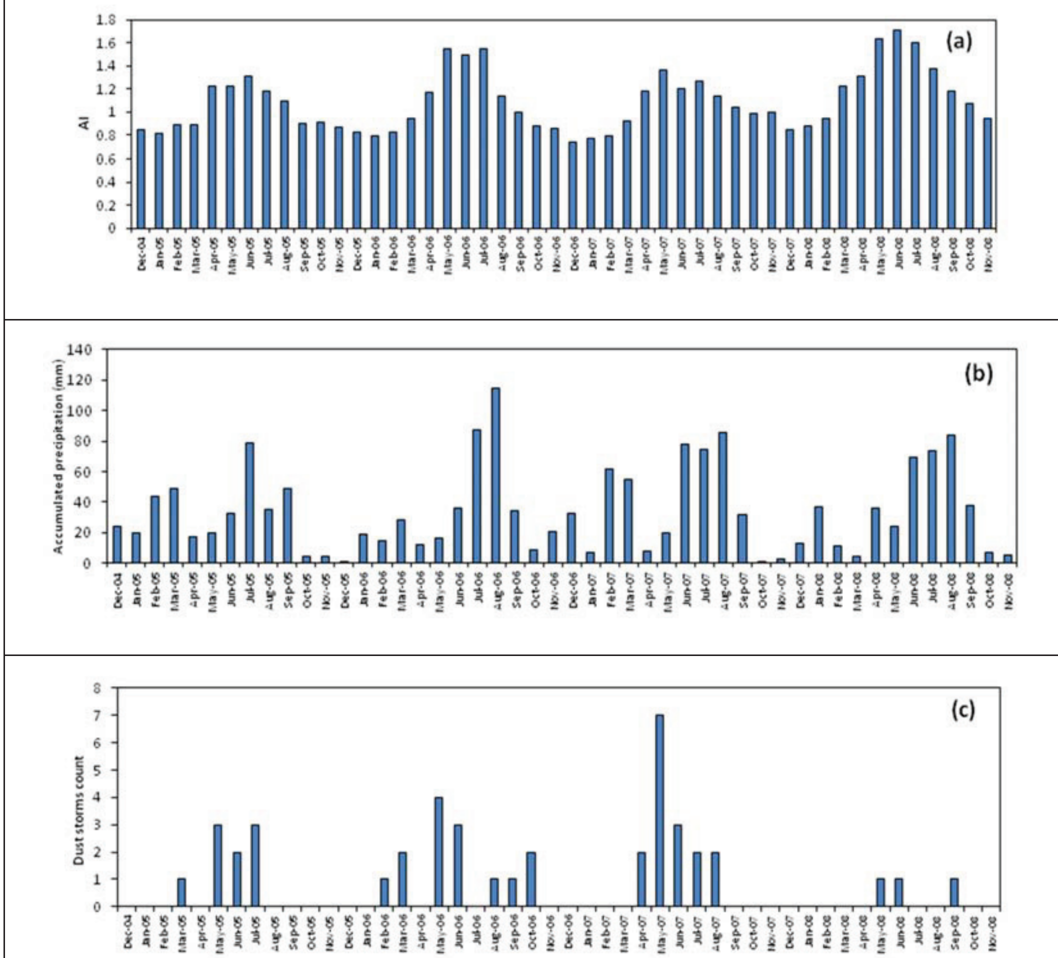


Figure 5. *Monthly variation of* ***(a)*** *AI, and* ***(b)*** *accumulated precipitation over Pakistan, and* ***(c)*** *dust storm count over Lahore during the study period.*

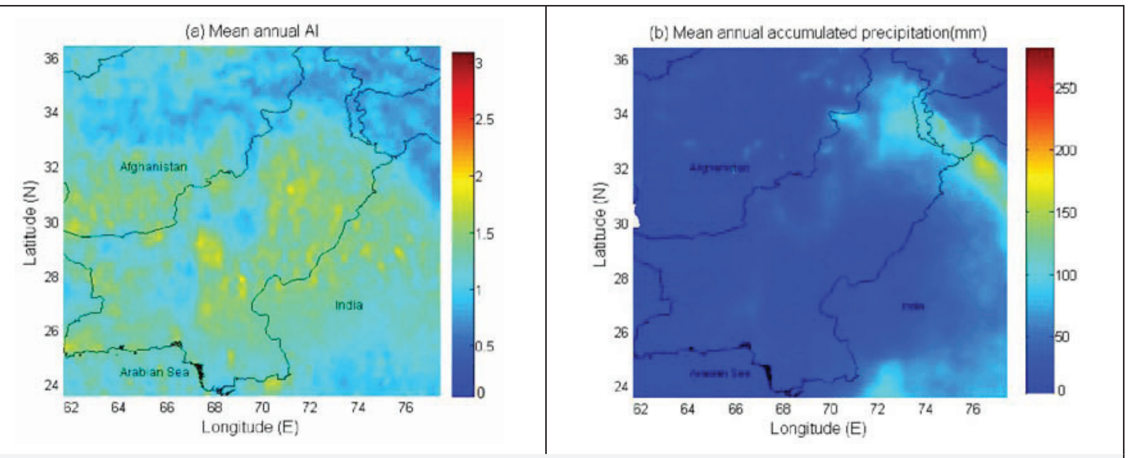


Figure 6. *Mean annual spatial distribution of* ***(a)*** *AI,* ***(b)*** *accumulated precipitation, and* ***(c)*** *correlation as scatter plot between mean annual AI and mean annual accumulated precipitation.*

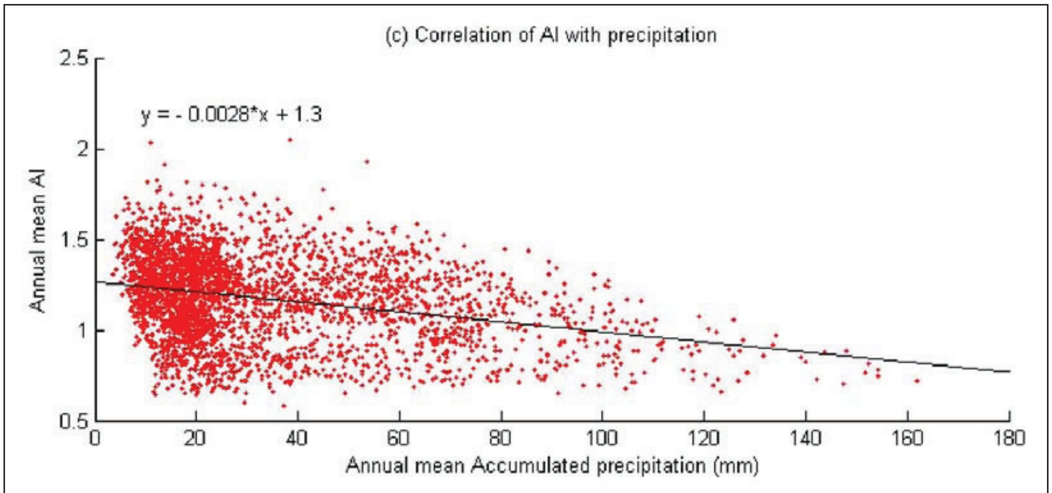


Figure 6. *(Continued).*

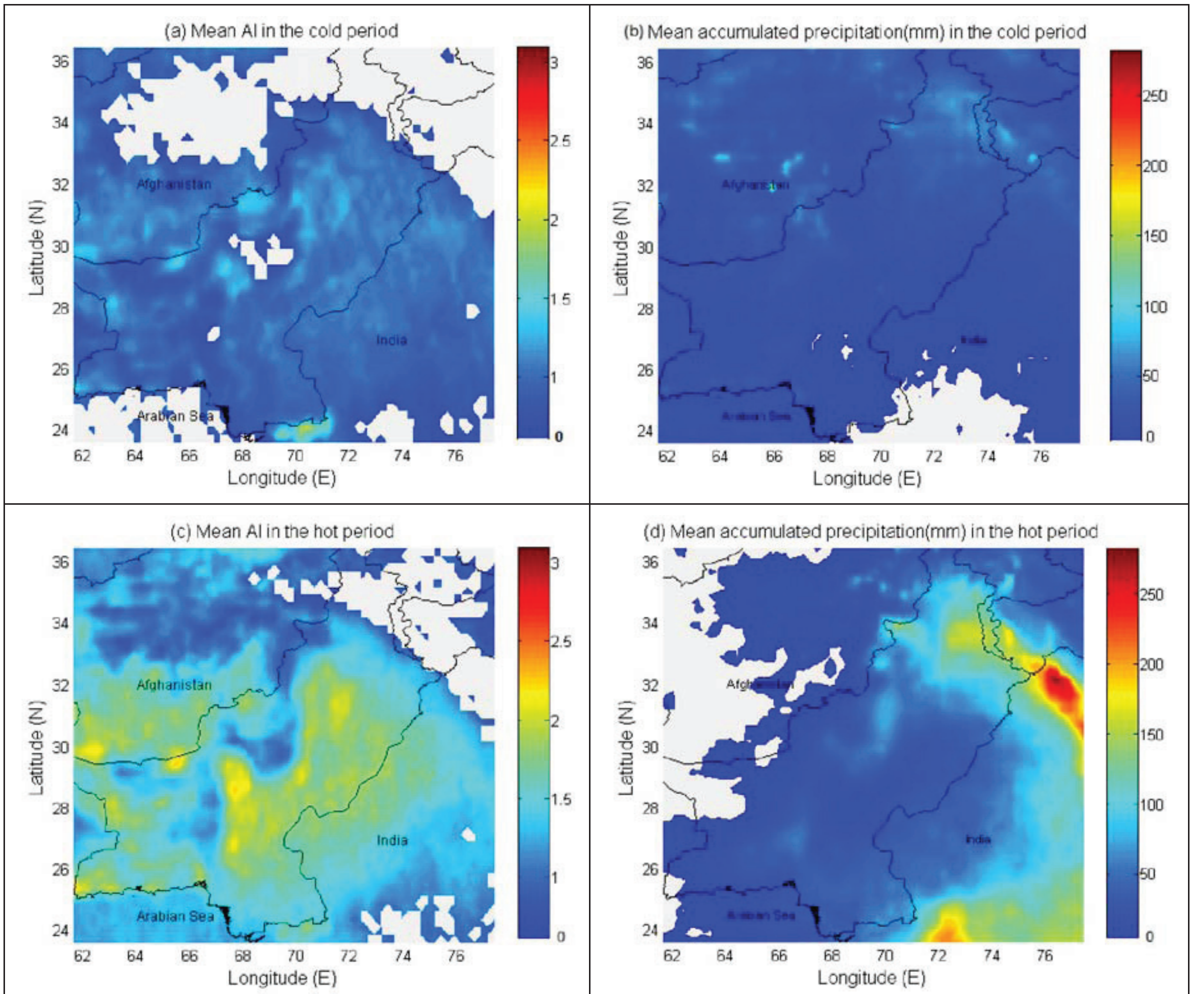


Figure 7. *Spatial distribution of **(a)** mean AI, **(b)** accumulated precipitation in the cold period (October to March), **(c)** mean AI, and **(d)** accumulated precipitation in the hot period (April to September). The white areas correspond to missing data.*

Figure 8 shows that in winter season (December–February), the spatial distribution of AI is less intense. It remains less than 1.4 in the month of December with relatively high values in the central region and some Southwestern parts of Pakistan, particularly over the adjoining areas of Sibi and Zhob. These high values occur primarily due to dust particles originating from local desert areas. Spatial distribution of AI in January is quite similar to that in December with relatively less intensity. In February, however, AI values increase with relatively intense distributions as compared to those in December and January. The correlations of AI and precipitation in the winter months are very weak because very little precipitation is received in these months (figures not shown). In spring season, the above mentioned situation becomes increasingly intense from March to April as observed from Figure 8. The noteworthy result in this season is the observed maximum AI values over Pakistan. In May, the highest AI values (above 2) are observed over almost whole of the upper areas of Southern Pakistan and its central areas. The increase in AI in spring, particularly in the month of May, is due to crop residue burning, wheat straws released from the harvester, and dust raising winds along with low precipitation values. The comparison of AI and precipitation shows that decreasing trend is more prominent in the months of March and April rather than in May because relatively more precipitation is received in the months of March and April.

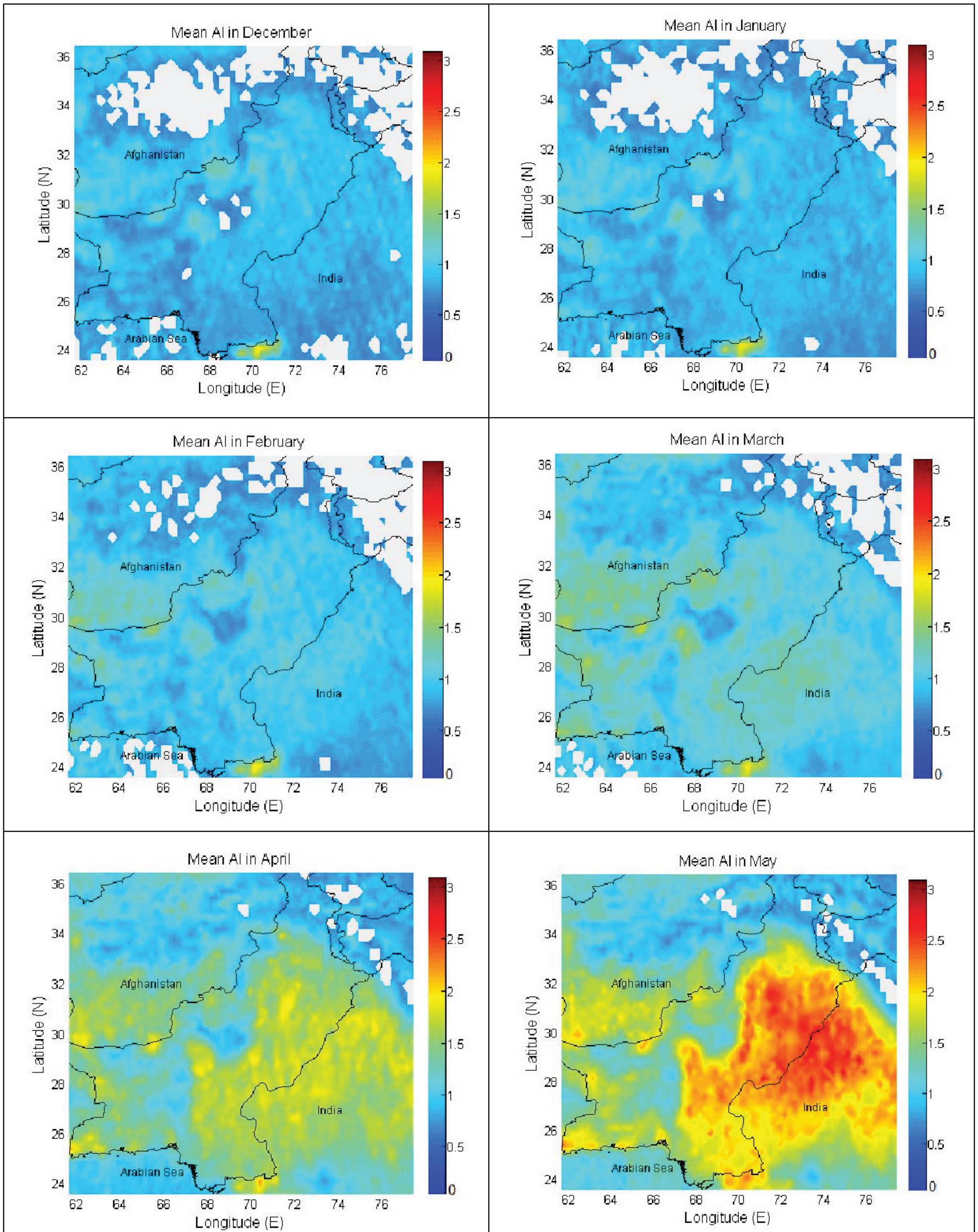


Figure 8. *Spatial and temporal variations of monthly averaged aerosol index (AI) over Pakistan during December 2004–November 2008. The white areas correspond to missing data.*

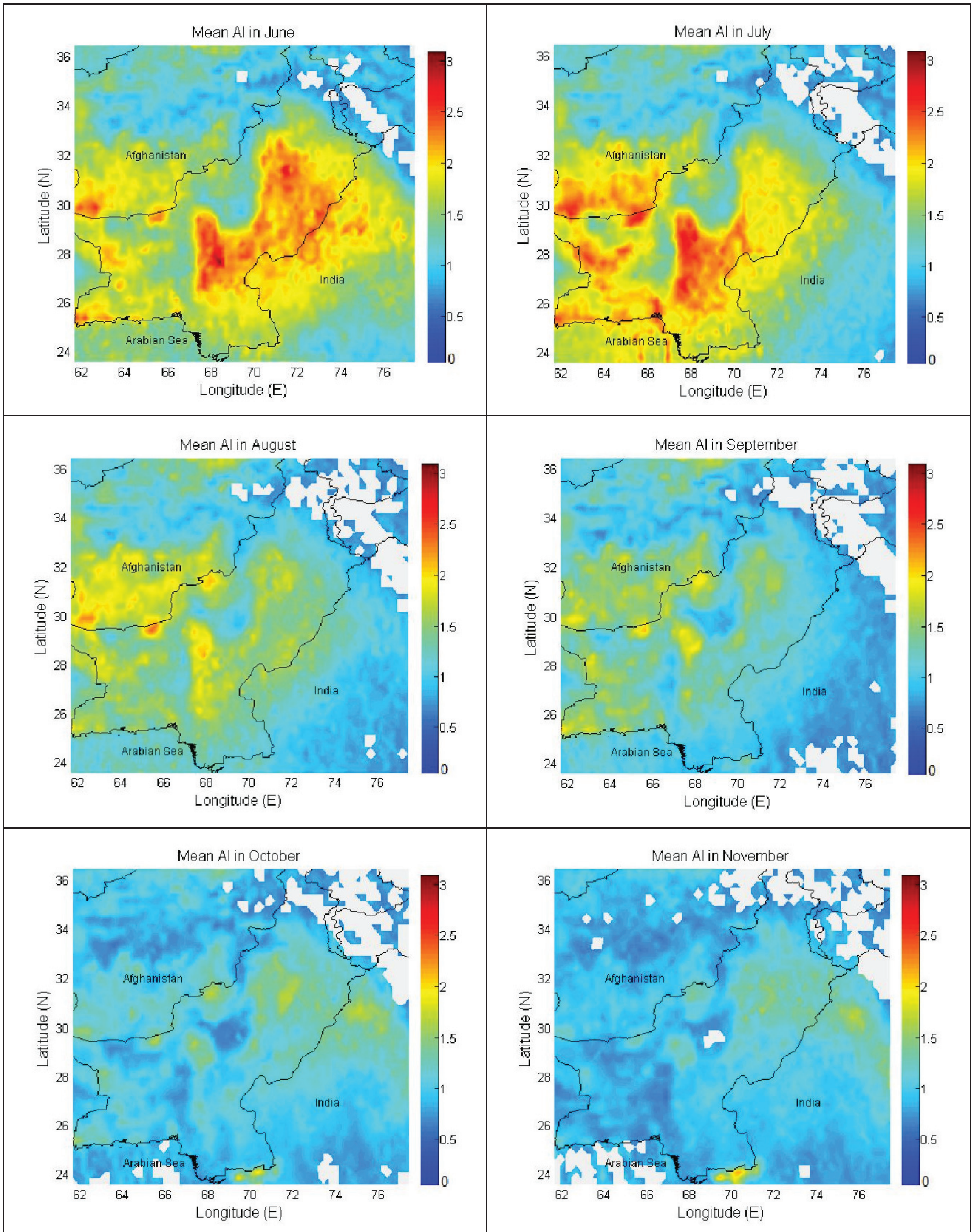


Figure 8. *(Continued).*

In summer, however, the aforementioned trend is modified. In June AI becomes less intense as compared to May (Figure 8). Figure 8 shows that in July, the spatial pattern of AI distribution changes. High AI values are found over Southern parts of Pakistan. This shift in pattern is due to the monsoon season because rainfall causes low AI values over northern regions of the country. A similar situation is observed during the month of August as shown in Figure 8. From June to July AI pattern shifts from north to south and southwest. In August the high AI pattern then shifts to west (Afghanistan). AI values start to decrease in autumn and hence spatial distribution of AI once again changes due to end of monsoon rains. Relatively high AI is observed in Western and Southwestern parts of Pakistan particularly over Sibi, Zhob and Thar and adjoining areas as shown in Figure 8. In October and November, AI gradually decreases, but high values of aerosol index are recorded over central parts of the country. Therefore, we note that summer and autumn seasons have large variabilities in spatial and temporal distribution of AI.

4. Conclusions

In the present work we have analyzed the Aura–OMI–AI data over Pakistan from December 2004 to November 2008. Seasonal and inter–annual variabilities in AI values have been investigated including the effect of precipitation. Our analysis shows that the OMI–AI observations represent the UV absorbing aerosol loading over Pakistan at least qualitatively. The AI spatial patterns have been explained on the basis of desert dust from Thar Desert, densely populated and industrialized areas in central and southern parts of the country. The biomass burning also contributes potentially to the aerosol load over Pakistan during post monsoon and winter seasons. We have shown that there exists a negative correlation between precipitation and AI values. This trend is significant particularly in the months of July, August and September with R^2 values 0.241, 0.249 and 0.333 respectively.

The general trend of seasonal variations found in the present study is in agreement with the trend obtained in earlier studies. In the 4–years examined period a significant increasing trend in the AI values (ΔAI=16.75%) was found as is generally accepted for the Asian continent. The origin and spatiotemporal distribution of absorbing aerosols have been successfully deduced by satellite remote sensing. Considerable differences in average AI values over Northern and Southern Pakistan require further research taking into account the meteorology of the area, source region of pollution and their transport. This study is the first one of its kind explaining spatial and temporal distribution of OMI–AI over Pakistan.

Acknowledgments

We are thankful to the OMI and TRMM science teams for processing data. Efforts of NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, for providing NCEP–Reanalysis 2 data are also gratefully acknowledged. The authors also gratefully acknowledge the Pakistan Meteorological Department for providing dust storm data. We specially thank Prof. Dr. Thomas Wagner and Dr. Muhammad Faheem Khokhar for useful discussions.

References

Ahmad, S.P., Torres, O., Bhartia, P.K., Leptoukh, G., Kempler, S.J., 2006. Aerosol index from TOMS and OMI measurements. *Proceedings of the 86th AMS Annual Meeting*, February 2006.

Ahn, C., Torres, O., Bhartia, P.K., 2008. Comparison of ozone monitoring instrument UV aerosol products with Aqua/Moderate Resolution Imaging Spectroradiometer and Multiangle Imaging Spectroradiometer observations in 2006. *Journal of Geophysical Research–Atmospheres* 113, art. no. D16S27.

Alam, K., Trautmann, T., Blaschke, T., 2011a. Aerosol optical properties and radiative forcing over mega–city Karachi. *Atmospheric Research* 101, 773–782.

Alam, K., Qureshi, S., Blaschke, T., 2011b. Monitoring spatio–temporal aerosol patterns over Pakistan based on MODIS, TOMS and MISR satellite data and a HYSPLIT model. *Atmospheric Environment* 45, 4641–4651.

Alam, K., Iqbal, M.J., Blaschke, T., Qureshi, S., Khan, G., 2010. Monitoring spatio–temporal variations in aerosols and aerosol–cloud interactions over Pakistan using MODIS data. *Advances in Space Research* 46, 1162–1176.

Ali, M., Tariq, S., Mahmood, K., Daud, A., Batool, S.A., ul–Haq, Z., 2014. A study of aerosol properties over Lahore (Pakistan) by using AERONET data. *Asia–Pacific Journal of Atmospheric Sciences* 50, 153–162.

Ali, M., Shaukat, M.A., Amjad, M., Sami, J., 1996. Satellite remote sensing for environment and resource management. *Proceedings of 33rd Space Congress* 6, 23–28.

Anderson, B.E., Grant, W.B., Gregory, G.L., Browell, E.V., Collins, J.E., Sachse, G.W., Bagwell, D.R., Hudgins, C.H., Blake, B.R., Blake, N.J., 1996. Aerosols from biomass burning over the tropical South Atlantic region: Distributions and impacts. *Journal of Geophysical Research–Atmospheres* 101, 24117–24137.

Andreae, M.O., Rosenfeld, D., 2008. Aerosol–cloud–precipitation interactions. Part 1. The nature and sources of cloud–active aerosols. *Earth–Science Reviews* 89, 13–41.

Baddock, M.C., Bullard, J.E., Bryant, R.G., 2009. Dust source identification using MODIS: A comparison of techniques applied to the Lake Eyre Basin, Australia. *Remote Sensing of Environment* 113, 1511–1528.

de Graaf, M., Stammes, P., Torres, O., Koelemeijer, R.B.A., 2005. Absorbing Aerosol Index: Sensitivity analysis, application to GOME and comparison with TOMS. *Journal of Geophysical Research–Atmospheres* 110, art. no. D01201.

de Vries, M.P., Wagner, T., 2011. Modelled and measured effects of clouds on UV Aerosol Indices on a local, regional, and global scale. *Atmospheric Chemistry and Physics* 11, 12715–12735.

Dey, S., Tripathi, S.N., Singh, R.P., Holben, B.N., 2005. Seasonal variability of the aerosol parameters over Kanpur, an urban site in Indo–Gangetic basin. *Advances in Space Research* 36, 778–782.

El–Askary, H., Gautam, R., Singh, R.P., Kafatos, M., 2006. Dust storms detection over the Indo–Gangetic basin using multi sensor data. *Advances in Space Research* 37, 728–733.

GES DISC (Goddard Earth Sciences Data and Information Services Center), 2014. http://disc.gsfc.nasa.gov/Aura/OMI/omto3g_v003.shtml, accessed in 2014.

Giovanni, 2014. Giovanni 3 Online Users Manual, http://disc.sci.gsfc.nasa.gov/giovanni, accessed in July 2014.

Gupta, P., Khan, M.N., da Silva, A., Patadia, F., 2013. MODIS aerosol optical depth observations over urban areas in Pakistan: Quantity and quality of the data for air quality monitoring. *Atmospheric Pollution Research* 4, 43–52.

Habib, G., Venkataraman, C., Chiapello, I., Ramachandran, S., Boucher, O., Reddy, M.S., 2006. Seasonal and interannual variability in absorbing aerosols over India derived from TOMS: Relationship to regional meteorology and emissions. *Atmospheric Environment* 40, 1909–1921.

Herman, J.R., Celarier, E.A., 1997. Earth surface reflectivity climatology at 340–380 nm from TOMS data. *Journal of Geophysical Research–Atmospheres* 102, 28003–28011.

Hsu, N.C., Herman, J.R., Torres, O., Holben, B.N., Tanre, D., Eck, T.F., Smirnov, A., Chatenet, B., Lavenu, F., 1999. Comparisons of the TOMS aerosol index with Sun–photometer aerosol optical thickness: Results and applications. *Journal of Geophysical Research–Atmospheres* 104, 6269–6279.

Husar, R.B., Husar, J.D., Martin, L., 2000. Distribution of continental surface aerosol extinction based on visual range data. *Atmospheric Environment* 34, 5067–5078.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007. The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K.M.B., Tignor, M., Miller, H.L., Chen, Z., Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change), 2001. Climate Change 2001, The Scientific Basis, Cambridge University Press, New York, USA, 881 pages.

Israelevich, P.L., Levin, Z., Joseph, J.H., Ganor, E., 2002. Desert aerosol transport in the Mediterranean region as inferred from the TOMS aerosol index. *Journal of Geophysical Research–Atmospheres* 107, art. no. 4572.

Kaskaoutis, D.G., Nastos, P.T., Kosmopoulos, P.G., Kambezidis, H.D., Kharol, S.K., Badarinath, K.V.S., 2010. The Aura–OMI Aerosol Index distribution over Greece. *Atmospheric Research* 98, 28–39.

Kubilay, N., Oguz, T., Kocak, M., Torres, O., 2005. Ground–based assessment of Total Ozone Mapping Spectrometer (TOMS) data for dust transport over the Northeastern Mediterranean. *Global Biogeochemical Cycles* 19, art. no. GB1022.

Kummerow, C., Barnes, W., Kozu, T., Shiue, J., Simpson, J., 1998. The Tropical Rainfall Measuring Mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology* 15, 809–817.

Levelt, P.F., Hilsenrath, E., Leppelmeier, G.W., van den Oord, G.H.J., Bhartia, P.K., Tamminen, J., de Haan, J.F., Veefkind, J.P., 2006. Science objectives of the Ozone Monitoring instrument. *IEEE Transactions on Geoscience and Remote Sensing* 44, 1199–1208.

Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E., Gill, T.E., 2002. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. *Reviews of Geophysics* 40, art. no. 1002.

Qureshi, S., 2010. The fast growing megacity Karachi as a frontier of environmental challenges: Urbanization and contemporary urbanism issues. *Journal of Geography and Regional Planning* 3, 306–321.

Sarkar, S., Chokngamwong, R., Cervone, G., Singh, R.P., Kafatos, M., 2006. Variability of aerosol optical depth and aerosol forcing over India. *Advances in Space Research* 37, 2153–2159.

Sharma, M., Kaskaoutis, D.G., Singh, R.P., Singh, S., 2014. Seasonal variability of atmospheric aerosol parameters over Greater Noida using ground sunphotometer observations. *Aerosol and Air Quality Research* 14, 608–622.

Sinyuk, A., Torres, O., Dubovik, O., 2003. Combined use of satellite and surface observations to infer the imaginary part of refractive index of Saharan dust. *Geophysical Research Letters* 30, art. no. 1081.

Torres, O., Bhartia, P.K., Herman, J.R., Sinyuk, A., Ginoux, P., Holben, B., 2002. A long–term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements. *Journal of the Atmospheric Sciences* 59, 398–413.

Torres, O., Bhartia, P.K., Herman, J.R., Ahmad, Z., Gleason, J., 1998. Derivation of aerosol properties from satellite measurements of backscattered ultraviolet radiation: Theoretical basis. *Journal of Geophysical Research–Atmospheres* 103, 17099–17110.

ul–Haq, Z., Tariq, S., Ali, M., Mahmood, K., Batool, S.A., Rana, A.D., 2014. A study of tropospheric NO_2 variability over Pakistan using OMI data, *Atmospheric Pollution Research* 5, 709–720.

Washington, R., Todd, M., Middleton, N.J., Goudie, A.S., 2003. Dust–storm source areas determined by the total ozone monitoring spectrometer and surface observations. *Annals of the Association of American Geographers* 93, 297–313.