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MODIS aerosol optical depth observations over urban areas in Pakistan: quantity and quality of the data for air quality monitoring

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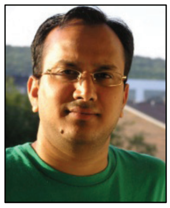
ABSTRACT

Ten years (2001–2010) of aerosol optical depth (AOD) observations from the MODerate resolution Imaging SpectroRadiometer (MODIS) over two large urban centers in Pakistan have been analyzed for atmospheric aerosol loading and surface level particulate matter air quality assessments. MODIS Level 2 AOD data over Karachi and Lahore were analyzed for availability of aerosols data, spatial gradients, and long term trends. MODIS AOD used in this analysis is retrieved using the dark target algorithm. Availability of AOD data over Karachi and its surroundings is seriously impacted by the presence of bright surfaces – a well known limitation of the retrieval algorithm. The Lahore region does not experience this problem due to its relatively darker surface, and therefore permits a more in–depth analysis. Due to the lack of available AOD data, analysis over Karachi has not been performed. A spatial gradient of 0.2/degree in AOD have been found over Lahore, which indicate high aerosol loading near the city center as compared to outside the city area. Long–term trend analysis over Lahore shows a decreasing trend in AOD with slope of –0.07 over the last decade. The surface level particulate matter estimates using AOD–PM relationship suggest that Lahore experience unhealthy air quality on more than 80% days in any given year.

Keywords: *Air quality, MODIS, aerosols, Pakistan, AOD*



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1. Introduction

The impact of atmospheric aerosols on the earth's climate system is poorly understood, and is a subject of considerable interest for the scientific community as well as policy makers (Kaufman et al., 2002). Aerosols are not only emitted directly into the atmosphere by anthropogenic and natural sources, but are also formed in the atmosphere through various physical and chemical processes (Seinfeld and Pandis, 2006). They impact the climate system by absorbing and reflecting solar radiation and modifying cloud properties. Aerosols are also referred to as particulate matter (PM), and human exposure to them is known to cause serious damage to human health (Pope et al., 2009).

The monitoring of aerosols by means of near the surface in–situ measurements and column integrated satellite observations is recognized as an effective tool for better understanding their impact on climate and human health. Optical properties of aerosols are estimated by AERONET measurements – a global network of ground based sun–photometers (Holben et al., 1998). The network provides continuous measurements of aerosol optical depth (AOD), which are often used to validate AOD retrieved from satellite observations (Kahn et al., 2010; Levy et al., 2010).

Daily global observations of aerosols under the cloud free conditions (Kaufman et al., 1997; Diner et al., 1998) became available during the last decade with the launch of two Earth Observing System (EOS) satellites, Terra and Aqua. Spectral measurements of reflected solar radiations at top of the atmosphere along with assumed aerosol models and radiative transfer calculations are used to estimate column integrated extinction due to aerosols. AOD can be considered a proxy for the amount of particulate matter present in the atmospheric column.

Historically, AOD retrievals over ocean from the Advanced Very High Resolution Radiometer (AVHRR) have been widely used to provide long–term aerosol trends (Husar et al., 1997; Mishchenko and Travis, 1997; Mishchenko et al., 2007). New AOD retrieval methods now utilize features of modern satellite sensors to provide more precise aerosol retrieval over land surface. These include, the MODIS multi spectral dark target land AOD retrieval algorithm (Kaufman et al., 1997; Remer et al., 2005; Levy et al., 2007a; Levy et al., 2007b), the MISR retrieval algorithm that makes use of multi angle capabilities along with spectral signature to retrieve AOD over land (Martonchik et al., 1998), the POLarization and Directionality of the Earth's Reflectances (POLDER) algorithm that utilizes polarization and directionality of earth reflectance to retrieve AOD over land (Deuze et al., 2001), Total Ozone Mapping Spectrometer (TOMS)/Ozone Monitoring Instrument (OMI) that provides absorption AOD and Aerosol Index (AI) in UV part of solar spectrum (Herman et al., 1997; Omar et al., 2005), and the Sea–viewing Wide Field–of–view Sensor (SeaWiFS) that uses ocean color channels (0.402–0.885 μm) to retrieve aerosol information (von Hoyningen–Huene et al., 2003). While these methods and sensors are capable of providing aerosol retrievals over land under certain conditions, there are many limiting factors. For example, the MISR AOD product matches very well with AERONET AODs even over bright targets but due to its limited swath (360 km), its global coverage is limited to once every 7–8 days; such limited coverage can potentially introduce bias in the long–term trend analysis for climate and air quality applications. Similarly, OMI provides almost daily global coverage but due to the use of UV channels, it is mostly sensitive to elevated aerosols (about 2 km above the earth's surface). OMI observations are also sensitive to only absorbing type of aerosols and its relatively large pixel size creates more challenges in masking clouds. The polarization method used by the POLDER sensor is sensitive to fine mode aerosols but this method is not suitable to obtain AODs where coarse mode aerosols dominate.

MODIS onboard the two EOS Terra and Aqua satellites, has been providing AOD retrievals for more than 11 years, twice daily (under cloud free conditions) on a near–global basis with high spatial resolution (10 km^2) with good accuracy over dark vegetated surfaces (Levy et al., 2010). The quality of the MODIS AOD retrievals decreases when the underlying surface becomes bright and/or heterogeneous; these conditions are typically found in desert and urban regions (Levy et al., 2010). Proper sampling of satellite AOD over a region is very important for correctly characterizing aerosol properties over the area of interest (Levy et al., 2009; Sayer et al., 2010). It is often convenient to utilize Level 3 gridded daily, weekly, or monthly mean products to analyze long–term trends and climate implications. However, Levy et al. (2009) have shown that different choices for aggregation and weighting result in estimates of global/regional means of MODIS AOD that differ by 30% or more. Levy et al. (2009) recommended that one must consider the spatial and temporal density of the measurements relative to the gradients of the true AOD, and that only retrievals of the highest quality should be utilized.

In this study, ten years of MODIS Terra aerosol optical depth data is utilized to examine the atmospheric aerosols loading over two urban regions in Pakistan. Karachi and Lahore are largest and the second largest populated urban areas in the country with very high levels of surface pollution. The human and vehicular population of Karachi is about 16 million and 1.5 million respect-tively whereas about 10 million people lives in Lahore (Alam et al., 2011). The mean $PM_{2.5}$ mass concentration over Lahore measured between December 2005 and February 2006 was 209 µg m^{-3} that is 20 times higher than WHO guidelines and 14 times higher than annual mean value in New York City (Biswas et al., 2008).

Various studies have used MODIS level 3 gridded one degree resolution AOD products to analyze long–term trends in atmospheric aerosol loadings and estimates of radiative forcing over urban centers (Alam et al., 2011; Kaskaoutis et al., 2011; Kishcha et al., 2011). As documented elsewhere (Levy et al., 2010), retrieval of AOD from MODIS becomes challenging and more uncertain over regions with high surface reflectance and complex mixture of aerosols. The primary objective of this study is to examine whether the quality of MODIS AOD retrievals over Karachi and Lahore is adequate for air quality and climate applications. The second objective is to document whether spatial and temporal trends are present in the available MODIS AOD data in this region, providing recommendation for future research.

This paper is organized as follows: Section 2 discusses the various ground and satellite data sets, quality controls, source of errors and briefly describes the methodology. Section 3 presents results on data availability, validation against AERONET observations, in addition to spatial and temporal trends analysis and discusses the implication of results on human–health related air quality assessment in Pakistan. Section 4 summarizes the research and provides some general recommendation for users interested in the use of satellite data for similar research over urban regions.

2. Data and Method

In this study we use the last ten years (2001–2010) record of aerosol optical depth at 0.55 µm (AOD) obtained from the MODIS instrument onboard the NASA EOS Terra satellite. MODIS instrument makes radiance observations in 36 spectral channels at spatial resolution ranging from 250 m to 1 km with a 2 300 km wide swath, allowing for almost daily global coverage. We use high resolution (10 x 10 km^2) Level 2 (collection 5) quality controlled MODIS aerosol retrieval, rather than the Level 3 gridded product used recently in a number of studies (Kosmopoulos et al., 2008; Kanakidou et al., 2011; Alam et al., 2011b; Alam et al., 2011c; Kharol et al., 2011). MODIS land aerosol algorithm makes use of the so–called dark target approach (Levy et. al., 2007). This retrieval algorithm is known to have large uncertainties when the underlying surface is not dark enough (Levy et al., 2010). Several validation studies over AERONET locations conducted over land reveal that about 72% of the retrievals fall within expected uncertainty levels of ±0.05±0.15AOD (Remer et al., 2008; Levy et al., 2010), which is an improvement over the previous version (collection 4). AERONET cloud free level 2.0 AOD data from Lahore has been used to validate MODIS AODs. Spatial and temporal collocation has been performed as used in standard global validation exercises (Ichoku et al., 2003; Levy et al., 2010).

MODIS AOD data have been collected over a larger area of 2 x 2 degree (about 200 x 200 km^2 area) latitude and longitude centered on each city to analyze local as well as regional aerosols loadings. As suggested in Levy et al. (2009), we use high resolution MODIS retrievals with only very good quality flags to generate AOD statistics over these regions. In order to show the difference in mean AOD values due to difference in spatial averaging four different grid box with size of 0.25 degree (quarter degree or QD), 0.5 degree (half degree or HD), 0.75 degree (three quarter degree or TQD) and 1 degree (one degree or OD) have been selected centered around each urban region (Table 1). The mean and standard deviation in AOD are estimated from all the pixels fall within each of these grid boxes and analysis on differences in mean AOD and sampling is presented. Spatial gradients in each direction from center to outside of the urban region have been calculated as function of seasons. Seasonal spatial distribution has been analyzed to see data gaps in MODIS dark target retrievals.

Table 1. *Geographical information and aerosol optical depth values from different spatial averaging for the two cities. Here AOD values are averaged over entire study period (2001-2010)*

Parameter	Karachi	Lahore
Latitude	24.85 N	31.53 N
Longitude	67.03 E	74.35 E
MODIS Data Period	2001-2010	2001-2010
AOD (QD)	NO data	0.76±0.39 (1 226)
AOD (HD)	0.45±0.21 (48)	0.69±0.40 (2 176)
AOD (TQD)	0.39±0.27 (90)	0.68±0.41 (2 630)
AOD (OD)	0.35±0.27 (166)	0.68±0.41 (2 781)
GIOVANNI AOD	0.69±0.33	0.67±0.29
GIOVANNI Grid	67 E 24 N	74E 31N

3. Results and Discussion

This study addresses two main issues related to the use of MODIS AOD for characterizing atmospheric aerosol loadings over urban centers; first the spatial and temporal availability of accurate aerosol measurements from Terra satellite and second goal is to utilize available datasets to analyze their spatial and temporal distributions in the city center and in the region surrounding the city.

3.1. Spatial sampling and data availability

Figures 1a and 1b present seasonal spatial distribution of AOD, top of the atmosphere reflectance in 2.1 µm (R21) and the number of available MODIS observations (COUNT) averaged over ten year time period. Quality controlled AOD and other data discussed in this paper have been gridded in equal angle grids of 0.1 x 0.1 degree. City center locations (shown as dot) have been identified based on the spatial distribution of urban development using high resolution Google Earth maps. The four grid boxes shown on the maps represent area of 0.25 x 0.25 deg^2 (QD), 0.5 x 0.5 deg^2 (HD), 0.75 x 0.75 deg^2 (TQD) and 1.0x1.0 deg^2 (OD). Seasonal maps over Karachi clearly show very limited AOD retrieval over the region. There are hardly any valid retrieved AOD pixels (with constraints as described in Section 2) within about 110 km radius around the city of Karachi in the spring (March, April and May) and summer (June, July, and August) months. Availability of data in fall (September October, and November), and winter (December, January and February) is low as well. As discussed earlier, after looking at the quality flags associated with the AOD pixels in the region, we found that the retrieval is limited mainly due to high surface reflectance and cloud cover in the region. The MODIS aerosol land algorithm is very sensitive to surface characterization and AOD retrieval depends on accurate estimation of surface reflectance in visible part of solar spectrum. Since the surface reflectance in the northern part of the Karachi is high (Figure 1a), the AOD retrieval is not available (or quality flag is reduced) over this area. MODIS land aerosol algorithm reduce the quality flag of retrieved AOD if R21 is greater than 0.25 (Levy et al., 2007). Coastal location of Karachi also makes it very difficult for MODIS to retrieve AOD over this city. Over the last ten years, the numbers of pixels that have high quality AOD observation in the four different averaging boxes (QD, HD, TQD and OD) are 0, 48, 90 and 166 respectively. The MODIS land dark target approach does not provide sufficient high quality AOD retrievals over Karachi that would enable reliable statistical analysis of aerosol loading in the area. Table 1 also reports corresponding AOD value for the grid centered at 24 North and 67 East from popular online data visualization tools GIOVANNI (http://disc.sci.gsfc.nasa.gov/ giovanni/) for the Karachi area. The magnitude of differences is significant, which can lead to erroneous conclusions regarding trends in surface level air quality concentrations in Karachi. Several previous research studies (e.g., Alam et al., 2011) have used GIOVANNI tools to represent urban scale aerosols and the data has been further analyzed for trend analysis, and conclusions have been drawn on the AOD trends and its impact on climate change and local air quality. Based on our analysis, we found that the current MODIS land dark target approach does not provide sufficient high quality AOD retrievals over Karachi and therefore limited statistics cannot be used to draw any conclusions on aerosol loadings in the area.

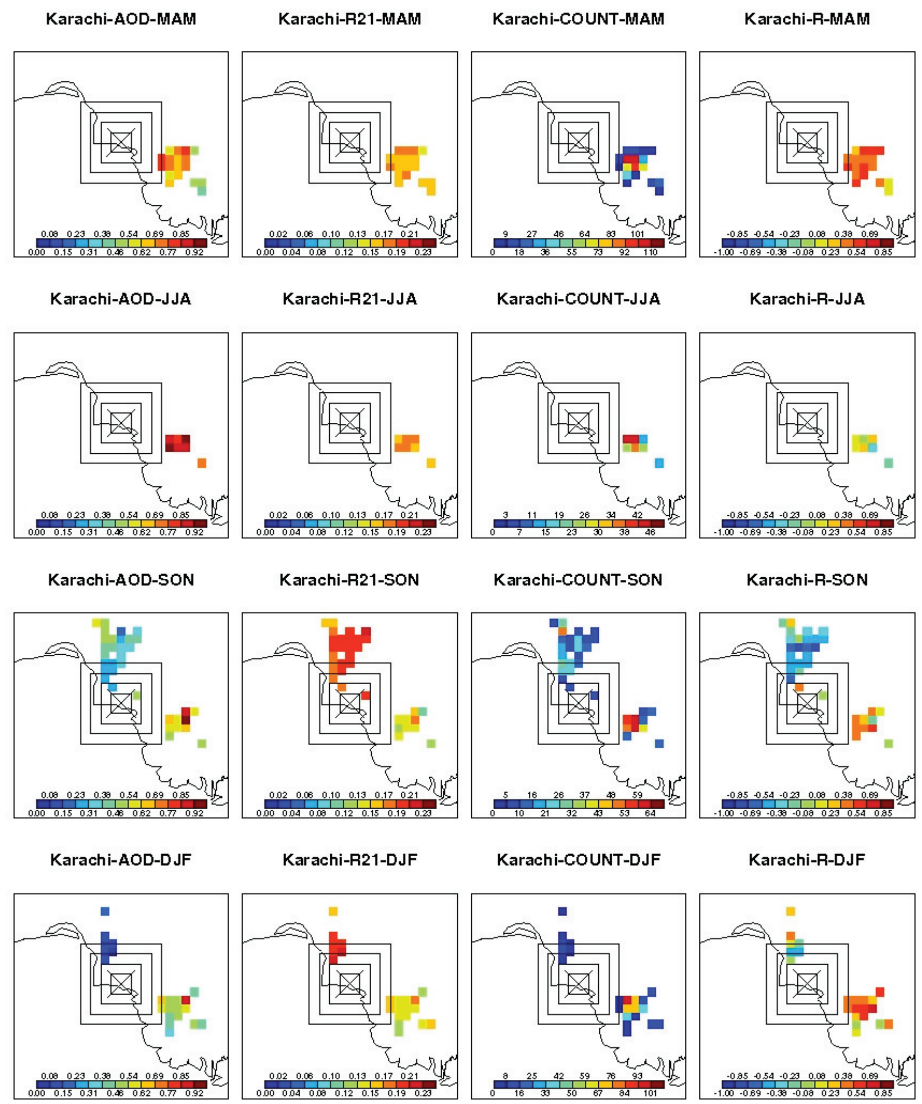

Figure 1a. *Ten year mean seasonal maps of AOD, R21, and Samples from MODIS Terra over Karachi.*

Seasonal spatial distribution of AOD over Lahore (Figure 1b) clearly shows typical seasonal cycle of AOD over urban region with high AODs in summer and fall, and low in winter and spring seasons. Table 1 also presents the statistics of available AOD retrievals. Spatial maps in Figure 1b show adequate coverage of AOD retrievals with high density of data pixels over the region. Again the AOD value (0.68) averaged at over OD box (represent regional value) is much lower than AOD value (0.76) averaged over QD box (represents urban region). The mean percentages of days with valid AOD data available in each month over Lahore for QD, HD, TQD, and OD are 43, 67, 77 and 81 percent respectively. The mean AOD value of 0.76 for a QD box is significantly higher than the mean AOD for other larger boxes therefore it could be due to high pollution near the city than further away from the city center. Therefore, in order to evaluate aerosol loading over cities and urban regions, it is important to consider spatial averaging carefully otherwise false conclusions can be drawn.

3.2. Validation of MODIS AOD with AERONET

MODIS Level 2, (10 km^2) AODs over Lahore have been compared against hourly averaged AERONET AODs. This AERONET site is located in urban populated area of the city at the roof of Institute of Space Technology. This comparison is performed using data from 2008 to 2010 and presented in Figure 2. Due to limited AERONET measurement over this site, only 51 coincident points were available for the comparison. The linear correlation coefficient (R_{mod}) between AERONET and MODIS is 0.85 with a root mean square error (RMSE) in AOD of 0.17. The slope value of 1.04 shows little overestimation of AODs by MODIS instrument. Most of these data points are from winter and spring months. Summer and fall months have very limited points, 3 and 4 respectively. In coincident data set, about 77% MODIS retrieved AOD falls within 0.05±20% AOD error limits whereas 65% falls within 0.05±15% AOD error limits as defined by MODIS science team.

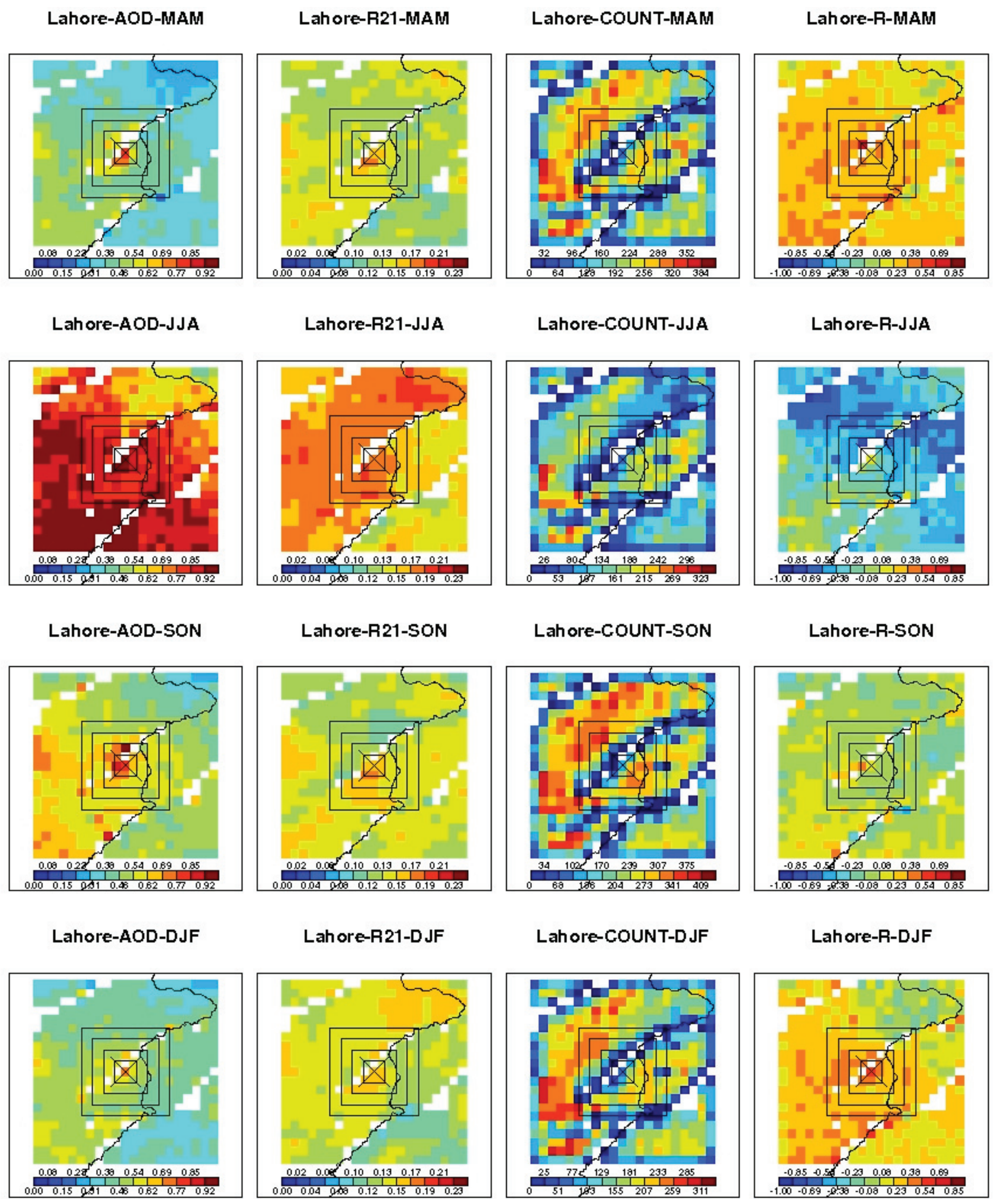

Figure 1b. *Ten year mean seasonal maps of AOD, R21, and Samples from MODIS Terra over Lahore.*

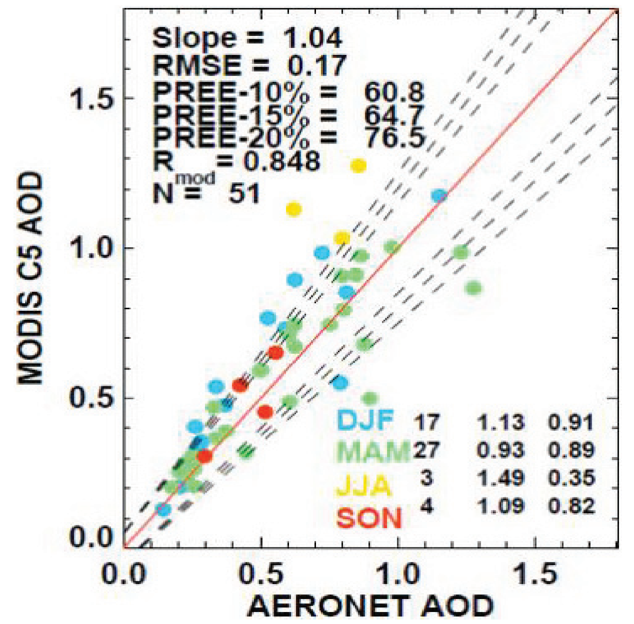

Figure 2. *Inter-comparison of MODIS AOD with AERONET AOD over Lahore for period of 2008-2010.*

3.3. Long term trends in MODIS AOD over Lahore

In recent years several studies (Mishchenko et al., 2007; Zhang and Reid, 2010; Dey and Girolamo, 2011) have used satellite derived AOD data to analyze long–term trends at regional to global scales. Recently, Dey and Girolamo (2011) utilized MISR AOD over Indian subcontinent and found an increase in AOD ranges from 0.1 to 0.4 over the last decade. Using MODIS data over ocean, another study (Zhang and Reid, 2010) found an increasing trend of 0.07, 0.06 and 0.06 per decade over the Indian Bay of Bengal, east coast of Asia and Arabian Sea respectively. Figure 3 presents the long–term time series of HD average MODIS AOD over Lahore starting from January 2001 to December 2010. AOD time series shows monthly mean AOD values with one standard deviation in blue color. The red line shows the monthly median AODs. There is almost no trend in AOD during 2001 to 2003 after which it started to decrease until 2007 and increased again in 2008. During 2009 and 2010, the AOD decreased. The linear best fit to the monthly mean values is also shown as thick blue line. The slope of the line is negative (–0.0006), which translates into decrease in AOD by 0.07 over the last decade with large seasonal and intra–annual variability. This decreasing trend is found to be statistically significant (95%) by t–test with 2 176 daily points (about 60% of the total days). This is a weak negative trend over the region, which could easily arise due to uncertainty in retrieved AOD or/and change in instrument's calibration over the time. The error associated with calibration of blue channel of MODIS Terra as reported in a validation study by Levy et al. (2010). Levy et al. (2010) found that Terra MODIS AOD seems to be biased high by 5% early in the mission; changing to a low bias of similar magnitude sometime after 2004. Therefore, without proper long–term ground records and lack of information on uncertainties associated with retrieval and calibration over the region; it is difficult to confirm these trends as actual trends in aerosol loading.

To further analyze the possible trends, seasonal normalized histograms in four AOD ranges [0.0<0.25 (very low), 0.25<0.5 (low), 0.5<1.0 (high), 1.0<5.0 (very high)] have been compared (Figure 4). During the spring months, AODs in high range dominate except in 2005 and 2009 when the peak in histogram shifted to low AOD range. Also, there is no clear visible trend in AOD frequencies for any AOD range during spring whereas during summer months very large AOD range has been shifted to large AOD ranges indicating decreasing in mean AOD value. It is important to note that very low and low AOD frequencies are almost negligible in summer months. During fall, high AOD range dominates and AOD frequencies shows decreasing trends, which makes low AOD frequencies to go high indicating decreasing in mean AOD values as well. Variations are more random in winter and do not clearly show any decreasing or increasing trends in different AOD ranges. Low AODs dominate winter months with highest frequencies.

3.4. Implication for surface particulate matter air quality mapping

There have been many research studies in the past decade relating satellite derived aerosol optical depth to surface level particulate matter air quality (Wang and Christopher, 2003; Engel–Cox et al., 2004; Liu et al., 2004; Al–Saadi et al., 2005; Gupta et al., 2006; van Donkelaar et al., 2010). The simplest approach used by majority of these research studies is to derive a simple two–variable regression equation between AOD and $PM_{2.5}$ mass concentration. Here it is important to remember that AOD is an optical measure of aerosol loading in the entire column of the atmosphere whereas $PM_{2.5}$ is the mass concentration near the surface. Therefore, AOD–$PM_{2.5}$ relationship depends on several other environmental factors including relative humidity, extent of atmospheric mixing, aerosol size distribution, chemical composition, etc. Several other studies have included these environmental factors in developing more complex statistical models by using other ancillary data sets along with satellite AODs (Liu et al, 2004; Gupta and Christopher, 2009; van Donkelaar et al., 2010). Satellite derived AODs have potential use in monitoring surface level of particulate matter air quality, although the level of confidence in derived $PM_{2.5}$ varies over different region and with seasons. Arguments, which go in the favor of application of satellite data for $PM_{2.5}$ estimations are: (1) Satellites provide almost daily global coverage, (2) satellite data provides spatial distribution of the aerosols, which is not possible from point observations at ground. There is a lack of ground monitors around the world to assess and monitor surface air quality and it is not feasible to put a dense ground monitoring network. Therefore, even though satellite AODs have some uncertainty, they can serve as surrogate to surface level particulate matter air quality. But, it is very important for the users to understand the limitations and uncertainties associated with satellite data sets. We highly recommend that users must pay attention to the quality flags and density of the data for a specific region.

AOD frequencies over 5 different 1 x 1 degree regions surrounding Lahore are shown in Figure 5. The locations of grid boxes (or regions) have shown in sketch given with the figure and are named the center (C), North East (NE), South East (SE), North West (NW) and South West (SW) regions. Each color in vertical histogram represents the range of AODs and the height of the bar shows percentage frequency of AOD range over last ten years. These histograms also represent the spatial frequency distribution of AODs in surrounding area of Lahore. In order to put these frequency distributions in prospect of surface level particulate matter air quality in the region, AOD to $PM_{2.5}$ conversion factors provided by van Donkelaar et al. (2010) have been used. Conversion factors of 87.5 $\mu g\, m^{-3}$ per unit AOD were read out of the map given in van Donkelaar et al. (2010) (Figure 2) and have been used to calculate $PM_{2.5}$ mass concentration to discuss these frequency distributions. van Donkelaar et al. (2010) estimated these factors based on GEOS–CHEM chemical transport model. These conversions may not be accurate enough but gives a first approximation of $PM_{2.5}$ mass concentration in the region where spatial distribution regular measurements are not available. The uncertainty in estimated $PM_{2.5}$ using this method is about 25% (van Donkelaar et al., 2010) and it varies over different parts of the world.

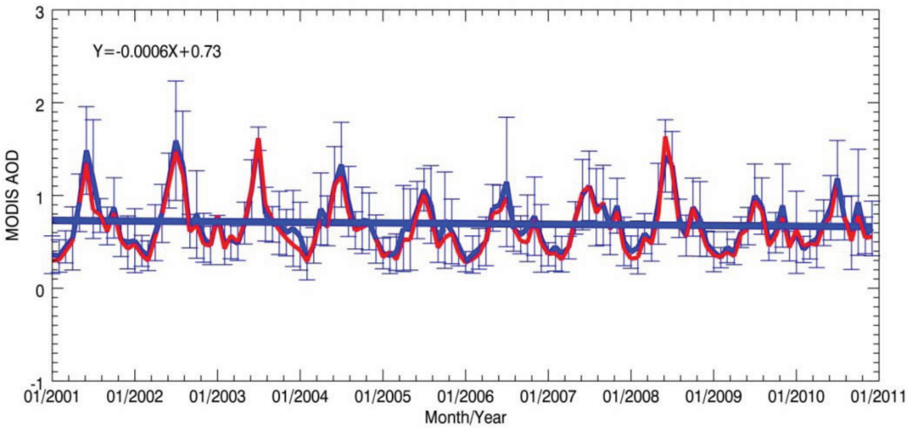

Figure 3. *Time series of monthly mean (blue) MODIS AOD averaged in half degree grid centered over Lahore. Vertical bar shows onestandard deviation and red line show the median values. Regression line is shown as thick blue line and its equation is also shown.*

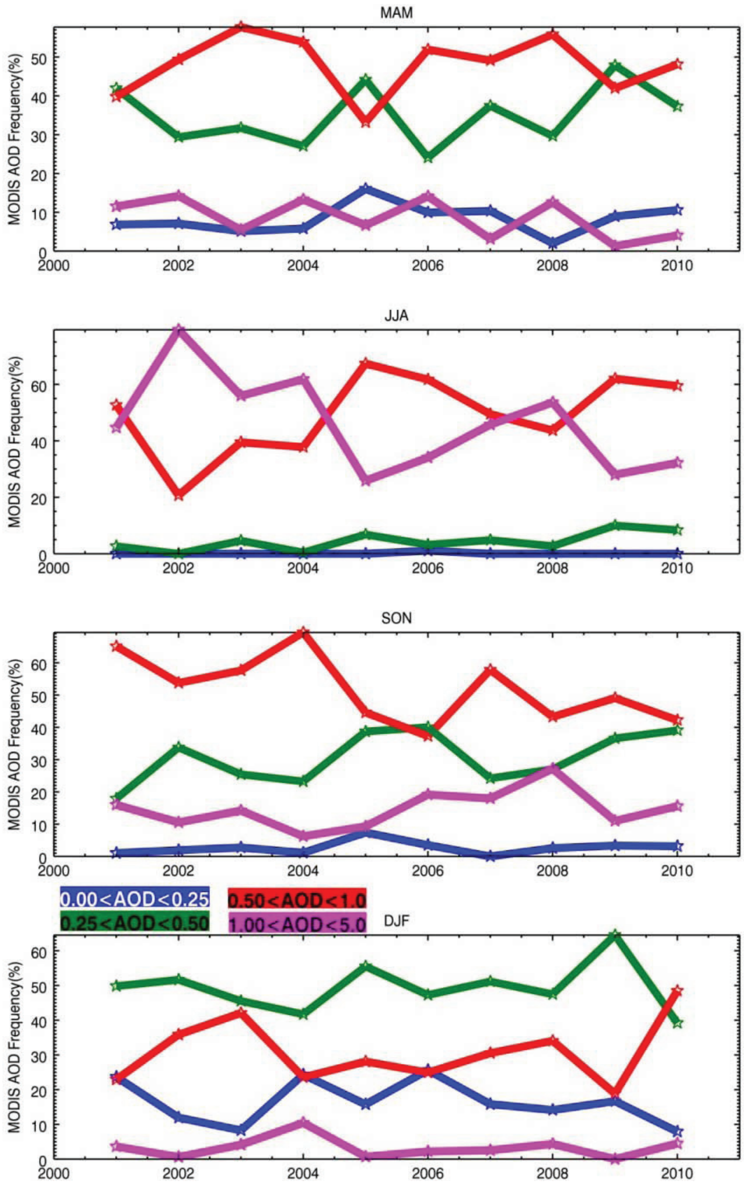

Figure 4. *Annual variations in MODIS AOD frequencies in half degree grid centered over Lahore. Frequencies have been shown for four AOD ranges for four seasons.*

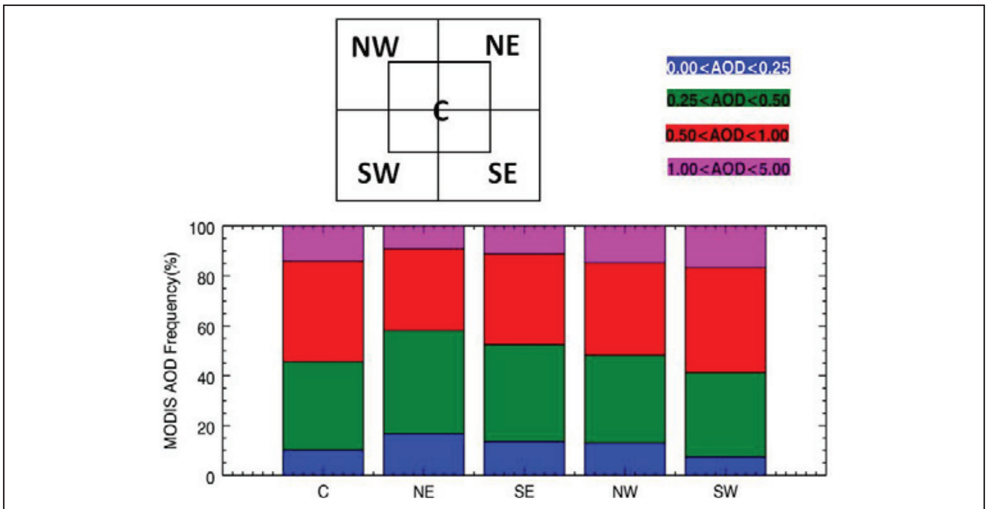

Figure 5. *Assessment of surface level particulate matter air quality has been performed based on low and high AOD frequencies. Frequency of occurrence of low and high AODs in five difference 1 x 1 degree boxes around Karachi (top) and Lahore (bottom). Five boxes are located in center (C), north east (NE), south east (SE), north west (NW), and south west (SW) direction from the city center.*

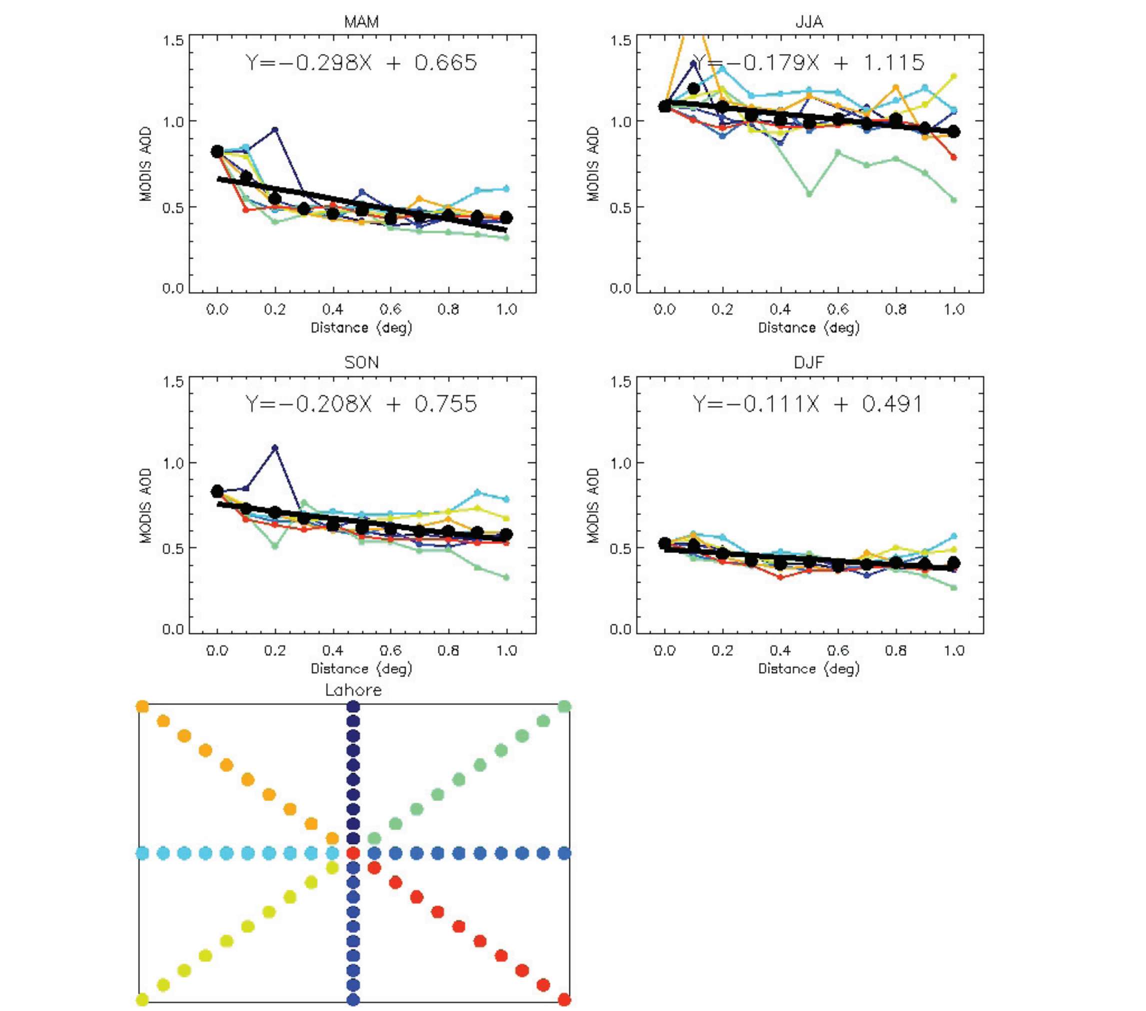

Figure 6. *Estimated spatial gradient in MODIS aerosol optical depth over Lahore. Top four panels represents four different seasons averaged over ten year time period. MODIS AODs are averaged on 0.1 x 0.1 degree equal angle grid and plotted against distance (in unit of degree) from the center of the city to outside the city. Color and location of each line is shown in sketch. The black dots and line are averaged over all directions.*

In the case of Lahore, where the number of AOD pixels for all five grid boxes are almost similar (88 000 to 103 000 pixels), differences in AOD distribution in the five grid boxes are almost similar. The center and SW grid boxes are dominated by high AOD values whereas dominance of high AOD values increases as we move from SE to NW and towards SW. Estimations show that almost 89% of the AODs in Lahore are greater than 0.25, which puts this city in moderate to unhealthy air quality category throughout the year. This first approximation of surface level particulate matter air quality shows high and growing risk of health related issues in this region. Satellite data analysis clearly shows that continuous monitoring of aerosol loading in this region is much needed. Looking back to Figure 4 and its analysis, it appears that poor air quality frequencies in these regions are decreasing over the years, but to confirm these trends, analysis of ground based pollution measurements will be needed.

3.5. Seasonal mean spatial gradients of AOD

In this analysis, we have attempted to explore the spatial gradients in AODs over urban Lahore region as shown in Figure 6. Variations in AODs are calculated along eight different directions from center of the city [shown in panel (e)]. AOD data from MODIS for ten years have been gridded into 0.1 degree longitude by 0.1 degree latitude for four seasons. AODs in 10 grids in each of the eight directions have been plotted on y–axis as a function of distance from the center of the city towards outside of the city. The hypothesis behind this exercise is that AOD should show high values near the city center and should decrease as we move out of the city due to obvious reason of more human activity inside the city than outside. This hypothesis will apply better to the isolated urban centers where population is concentrated inside the city limits but may not be true in the areas where population densities are homogeneous in surrounding areas as well. Other factors such as aerosols source locations, industrial activities, and transport could also have significant impact on this analysis. Clearly there are seasonal differences in the gradients and overall in all four seasons the mean AOD values are decreasing as we move from center to the outside of the city. The negative slope of the least square fit line shows the decrease in AOD. The slope is highest (–0.3) in spring with minimum (–0.11) in winter. Summer months do not show clear decreasing trends in all directions whereas trends are clearer in other three seasons. The intercepts for each season can be interpreted as mean AOD value in each season at the center of the urban region. There can be counter arguments on these decreasing trends, which relate these gradients to elevated MODIS AOD retrievals over bright surface such as urban centers. In other words, these gradients in AODs may not be real and just depict a high bias in MODIS AOD over high reflectance surfaces. Partially, we can evaluate this by analyzing the observed R21 as shown in Figure 1 but it will be very difficult to quantify the magnitude of elevated AODs due to bright surface unless we perform sensitivity analysis using radiative transfer calculations, which will require accurate surface characterization. Definitely, center grid box not only shows high AOD value but also high surface reflectance, therefore it is possible that AOD in center grid box is biased high. After removing center grid pixels from the analysis, we still see some gradients in AOD over Lahore region, which may not be as strong as represented by slope values here. Therefore, these high slope values reported here can be considered as qualitative numbers, which may be lower in reality. Based on this analysis, we strongly recommend that current MODIS dark target algorithm retrieved AODs over urban areas should be used very carefully otherwise it can lead to erroneous conclusions.

4. Summary

Ten years of high quality satellite derived aerosol optical depth data have been used for the first time over two growing urban regions in Pakistan to analyze temporal and spatial trends in atmospheric aerosols. There is a lack of availability of high quality MODIS AOD observations over the urban area of Karachi due to the high surface reflectance in this region and its proximity to coastal region. This was not a problem over Lahore, which is an inland urban region.

The analysis of AOD averaged over varying spatial scales demonstrates that there is a trade–off between data volume and data quality and one of them should be chosen very carefully depending on the application. The mean AOD values for QD box are much higher than OD box over both cities, therefore, it is not recommended to use coarse resolution data sets for studies, which analyse aerosols loading at urban city scales.

Inter–comparison of MODIS AOD with AERONET AOD over Lahore shows a good agreement and 65% MODIS AODs falls within MODIS uncertainty limits as defined by MODIS science team (Levy et al., 2010). Due to limited MODIS retrieval over Karachi, detailed analysis have been performed only over Lahore.

High variability in AOD values during summer and low in winter have been observed. Lahore experienced more frequency (% of PDF) of high AODs (>0.5) over the study period and therefore surface air quality in Lahore is assessed to be poor throughout the analysis period.

The occurrence frequency of high AODs over Lahore show a decreasing trend and frequency of low AODs are increasing over the years. Spatial gradients in AODs exist as one move away from the city center. These gradients are much stable in fall and winter when compared to spring and summer, when gradients are more random. This could be due to increased transport of aerosols in summer by unstable atmospheric conditions compared to more stable winter months.

There is decreasing trends in AODs over Lahore and over the last decade MODIS AOD has been decreased by 0.07. Here it is important to note that these trends may not necessarily represent actual trends in surface particulate mass concentration over Lahore. Surface trends estimation need ground measurements of PM analysis.

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