Validation of MODIS and MISR Based Satellite AOT Data with In- Situ Data for Lahore, Pakistan

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Abstract

Satellite data is important for determination of variations in aerosolsin space and time. The accuracy and validation of satellite data is necessary to evaluate theaccuracy for air quality in a particular region. Satellite derived air pollution measures offer the advantage of providing global coverage. The aerosol optical thickness (AOT) measured from satellite data was validated with the ground based sun photometer AERONETmeasured AOT for Lahore metropolitan city of Pakistan. The satellite based AOT data of MODISand MISR sensors on board TERRA satellite were extracted inradial spatial regions of 25 Km and 44 Km respectively from the AERONET station. The level 2 satellite data and AERONET data products were used for the validation purpose. The green wavelength bands had higher values and good correlation for both MISR and MODIS satellites, having values of coefficient of correlation as 0.86 and 0.84 with RMSE of 0.08 and 0.22 respectively with AERONET mean AOT data measured for 2 hour (± 1hour) time interval centered at satellite pass time.Thus proving the validity of aerosol satellite data as proxy to ground measurements.

Introduction

The issue of air pollution affects the entire globe,but the countries having huge urban growth and industries are specially confronted with the higher amounts of the suspended particles in atmosphere.According to WHO recommendations the areas where air pollution is monitored in Pakistan, theair pollution is reducing the air quality as the time passing (WHO, 2000).Atmospheric aerosols are liquid and/or solid particles in the form of dust, smoke and haze suspended in the air from natural or man-made sources. Aerosols are a constituent of smog and air pollution (USEPA, 2003;Chen et al., 2002)andaffect the climate change, hydrological cycle, cloud microphysics and global carbon, sulfur and nitrogen cycles directly or indirectly(Andreae, 1995; Charlson&Heintzenberz, 1995; IPCC et al., 2001; Rosenfield&Lensky, 1998; Twomey, 1977). These particles also affect the human health and reduce the visibility (Samet et al., 2000) and originate from sources with different properties (d'Almeida, Koepke, &Shettle, 1991). From the air quality point of view, spatial and temporal distribution of aerosols and its variations are very important (Yoram J Kaufman, Tanré, & Boucher, 2002).The variations in the atmospheric aerosol, land surface properties, greenhouse gases, solar radiations and climatic changes alter the energy balance of the earth atmospheric system(d'Almeida et al., 1991; Papadimas et al., 2009). The addition of aerosol particles to the atmosphere is not only dependent upon the natural and anthropogenic sources but these are also formed by physical and chemical atmospheric processes (J. H. Seinfeld &Pandis, 2012).aerosols are a mixture of particles and these are characterized by their shape, their size (from nanometers (nm) to micrometers (µm) in radius) and their chemical composition (Y J Kaufman et al., 1997; Levy, 2009).

The first application of satellite remote sensing using Landsat, GOES, and AVHRR data began in the mid-1970s to detect the desert particles above the ocean (Carlson &Wendling, 1977; Fraser, 1976; Griggs, 1979; Mekler, Quenzel, Ohring, & Marcus, 1977; Norton et al., 1980). The maps of Aerosol Optical Depth (AOT) over the ocean were produced using the 0.63 µm channel of Advanced Very High Resolution Radiometer (AVHRR) (Y J Kaufman et al., 1997). Aerosols properties were retrieved using AVHRR (Higurashi& Nakajima, 1999; Husar, Prospero, & Stowe, 1997; Nakajima &Higurashi, 1997; Stowe, Ignatov, & Singh, 1997). The useable range of wavelengths of spectrum (shorter wavelengths and the longer wavelengths) for the remote sensing of the aerosols particles is mostly restricted due to ozone and gaseous absorptions. Four basic methodologies were identified to determine one or more of the aerosols optical properties as given in the Table 1(Y J Kaufman et al., 1997)

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Table 1: Four basic methodologies for AOT information

S/N	Methodology	Satellites	Information
1	A single measurement	AVHRR, GLI-land, GOES, Meteosat, MODIS-land, TOMS	Total AOT over land in red λ = 670nm Total AOT over ocean $\lambda \geq$ 670 nm Aerosol size information Land surface Reflectance PBL portion of AOT
2	Multispectral measurements	AVHRR, GLI-ocean, MERIS, MISR, MODIS-ocean, OCTS, POLDER, SeaWiFS	AOT in visible and near-infrared Aerosol size information Aerosol absorption might be retrieved in the blue portion of the visible spectrum
3	Multi-angle measurements	EOSP, MISR, POLDER	AOT in visible and near-infrared Aerosol size information Aerosol refractive Index Phase function Aerosol Absorption
4	Polarization	EOSP, POLDER	

The focus of this studywas to validate the AOT measured from the MISR satellite with the observed AOT from the AERONET for the MetropolitanArealike Lahore city.(Jiang,Liu, Yu, & Jiang, 2007, pp. 242-243; Kokhanovsky et al., 2007). Lifetime of the aerosols varies from days to hours and to minutes according to size of the particles. In volcanic eruption the stratospheric aerosols have life time span of years (J. Seinfeld, 1996).Geographically the aerosols are subdivided as urban, rural, remote continental, maritime, desert dust storm and background aerosols (Kiehl, Schneider, Rasch, Barth, & Wong, 2000).

In Asia, the concentration of aerosols is increasing due tounchecked growth in urbanization and industrialization.Rapidly increasing population causes the change in land cover and land use, increased vehicular traffic and reduction of agricultural land.The number of studies of aerosols in Pakistanare relatively very few. However elsewhere, many such studies could be quoted, such as, the seasonal variability of Aerosols Optical Thickness (AOT) was reported lower in winter season and higher in summer season due to higher wind velocities creating large number of wind derived dust particles(Ranjan, Joshi, &Iyer, 2007). In southern Africa, for the period of August to September 2000MISR AOT has been indicated to have overestimatedby 10%, while comparing MISR AOT and ground based observations.

Over the Indo-Gangetic plain, the AOT values were higher in the summer season than in the winter season (Dey, Tripathi, Singh, &Holben, 2005). For Khanpur (India), whereas in post-monsoon and winter seasons more than 75% AOT was assigned to industrialization and urbanization. In pre-monsoon and monsoon seasons, 60% of the total AOTis due to natural sources(Prasad et al., 2007).Similarly, for various cities in Pakistan there are higher AOT values in summer and lower values in winter(Alam, Iqbal, Blaschke, Qureshi, & Khan, 2010).

The correlation between MODIS and AERONET AOT over Kanpur, India during the 2004 post-monsoon andwinter seasonswas almost the same as during the pre-monsoon andmonsoon seasons (Tripathi et al., 2005), but Prasad and Singh (2007) found a moderate correlation between MODIS and AERONET AOT over Kanpur, India during the longer period from 2001 to 2005.

The atmospheric aerosols are described by the radioactive transfer theory, according to which total radiations measured on board sensor is equal to sum of radiant energy scattered towards satellite minus the scattered energy away from the satellite which is absorbed in atmosphere (Durkee, Jensen, Hindman, &Haar, 1986).

$$L_t = L_S + L_r + L_a$$

Where;Ls= Radiance leaving the surface, Lr=Radiance due to Rayleigh scattering by atmosphere, and La =Radiance due to scattering by aerosols.For land cover like water, Ls= water high absorption in Near Infraredand Red bands of wavelength.

The purpose of the study was to validate the satellite Aerosol Optical Depth (AOT) data with In- Situ measurements for Lahore, Pakistan at regional and local scale for Pakistan and to develop a methodology through following steps :.

1. Validation of MISR AOT level 2 products of 446, 558, 672, 866 nm data against interpolated AERONET AOT measurements at the same wavelengths for Lahore.
2. Validation of MODIS AOT level 2 product of 412, 470, 550 and 660 nm data against AERONET AOT measurement at the same wavelengths for metropolitan city of Lahore.
3. Seasonal and yearly analysis for the variations of AOT Lahore using MISR, MODIS and AERONET data.

Aerosol Optical Depth (AOT)

The aerosol optical thickness (AOT) is defined as the integral of aerosol coefficients from the surface to top of the atmosphere:

$$\tau_{e,s,a} = \int_{0}^{TOA} \sigma_{e,s,a} \ (Z)dz$$

For extinction, scattering, and absorption, the Angstrom exponent provides the information of the aerosols particle size by calculating the scattering properties at two or more wavelengths (Eck et al., 1999). Fine aerosol particles have larger values of angstrom exponent $\alpha \geq 1.6$ and coarse aerosol particles have smaller values of $\alpha \leq 0.6$.

Data and Methodology

MISR AOT Data:

There are nine push broom cameras in MISR sensor having capability of global coverage every nine days with a polar orbital height of 705-km in descending polar orbit. The cameras are arranged such that one camera in the middle is pointed at nadir (designed as An), and another set of four cameras (Af, Bf, Cf, and Df) are pointed in the forward direction in order of increasing off-nadir angle, and one set of four cameras (Aa, Ba, Ca, and Da) are pointed in the aft ward direction. The view angle acquired images are arranged in a surface ellipsoid, of 0^o, 26.1^o, 45.6^o, 60.0^o, and 70.5^o for An, Af/Aa, Bf/Ba, Cf/Ca, and Df/Da, respectively. Each camera in a single focal plane has four line arrays relative to the surface reference ellipsoid. There are 1504 photoactive pixels plus 16 light-shielded pixels in one Charge-Coupled Device (CCD line array, each 21 µm by 18 µm). Each line array is filtered to provide one of four MISR spectral bands. The spectral band shapes are approximately Gaussian and centered at 446nm, 558nm, 672nm, and 866 nm.

MODIS AOT Data:

The MODerate Resolution Imaging Spectroradiometer (MODIS) sensor onboard Terra and Aqua earth observation system satellites with the multispectral data of 36 bands span visible, near infrared and far infrared portion of the spectrum. It has 1km, 500m, 250m multi-resolution sensors and cover the entire globe. Its revisit time is 12 hours and has a swath width of 705 Km. (Jensen, 2009)

However, the coarse spatial resolution (10x10km) of MODIS AOT values as obtained from the NASA algorithm cannot provide detail spatial variation for local/urban scale aerosol monitoring (Source: http://modis-sr.ltdri.org) .MODIS provides global coverage of aerosol products with moderately high spatial resolution, which are derived from Channels 1 and 3(visible light) in conjunction with band 7(near infrared) based on dark pixel algorithm at a spatial resolution of 10km (Kaufman et al., 1997). Recently, Wong et al. (2009a, in press) presented a modified Minimum Reflectance Technique (MRT) to derive AOT over both bright and dark surfaces (e.g. urban and vegetated areas) at a relatively high resolution of 500m with high accuracy, thus avoiding the uncertainties of particle pollution monitoring.

AERONET AOT Data

The sun photometer AERONET (AErosolRObotic NETwork) was used for the insitu measurements of spectralAerosol Optical Depth (AOT) in seven wavelengths of 315nm, 400nm, 500nm, 675nm, 870nm, 940 and 1020 nm in the atmospheric column. Figure 1 shows the Cimel sun photometer used for ground based aerosol data. The network of sun photometer spread all over the globe that provide the observations in every 10 minute interval for this purpose a robotic system take the readings by an auto sun tracking system.

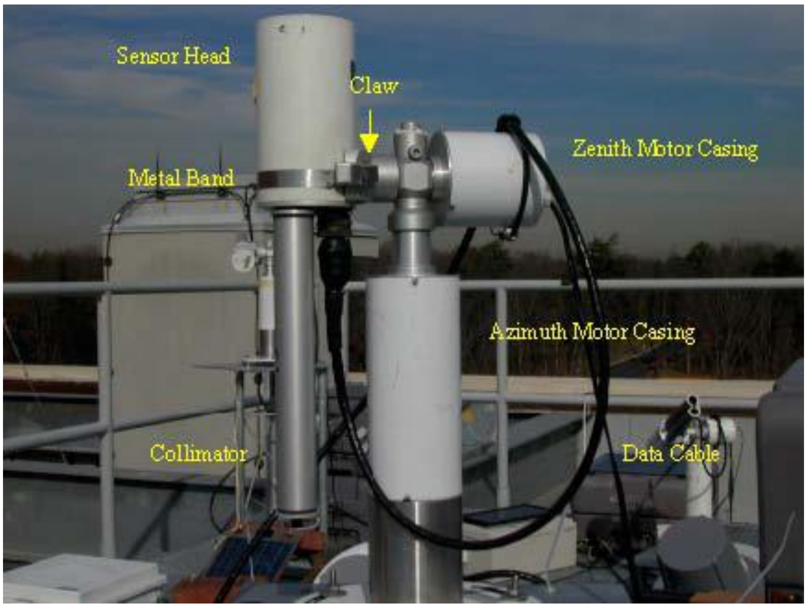


Figure 1: AERONET Instrument

The network provides continuous measurements of aerosol opticaldepth (AOT), which are often used to validate AOT retrieved fromsatellite observations (Kahn et al., 2010; Levy et al., 2010).

The Beer-Lambert-Bougurer principle is used to retrieve the AOT

$$V_\lambda = V_o d^2 e^{-\tau_\lambda m_{t_y}}$$

Where;

V_λ = Digital Voltage

V_o= Experimental voltage

d = Ratio of the average to the actual Earth-Sun distance

τ_λ= Total optical depth at wavelength λ

m= Optical Air mass

T_y= Transmission of absorbing gases

The location of CIMEL -318A radiometer sun photometer is located at Lahore near the Lahore Canal on the roof of building of SUPARCOat Lahoreat 31°.542 NLatitude, 74°.325 E Longitude and at 270m Altitude.

Study Area

The area selected for the purposeof this study was Lahore, one of the main metropolitan citiesof Pakistan.This city is densely populated, having high urban growth rate and the problem of high air pollutionowing to heavy traffic and otheranthropogenic sources like industries. Dust storms are also a common occurrence. Lahore, the second largest metropolitan area is located near the Indian border on bank of river Ravi,extent from 31.25°N to 31.66°Nand 74° E to 74.65° E.The city covers an area of 404 square Kms and has a population of more than 10 million. The city is surrounded by fertile agricultural areas irrigated bywells and canals.The weather is divided into four seasons;pre monsoon (March to May), monsoon (June to August), post monsoon (September to November) and winter (December to February) from December. Lahore has three large industrial estates namelyQuaid-e-Azam Industrial estates and KotLakhpat and Sundar Industrial estates.Besides these, there are many large and small industries distributed in the surrounding area. The major industries arepharmaceuticals, chemicals, engineering goods manufacture, vehicles, food processing, and textile, plastic and steel industries. There are2.2 million registered vehicles in the city and traffic is one of the main sources of Aerosols and particulate matter intrusion into atmosphere.The coal and oil combustion and traffic are the primary anthropogenic sources of aerosols. Secondary aerosols are formed through atmospheric chemical reactions (Alam, Blaschke, et al., 2011; Alam, Trautmann, &Blaschke, 2011).The city is surrounded by green agricultural fields, however the patches of land to the south of the city are not fertile and the soils are sandy.Rapid urban growth and anthropogenic activities are resulting in loss ofagricultural fields in favor of residential areas. The landuse and landcover map of Lahore metropolitan city for the year 2008 is shown in Figure 2

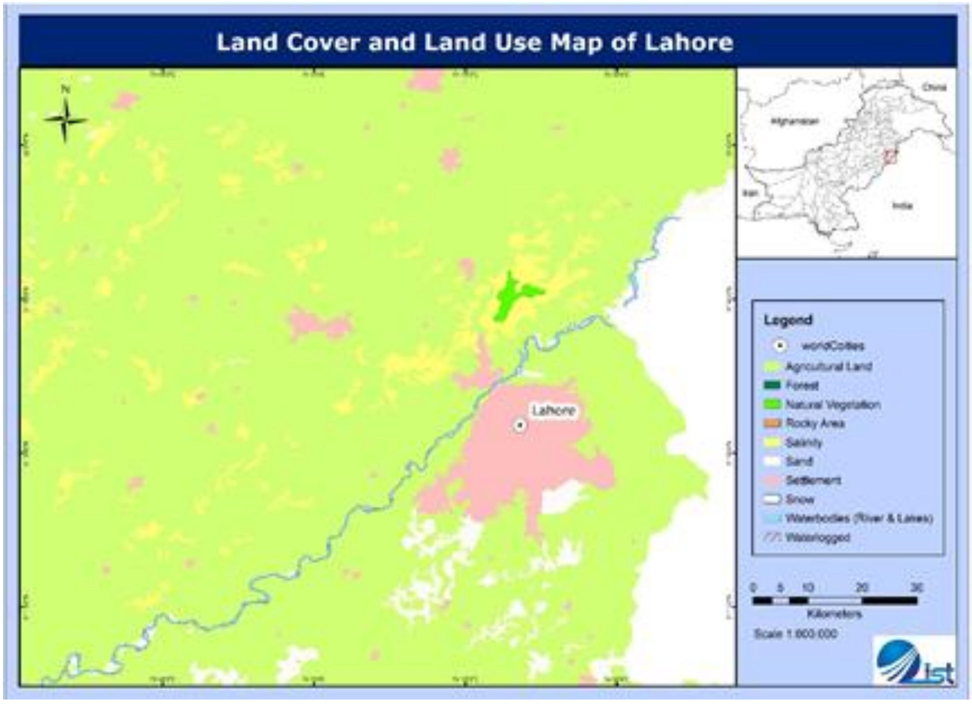


Figure 2: Land Cover and Land use map of Lahore

Methodology

The AOT from MISR and MODIS data was extracted from Level 2 products by an IDL code. The MISER product containsthe regional mean aerosol optical thickness (RegMeanSpectralOpt Depth) parameter which is recommended by MISR team for the measurement of AOT using the extraction technique (Abdou et al., 2005). For this purpose, 896 MISR AOT files were used from Dec 2006 to Dec 2014.Level 2 AOT product of MISR, MODIS and AERONET were used for the purpose of this study. The MISR Level 2 product usedcomprises four wavelength bands (446, 558, 667 and 862 nm)whereas, the MODIS Level 2 AOT product used wereof fourwavelength bands (412,470,550 and 660nm). The e wavelength bands available for Level 2 AERONET AOT product were 340,412,440,443,500 ,675,870,1020,1640nm.The only common wavelength band available for comparison of MODIS with AERONET AOT data was412nm. In order to compare satellite data with AERONET data, itwas needed to interpolate the AERONET AOT values in same wavelengths as that of satellite data.AERONET data of AOT at 440 nm was interpolated to 558nm (MISR) and 550nm (MODIS) using Angstrom exponent (α440-660 nm) provided by AERONET data file by using the following relationship;

$$\tau_{\alpha}(\lambda) = \beta * \lambda^{-\alpha}$$

Where τ_a (λ) = AOT at a given wavelength, λ (in μm),

β = turbidity coefficient(is equal to the AOT at 1μm)

α = Angstrom exponent.

AERONET sun photometer data was interpolated at 550nmform 500nm and 675 nm wavelengths. The satellite data of MODIS and MISR were extracted using a 5x5 pixel based spatial window centered at the Lahore AERONET sunphotometer station (31.54249° N, 74.32475° E, Elevation: 270.0 m)making a circular area of 25 Km and 44 Km radius respectively for MODIS and MISR. AERONET AOT was available at 10 minute intervals. However, in order to perform a comparison between the AERONET and satellite data, the AEORNET AOT datawere averaged for 2 hour interval (± 1hour to satellite pass time).

For temporal analysis the daily, weekly, monthly and annual averages of AOT data from both satellite and ground stationwere prepared into data column bar graphs for performing visual comparison. The validation of satellite data using the ground based data was performed using quantitative and statistical methods. These methods include determining the correlation coefficient, coefficient of determination (R square or R2) and for calculation of errors, Bias, Mean Square Errors and Root Mean Square Errors (RMSE)were calculated for each specific wavelengths of radiations. The linear regression models were developed from satellite data and in situ data for prediction of AERONET AOT data from satellite data. The flowcharts of methodology is shown in Figure 3.

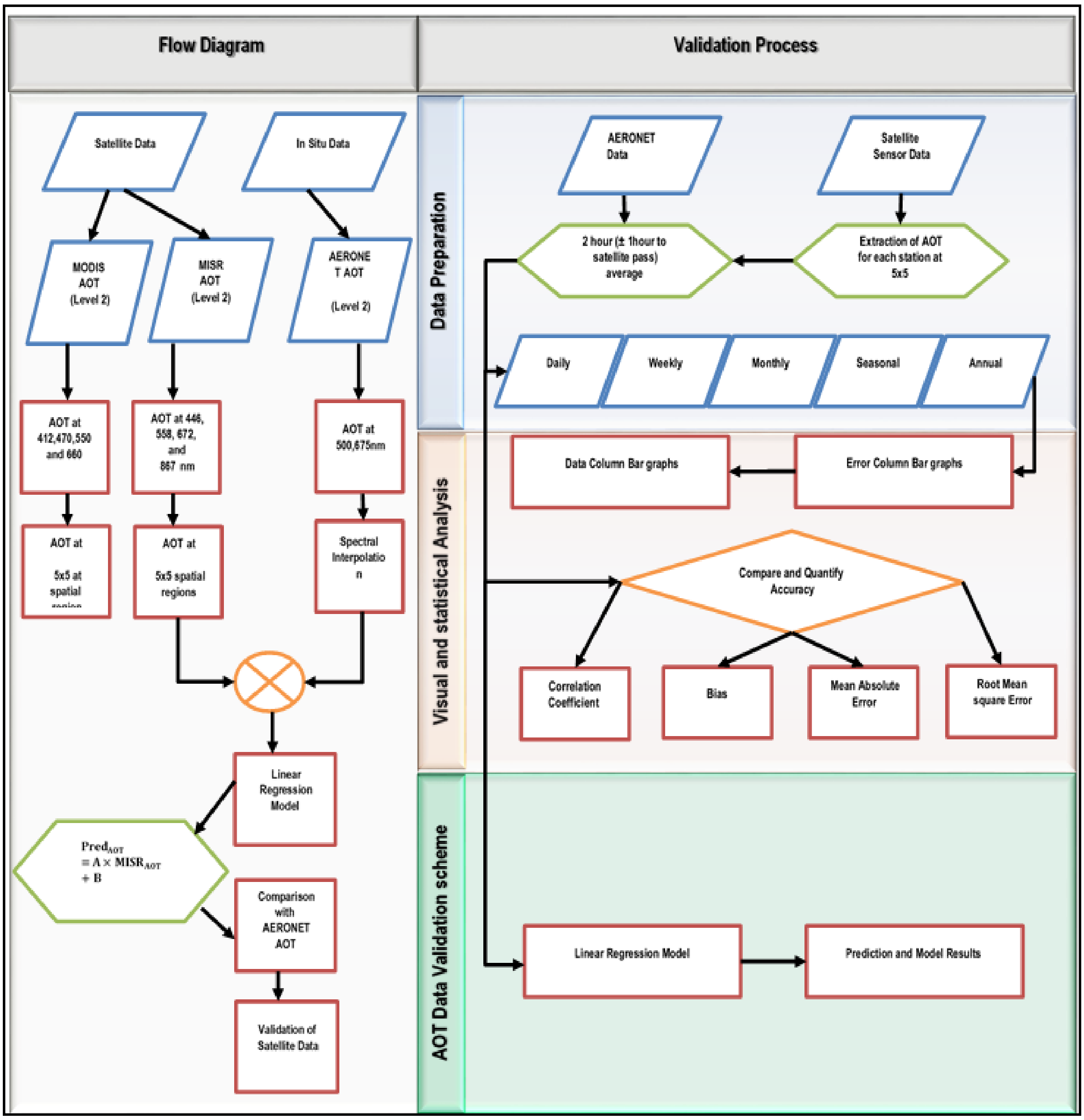


Figure 3:Flowchart of Methodology.

Results and Discussion

The satellite based AOT data of MODIS and MISR satellites werevalidated from Dec 2006 to 2013 for all available common AOT observations recorded by AERONETat the same time of satellite pass and in two hour interval (± 1h at time of passage of satellite). The correlation coefficient, R2, bias, mean square error and root mean square error was calculated for validation of each wavelength of radiation in satellite data. The regression model describes the relation between satellite data and in situ data. The analysis shows that there is a strong correlation between satellite based AOT and AERONET recorded AOT for green band with wavelength at550 nm and 558 nm compared to blue, red and infrared wavelength channels of radiations.

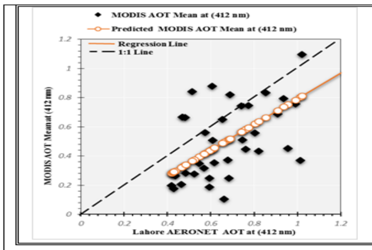
MODIS Based AOT Data Validation

The MODIS satellite has 32 channels of radiation.Level 2 AOT product of four channels (412 nm, 470nm, 550 nm, 660 nm) was used for the purpose of this study.The regression analysis showedthat the highest value of correlation coefficient between MODIS AOT and AERONET AOT was 0.84 with an R2of 0.7 andRMSE of 0.22 forgreen band (550 nm) wavelength radiation. The lowest value of correlation coefficient was 0.73 with RMSE of 0.19 for blue band of 470 nm. The regression model equations and the regression statisticsare shown in Figure 4.

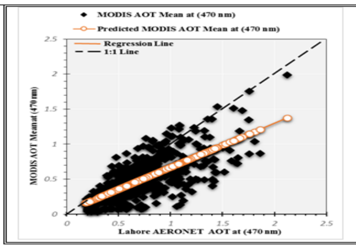
$$AOT_{Pred(412\,nm)} = 0.877 * AOT_{MODIS(412)} + 0.084$$
$$AOT_{Pred(470\,nm)} = 0.627 * AOT_{MODIS\,(470nm)} + 0.045$$
$$AOT_{Pred(550\,nm)} = 0.971 * AOT_{MODIS\,(550nm)} + 0.082$$
$$AOT_{Pred(660\,nm)} = 0.947 * AOT_{MODIS\,(660nm)} + 0.082$$

Figure 4: Linear Regression Models for MODIS AOT data

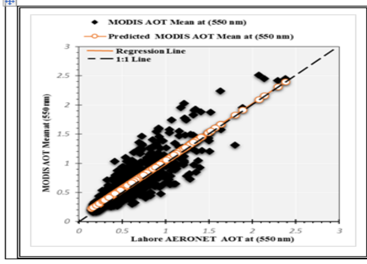
Table2shows the regression results for MODIS AOT against AERONET AOT at all wavelengths.Evaluation of these regression results show that the regression lines are below the 1:1 line, except the 550nm. This shows that MODIS sensor has underestimated AOT values in the wavelength bands of 412, 470 and 660nm. In the case of 550 nm, the MODIS sensor slightly overestimated the AOT values that are less than 1.8 and either underestimate or are equal to the AOT values higher than 1.8.The strongest value of correlation coefficient and highest number of observations were recorded for green radiation band of 550nm. The gradient of the regression line for the 550 nm wavelength band is 0.97, which is near to 1:1 regression line,therefore the overall values of MODIS AOT for 550nm wavelength band were in agreement with the AEORNET data.The green band of MODIS has thus been found to be best for use in air pollution based ap



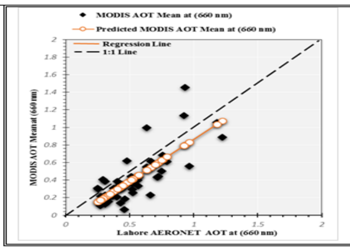
Regression Statistics	
Multiple R	0.823
R Square	0.677
Adjusted R Square	0.670
Bias	0.181
Mean Square Error	0.049
RMSE	0.222
Intercept	-0.084
Gradient	0.877
Common Observations	44



Regression Statistics	
Multiple R	0.726
R Square	0.528
Adjusted R Square	0.527
Bias	0.211
Mean Square Error	0.037
RMSE	0.193
Intercept	0.045
Gradient	0.627
Common Observations	620



Regression Statistics	
Multiple R	0.839
R Square	0.704
Adjusted R Square	0.703
Bias	-0.065
Mean Square Error	0.042
RMSE	0.204
Intercept	0.082
Gradient	0.971
Common Observations	632



Regression Statistics	
Multiple R	0.775
R Square	0.601
Adjusted R Square	0.592
Bias	0.111
Mean Square Error	0.033
RMSE	0.182
Intercept	-0.082
Gradient	0.947
Common Observations	47

Figure 5: Regression Analysis of MODIS and AERONET AOT data.

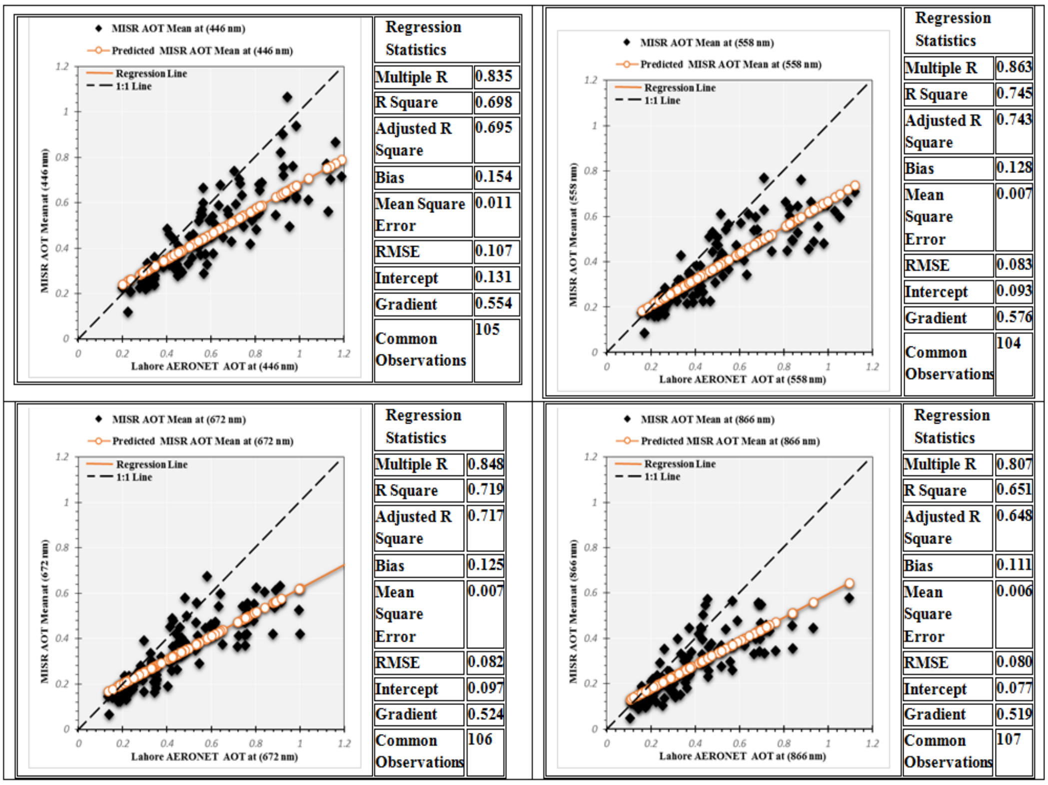
The AOT values recorded for blue 412nm wavelength band have a lower correlation coefficient as compared to the green band. Also the number of observationsfor the blue band weremuch less. This behavior can be attributed to higherscattering of the lower wavelength of the blue band. Therefore for the purpose of aerosol monitoring, blue wavelength did not perform as good as the green wavelength band of the MODIS. However, this bands can be useful in observing very fine particles because it demonstrated a good value of correlation coefficient(0.82) with ground data. Similarly the red band (660nm)also has good value of coefficient of correlation (0.78) but number of observations were less due to high scattering.The AOT recorded from green bands 470nm and 550nm had high number of observations and a high value of correlation coefficient, therefore these wavelength bands are recommended for aerosol monitoring for medium sized particles.

MISR Based AOT Data Validation

MISR level 2 AOT satellite data was validated against level 2 AERONET AOT data. The MISR data showsrelatively highervalue of correlation coefficient as compared to MODIS AOT satellite data. Therewasfound high correlation for green wavelength band of 558nm as compared to blue, red and infrared bands of wavelength. The value of correlation coefficient of MISR AOT data at 558nm wavelength band against AERONET AOT data was foundto be 0.86 and R2was 0.745 with RMSE of 0.08. Foe other wavelength bands, thevalues of correlation coefficient and RMSEwere 0.84 ± 0.1, 0.85 ±0.082 and 0.81 ± 0.08respectively for blue (446 nm) red (672 nm) and infrared (0.866 nm). Figure 6 shows the linear regressing models for each wavelength.

$$AOT_{Pred(446\,nm)} = 0.554 * AOT_{MISR\,(446\,nm)} + 0.131$$
$$AOT_{Pred(558\,nm)} = 0.576 * AOT_{MISR\,(558nm)} + 0.093$$
$$AOT_{Pred(672\,nm)} = 0.524 * AOT_{MISR\,(672\,nm)} + 0.097$$
$$AOT_{Pred(866\,nm)} = 0.519 * AOT_{MISR\,(866\,nm)} + 0.077$$

Figure 6: Regression Analysis of MODIS and AERONET AOT data



Regression Statistics (446 nm)	
Multiple R	0.835
R Square	0.698
Adjusted R Square	0.695
Bias	0.154
Mean Square Error	0.011
RMSE	0.107
Intercept	0.131
Gradient	0.554
Common Observations	105

Regression Statistics (558 nm)	
Multiple R	0.863
R Square	0.745
Adjusted R Square	0.743
Bias	0.128
Mean Square Error	0.007
RMSE	0.083
Intercept	0.093
Gradient	0.576
Common Observations	104

Regression Statistics (672 nm)	
Multiple R	0.848
R Square	0.719
Adjusted R Square	0.717
Bias	0.125
Mean Square Error	0.007
RMSE	0.082
Intercept	0.097
Gradient	0.524
Common Observations	106

Regression Statistics (866 nm)	
Multiple R	0.807
R Square	0.651
Adjusted R Square	0.648
Bias	0.111
Mean Square Error	0.006
RMSE	0.080
Intercept	0.077
Gradient	0.519
Common Observations	107

Figure 7: Regression Analysis of MISR and AERONET AOT data.

The regression lines for the four wavelength bands of the MISR are shown in Figure 7.Analysis of these regression lines shows that MISR underestimates the AOT values greater than 0.2 and slightly overestimates the AOT values less than 0.2 since the linear regression line crosses the 1:1 regression line at nearly 0.2 for each wavelength.

The regression line of 558, 672 and 866nm bands have nearly the same gradient,value of intercept of regression lines and similar number of observations. The blue band of 446 nm has higher values of gradient, intercept and root mean square error (RMSE). The MISR satellite data has comparatively less number of observations then MODIS data but has higher agreement with AERONET AOT recorded values. Previous studies show that MISR sensor AOThad higher correlation with AERONET AOT data.

Prediction of AOT from Satellite Data

The prediction model was prepared using the AOT data from the year 2007 to 2013.AOT was predicted from MISR and MODIS AOT satellite data for the years 2013 and 2014.There were less values of MISR satellite data available after quality assurance as compared to MODIS data. The bar graphs in Figures8 and 9 show the predicted AOT (obtained by applying the linear regression models)using MODIS and MISR data at 550nm and 558nm respectively. There was high agreement in AOT values for MODIS and MISR data against AERONET AOT data. In May, June, July and August, MODIS AOT overestimates for values less than 1.8against AERONET AOT values but in October 2013 MODIS values were nearly equal to and greater than 1.8 so these wereunderestimated. The predicted results for MISR satellite data shows (in Figure 9) that MISR overestimated the AERONET AOT for values greater than 0.2 and underestimated for the values equal to and less than 0.2.

Temporal Analysis

Figures (10-13) show the mean monthly, seasonal and annual AOT recorded from MODIS, MISR and AERONET data. It was observed that there were higher values of AOT in the months of June, July and Augustwhich is attributed to monsoonal gusty winds from the east.Lowest values of AOT were recorded inwinter season in the months of December, January and February. In Figure 11, it was observed that in monsoon season and pre monsoon season the seasonal mean AOT values were higher as compared to the winter season, when AOT values are low. MODIS at 550 nm overestimates whereas MISR underestimatesthe valuesof AOT as compared to AOT values from AERONET in monsoon and post monsoon seasons in most of the cases. In pre monsoon and winter seasons MODIS and MISR AOT are mostly less than or nearly equal to AERONET AOT. The highest recorded seasonal average AOT value of AERONET AOTwas 0.89 in pre monsoon season of 2008 and the lowest recorded (0.2)wasin winter season of 2008.

Theannually averagedAOT recorded by MODIS is overestimated and annually averaged MISR AOT is underestimated as compared to AERONET annually averaged AOT.From all the data of MISR, MODIS and AERONET from 2006 to 2013, the highest annual average AOT was recorded in 2008.Average AOT for weekends was compared with average AOT of weekdays on yearly basis. Mostly the average AOT for weekend days recorded was slightly higher than average AOT of working days. This difference was found the highest in year 2008.

Spatial Analysis

The annual average PM 2.5 from MISR and MODIS AOT data grid at 5ox5oat global scale was used to develop spatially interpolated maps as shown in Figure 14. It shows there is a high concentration of PM 2.5 along the Himalayan mountain range. It is also shown in Figure 11 that main contribution of AOT is by the monsoon season.The path of PM 2.5 concentration is same as the south west monsoon of South Asia region. The major contribution of AOT for Lahore is due to monsoonal winds from eastern Indian side. The Monsoonal winds bring dust from large plains of Indian Subcontinent.

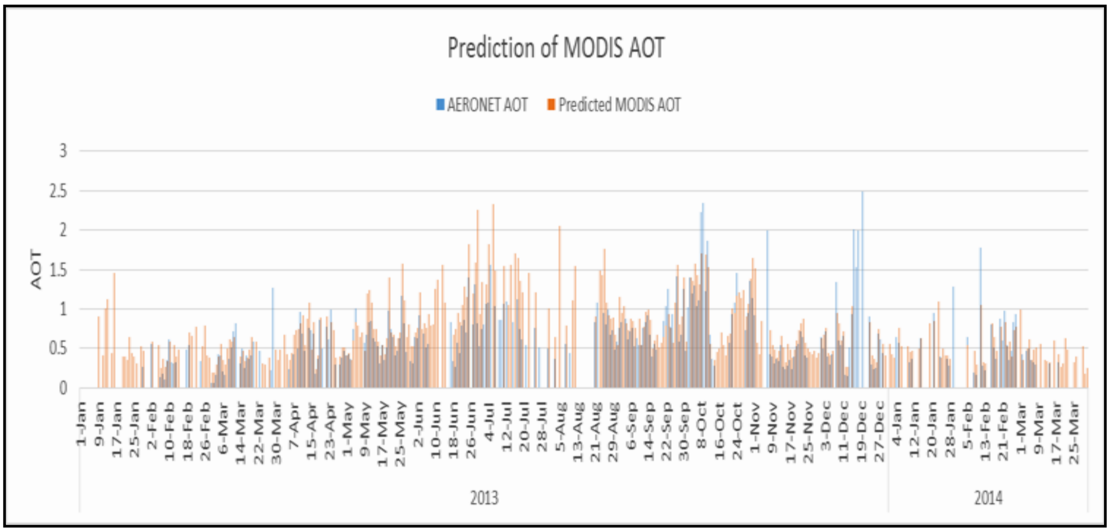


Figure 8: Prediction results of MODIS AOT Data.

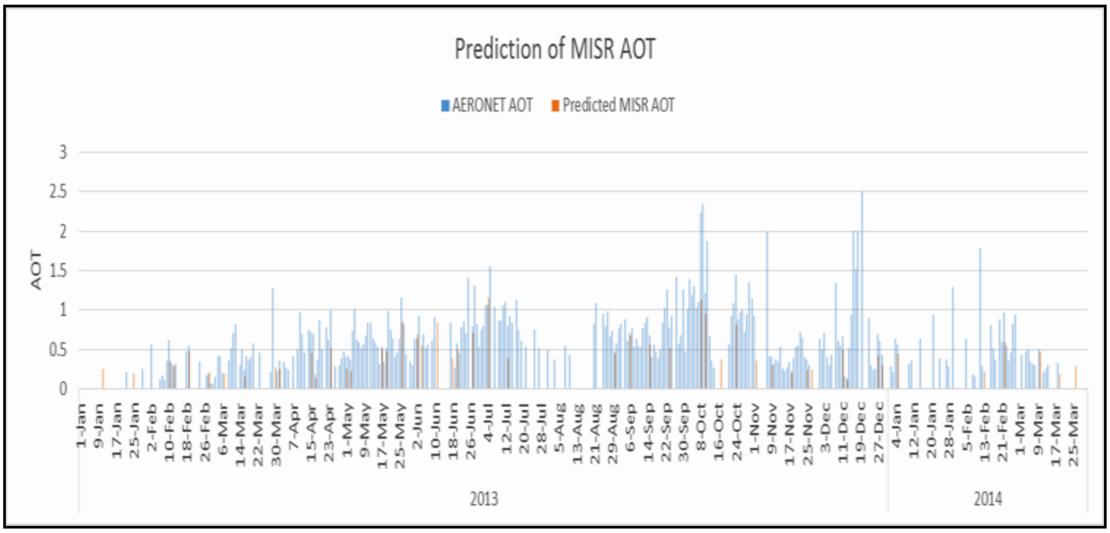


Figure 9: Prediction results of MISR AOT data.

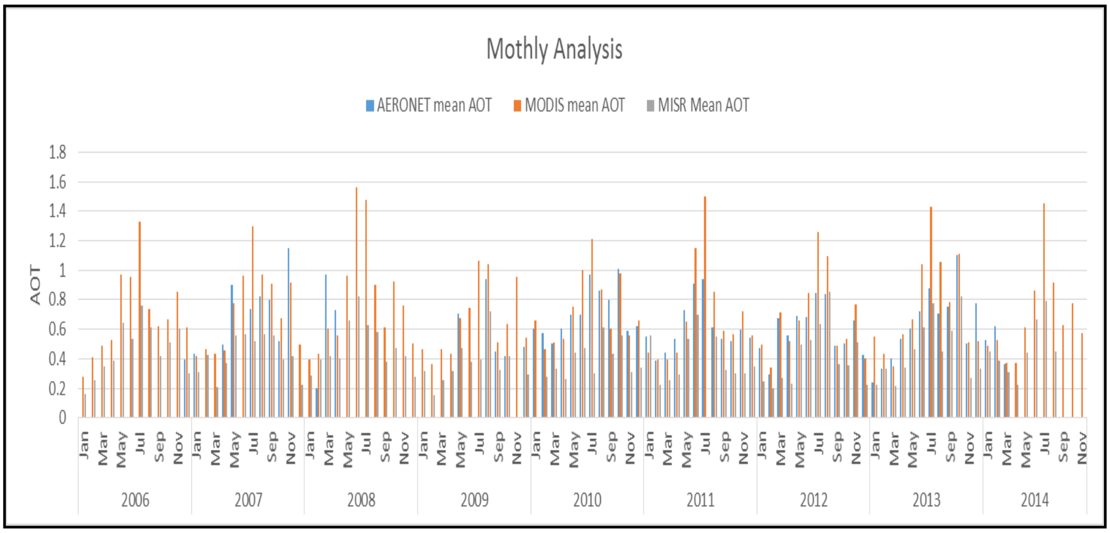


Figure 10: Mean Monthly AOT recorded from AERONET, MODIS and MISR.

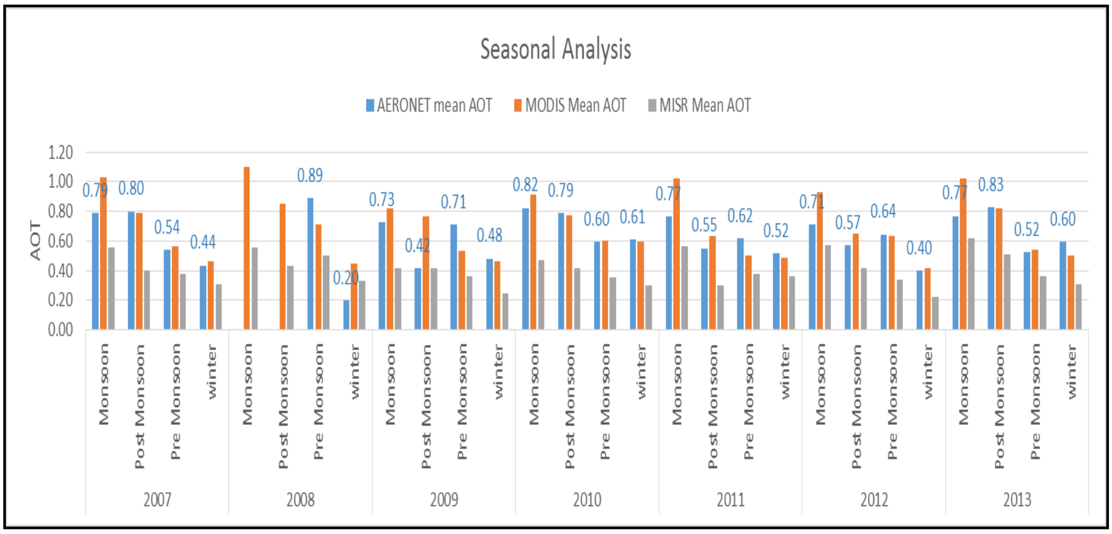


Figure 11: Seasonal Mean AOT recorded from AERONET, MODIS and MISR.

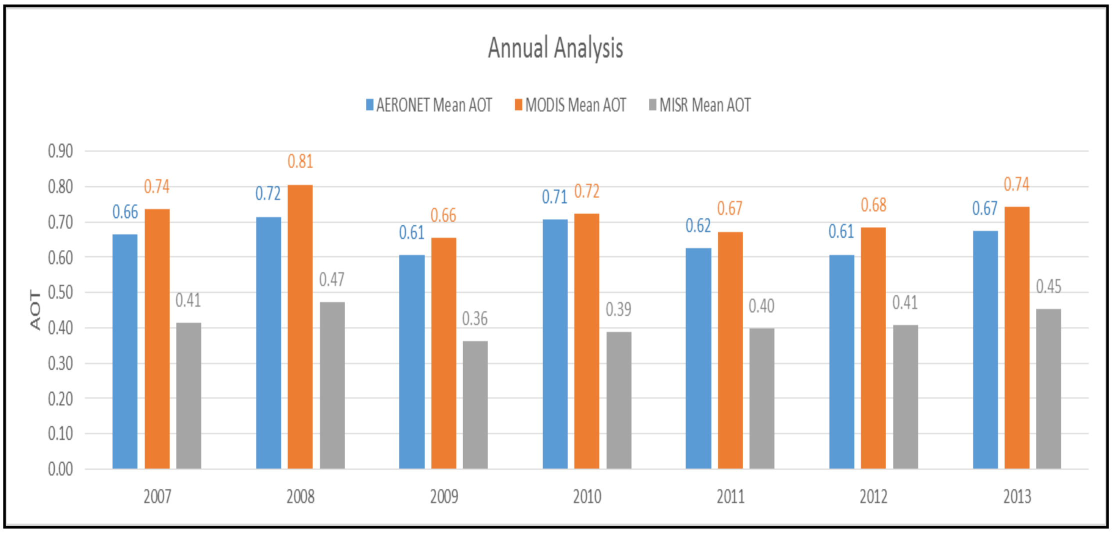


Figure 12: Annual Mean AOT recorded from AERONET, MODIS and MISR.

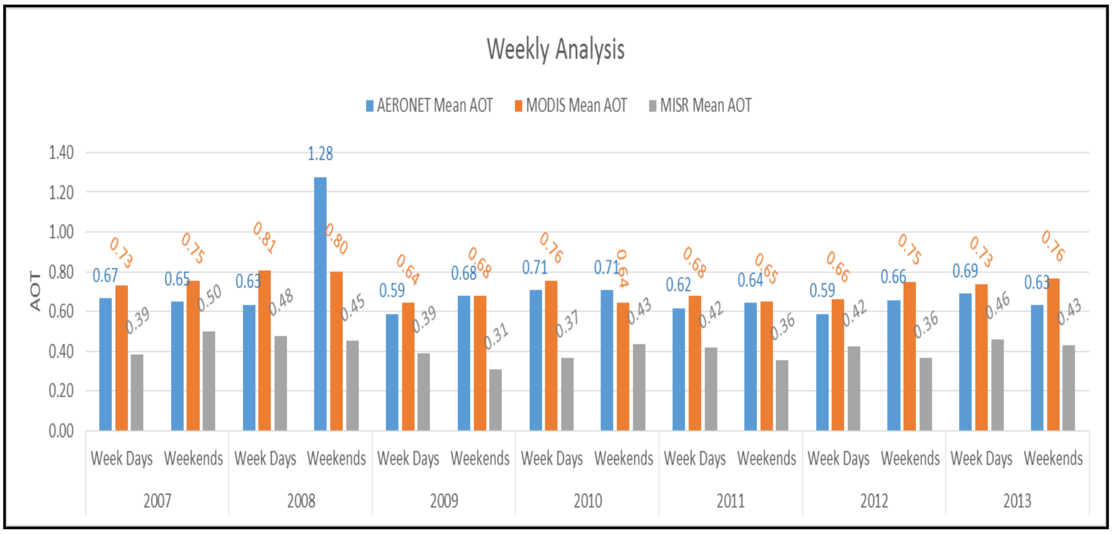


Figure 13: Mean AOT recorded in weekends and week days from AERONET, MODIS and MISR.

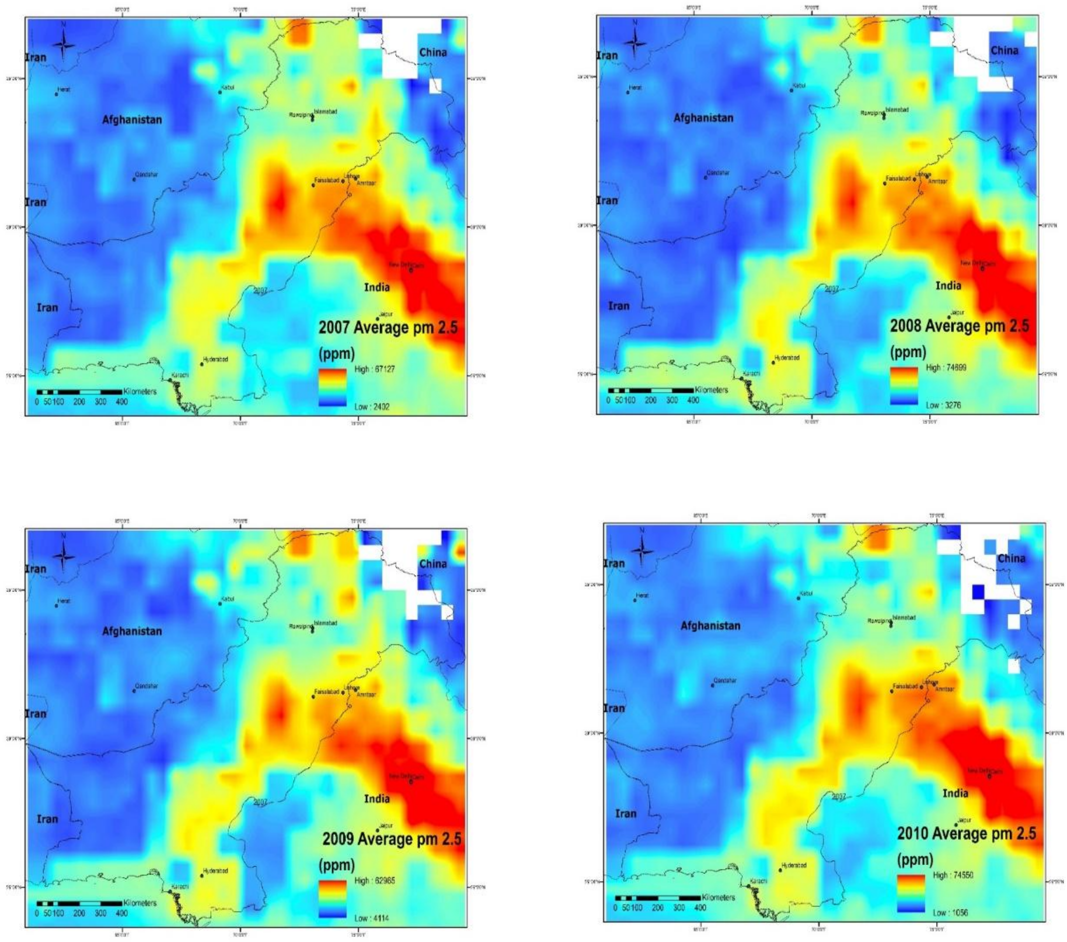


Figure 14: Annual average of PM 2.5 extracted from MODIS and MISR data.

Conclusionsand Recommendations

The AOT cloud free quality assured level 2 products of MODIS, MISR were validated at 5x5 spatial window in a fixed radius with AERONET location centered and averaged for 2 hour interval (± 1 hour centered at satellite pass time) against AERONET AOT Level 2 products at several wavelength bands for Lahore metropolitan city.High values of correlation coefficients were observed for green wavelength bands of 550 nm and 558 nm as compared to blue, redand infrared bands of wavelength. MISR aerosol AOT products were more accurate than MODIS AOT products as they had higher correlation and lesser root mean square error. The number of values for MODIS AOT data were higher than MISR AOT data. MISR underestimated AOT values above 0.2 and slightly overestimated below 0.2 AOT value. The MODIS satellite data also underestimated the AOT values except at 550 nm, where it slightly overestimated the AOT for less than or equal to 1.8 AOT values.Linear regression models were developed for each wavelength for MODIS and MISR satellites.The values ofcorrelationcoefficient were found to be 0.86 and 0.84respectively for MISR and MODIS AOT with AERONET data for the green radiation bands.

This study will promote the satellite data for monitoring of areoles on larger spatial extent with an accurate estimation of AOT. Data from other satellites could also be used to validateAOT values withAERONET. Further accurate validation of AOT values for the whole south Asia region could be performed by installing more AERONET sun photometer stations for all climatic zones and mega cities.

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