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Comparison of MISR-MODIS aerosol optical depth over the Indo-Gangetic basin during the winter and summer seasons (2000–2005)

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Abstract

Satellite aerosol data provide good temporal sampling and superior spatial coverage relative to ground-based stations, especially over the Indian subcontinent. We have used ground-based Kanpur Aerosol Robotic Network (AERONET) station aerosol optical depth (AOD), located in the central part of the Indo-Gangetic (IG) basin, to validate Multiangle Imaging SpectroRadiometer (MISR) and Moderate Resolution Imaging Spectroradiometer (MODIS) Terra level 3 AOD products for the 2001–2005 summer and winter seasons. MISR has been found to perform better than MODIS during both seasons, which we attribute to its unique design (viewing and spectral capability), despite its lower revisit frequency compared to MODIS. In both seasons, the MISR level 3 product distinctly shows a large gradient of AOD along north–south (N–S) and west–east (W–E) transects over the IG basin, compared to the southern part of the Indian subcontinent. An increase in satellite-derived aerosol loading over the 2000–2005 time period has been found over major cities located in the IG basin; this increase is also reflected in ground-based air quality data of the Central Pollution Control Board (CPCB). High MISR AOD during the winter season can be attributed primarily to anthropogenic activities, as major dust storms take place during summer (April–June). We have computed the spatial correlation between MISR and MODIS AOD during the 2000–2005 winter (November–January) seasons, when the effect of desert dust is smallest and the anthropogenic component over the IG basin is largest. The average pixel count with MISR-MODIS correlation coefficient >0.6 during the winter season has been found to be higher over the IG basin and India (35.6% and 32.2% of pixels, respectively) compared to the world (20.4% of pixels). Since the MODIS AOD retrieval algorithm works best for dense and dark vegetative regions, whereas the MISR retrieval is generally less sensitive to surface type, we attribute this result to the relatively high vegetation cover (using MISR Normalized Difference Vegetation Index as a proxy) found in the IG basin and over India.

Keywords: MISR; MODIS; AERONET; Indo-Gangetic Basin; Aerosol; NDVI

1. Introduction

One of the main concerns of scientists working in the field of atmospheric science is the accuracy of satellite-derived parameters, such as aerosol optical depth (AOD) which are extensively used in modeling earth system processes and global climate change (Andreae, 1995; Dubovik et al., 2002; Kaufman et al., 1997; King et al., 1999). A long term study of satellite data is important as a change in the level of aerosols has the potential to bring large changes in radiative forcing and climate (Boucher & Haywood, 2001; Boucher & Tanré, 2000; Charlson et al., 1992; d'Almeida, 1987; Hansen et al., 1997; Harrison et al., 1990; Liao & Seinfeld, 1998; Miller & Tegen, 1998; Miller et al., 2004c,a; Parungo et al., 1995; Ramanathan et al., 2001a,b; Rotstayn et al., 2000). Satellite data from the Multiangle Imaging SpectroRadiometer (MISR) and Moderate Resolution Imaging Spectroradiometer (MODIS) are available with good spatial and temporal (2000–2006) coverage (Kaufman et al., 2002) and are being widely used to understand atmospheric processes and climate variability.

Ground stations are useful in the validation of satellite aerosol products (Chu et al., 2002; Diner et al., 2001; Ichoku et al., 2002, 2004; Kahn et al., 2005; Remer et al., 2005). Recently, ground-based AERONET (Holben et al., 1998; Smirnov et al., 2000) and satellite data (Polarization and Directionality of the Earth's Reflectances, POLDER; Total

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Ozone Mapping Spectrometer, TOMS; MODIS; and MISR) have been used extensively to explain aerosol optical properties over the Indo-Gangetic basin (Deepshikha et al., 2005; Di Girolamo et al., 2004; Golitsyn & Gillette, 1993; Goloub et al., 2001; Massie et al., 2004; Prasad et al., 2006a, 2005a, 2004, 2006b, 2005b; Ramanathan & Ramana, 2005; Singh et al., 2004) which is one of the "hot spots" of the world in terms of high aerosol loading. Singh et al. (2004) have shown high AOD over the IG basin (outlined in Fig. 1d) using multi-year (2000–2004) ground-based AERONET and MODIS satellite data (Prasad et al., 2006a, 2005a, 2004, 2006b, 2005b). Recently, validation of MODIS AOD data, for a limited time period, has been carried out over the Indian subcontinent using Kanpur AERONET observations (Jethva et al., 2005; Tripathi et al., 2005). Tripathi et al. (2005) carried out MODIS AOD validation using only 11 months of level 2 MODIS data in 2004, whereas 22 months of level 3 MODIS data (years 2001–2003) were used by Jethva et al. (2005). MISR data have been validated for the winter season (December, January and February 2001–2004) over the IG basin by Di Girolamo et al. (2004). The winter season is of particular interest as dust storm activity is absent and the anthropogenic component is large (Massie et al., 2004). AOD over the IG basin has been increasing since 2000 (Prasad et al., 2005a, 2006b).

We have carried out a validation of monthly average level 3 MODIS and MISR AOD over Kanpur for the summer and winter seasons (2001–2004). The level 3 monthly mean and daily AOD data for MODIS and MISR are available at 1° and 0.5° spatial resolution respectively, and are produced from higher order level 2 data. The level 2 products consist of higher resolution (10 km for MODIS; 17.6 km for MISR) scene level data at the time of overpass on a given day. Near-global coverage is obtained in 2 days for MODIS and 9 days for MISR. We also analyzed aerosol loading over major cities of the IG basin using MISR and MODIS data (2000–2005) and inferred similar trends as observed in air quality data (2001–2005). South to north (S–N) and west to east (W–E) MISR AOD profiles have been obtained to study spatial variability of aerosol loading across the Indian subcontinent. The variability and magnitude of AOD observed over the IG basin are related to the wind pattern and regional topography of the basin (e.g., Di Girolamo et al., 2004).

Intercomparison and validation of satellite products from different instruments is necessary to build a long term database for climatological studies and potentially to improve upon the accuracy and coverage achievable with a single sensor. In this paper, we compare MISR and MODIS AOD for the winter season (November, December and January, 2000–2005) over the IG basin, India, as well as for the entire Indian subcontinent including the Arabian Sea and the Bay of Bengal. Correlation between MISR and MODIS based on 5 years of data reveals

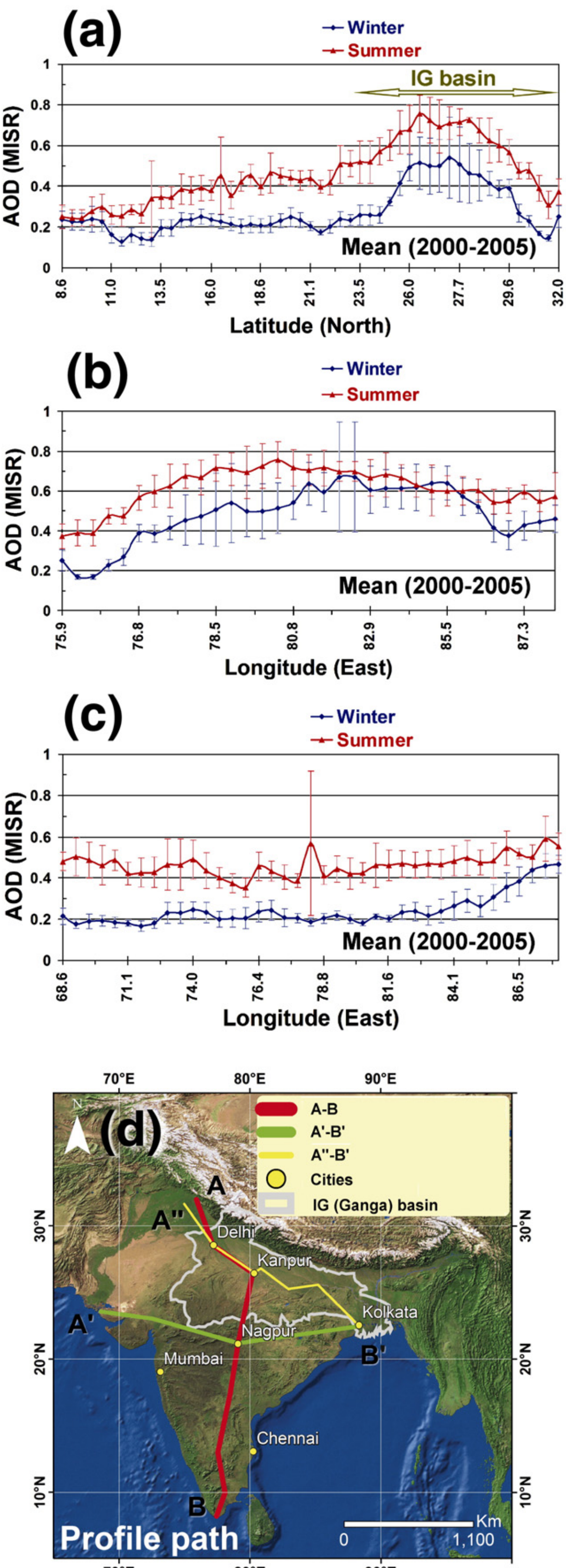

Fig. 1. Profile of average MISR AOD (558 nm) in (a) South to North (S–N) direction (A–B profile), (b) West to East (W–E) direction passing through the IG basin (A″–B′ profile) and (c) West to East (W–E) direction passing through the central India (A′–B′ profile) during the winter (2000–2005) and the summer season (2000–2004).

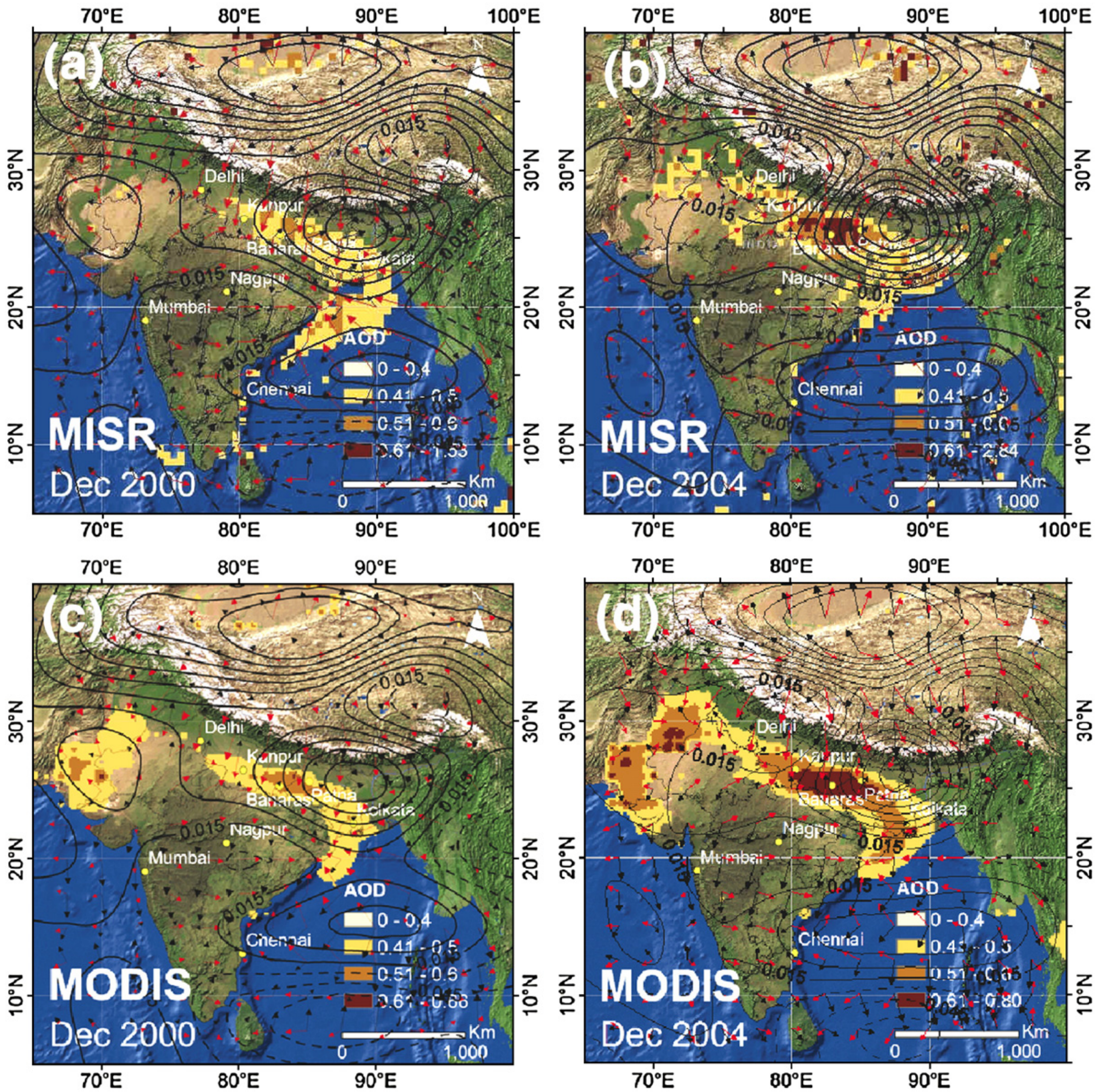

Fig. 2. Spatial distribution of MISR AOD (558 nm) over the Indian subcontinent during (a) December 2000 and (b) December 2004 and MODIS AOD (550 nm) during (c) December 2000 and (d) December 2004 with overlay of NCEP reanalysis wind vectors.

interesting details on the spatial variability of the correlation coefficient.

2. Air quality and variability of MISR-MODIS AOD over the IG basin

Fig. 1 shows variations of average MISR AOD (558 nm) during the winter (average of November, December and January; 2000–2005) and summer (average of April, May, and June; 2000–2004) along south to north (Fig. 1a) and west to east transects over the IG basin (Fig. 1b), and over the Indian subcontinent (Fig. 1c). The profile paths are shown in Fig. 1d. The mean of MISR AOD is shown as dots and corresponding standard deviation with error bars. The IG basin shows very high AOD, as shown in Fig. 1. During the summer season, MISR AOD increases rapidly from 0.25–0.45 in the southern parts of India to 0.6–0.75 over the IG basin. The high AOD over the IG basin can be attributed to the large influx of desert dust from the western arid and desert regions of Arabia, Africa and Thar (Rajasthan) during the pre-monsoon season (April–June) (Dey et al., 2004; El-Askary et al., 2004, 2006; Middleton, 1986; Miller et al., 2004b; Singh et al., 2005). The IG basin during winter also shows a sharp contrast in MISR AOD (0.3–0.5) compared to southern India (0.15–0.25) (Fig. 1a). The winter season is characterized by accumulation of aerosols over the IG basin due to unique topography as the alluvial basin valley (elevation <150 m from mean sea level) is bounded by the towering Himalayas to the north and Vindhyan Mountains to the south. Monthly mean wind vectors (Fig. 2) have been obtained from NCEP reanalysis (http://www.cdc.noaa.gov) where horizontal components (u and v wind) are shown as arrows and omega (vertical velocity) as contours. The

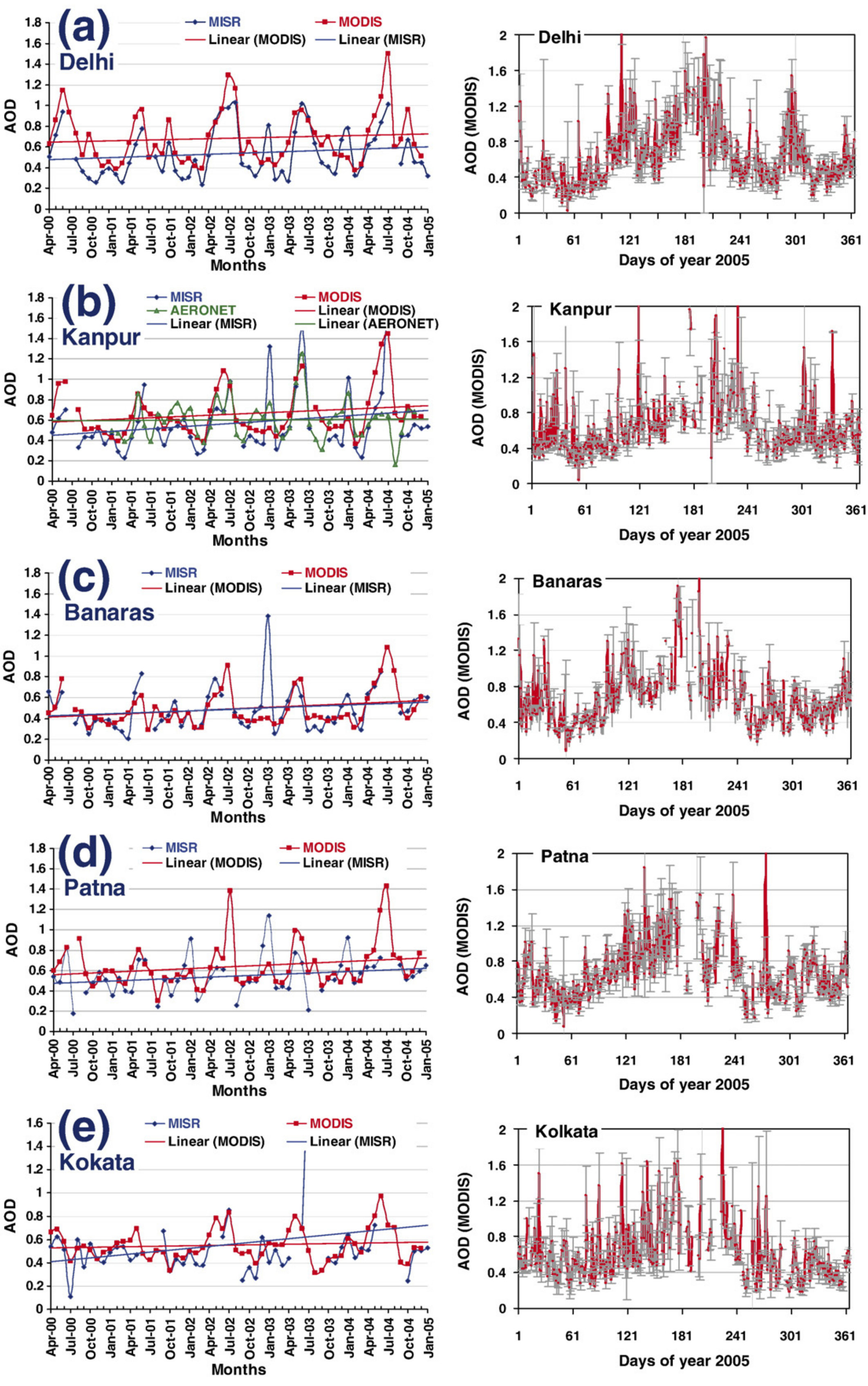

Fig. 3. Increase in MISR (558 nm) and MODIS (550 nm) AOD over major cities of the IG basin, (a) Delhi, (b) Kanpur (with AERONET, 500 nm), (c) Banaras, (d) Patna and (e) Kolkata during 2000–2005. Daily mean and standard deviation of MODIS AOD for year 2005 is also shown for major cities of India. Location of major cities is shown in Fig. 2.

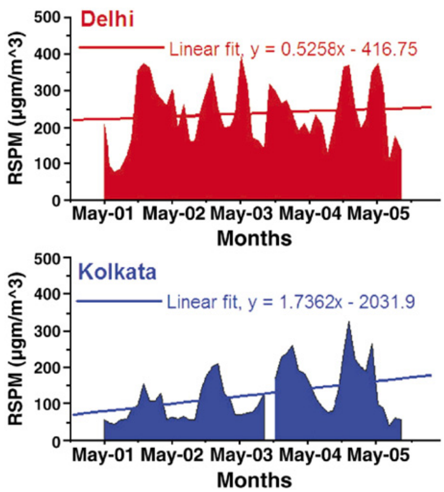

Fig. 4. Central Pollution Control Board (CPCB) monthly surface concentration of RSPM for major cities (Delhi, Kanpur and Kolkata) of India during 2001–2005.

prevailing wind converges from north and south bisecting the IG basin around an imaginary line that favors accumulation of aerosols over the basin (see Fig. 2).

Increase in aerosol loading over major cities of India (Delhi, Kanpur, Banaras, Patna and Kolkata) is evident from the positive slope in AOD based on more than 5 years of satellite (MISR and MODIS) data (Fig. 3). This trend is also reflected in ground-based AERONET data over Kanpur and is found to be prominent especially during the summer and winter seasons (Fig. 3b). This is corroborated qualitatively by air quality data that tracks respiratory suspended particulate matter (RSPM, 2001–2005), obtained from the Central Pollution Control Board (CPCB, http://www.cpcb.nic.in/) for major cities in India (Fig. 4). The air quality data show suspended particulate air pollution at moderate to critical levels over major Indian cities with respect to CPCB monthly mean concentration thresholds for air pollutants. The moderate (M) level range for industrial (residential) areas is 180–360 (70–140) µg/m^3 and the critical (*C*) level is 540 (210) µg/m^3 for suspended particulate matter (SPM). The increase in concentration of air pollutants over major cities can be attributed to the increase in consumption of fossil fuel (coal and petroleum) in thermal power plants,

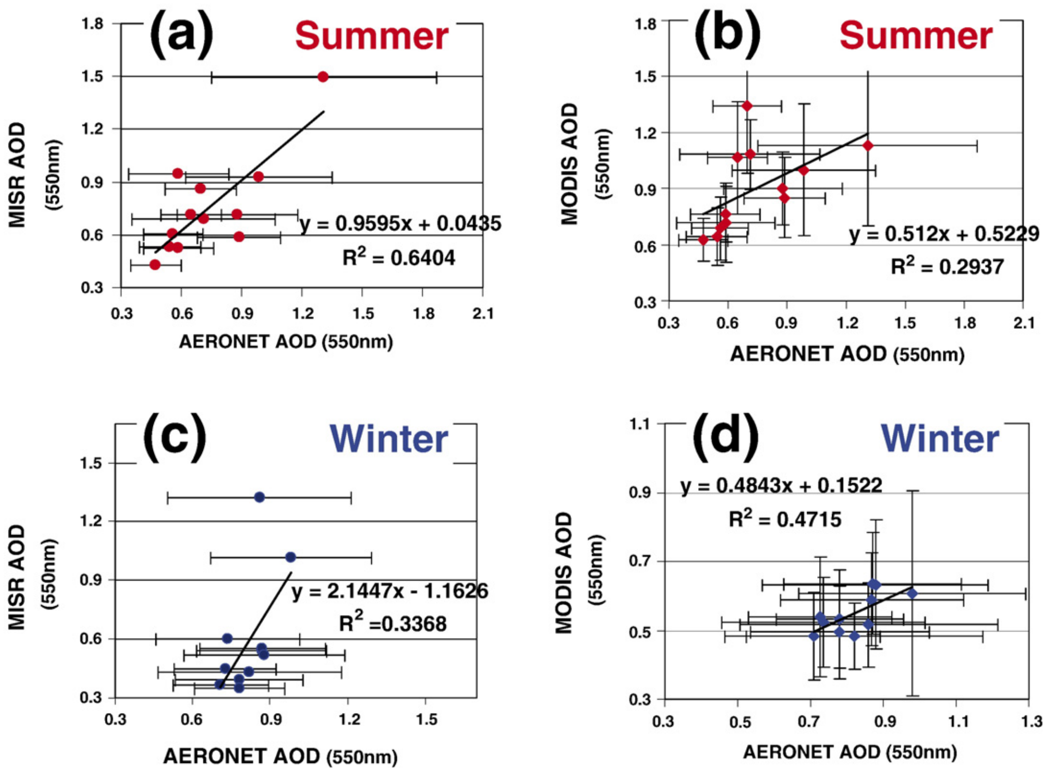

Fig. 5. Validation of level 3 MISR and MODIS AOD over Kanpur using quality assured level 2 AERONET AOD, at 550 nm, during the winter (November–January, 2001–2004) and summer season (April–June, 2001–2004).

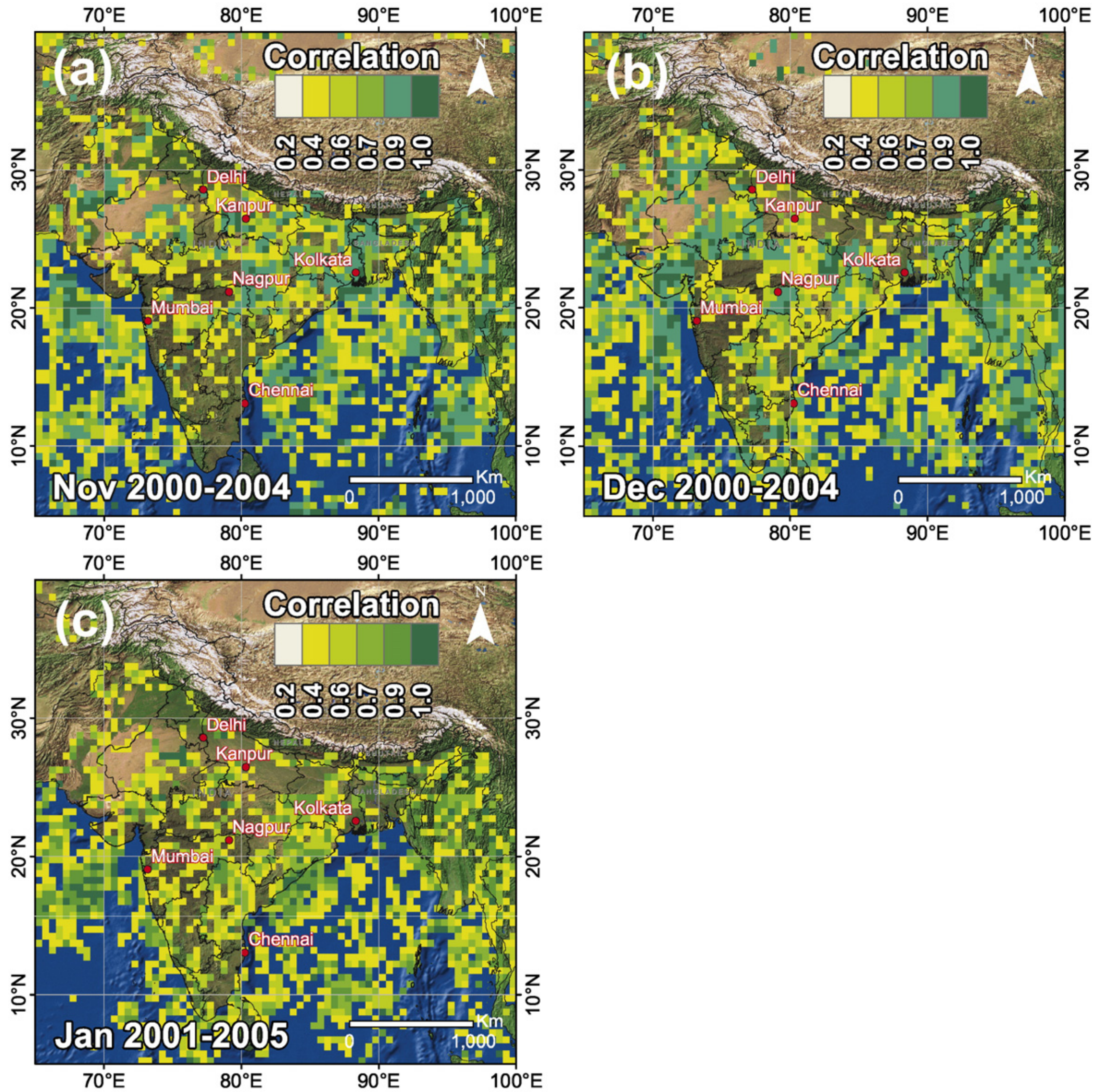

Fig. 6. Spatial correlation of MISR-MODIS over the Indian subcontinent for (a) November (2000–2004), (b) December (2000–2004) and (c) January (2001–2005) months.

transportation, smelters, and industries. Indicators of air pollution such AOD and RSPM from satellite and ground-based data show disturbing trends that can explain visible changes in the environment of the IG basin (Andreae, 1995; Engel-Cox et al., 2004; Garg et al., 2001; Massie et al., 2004; Menon et al., 2002; Reddy & Venkataraman, 2002; Smith et al., 2001; Streets et al., 2003, 2001; Venkataraman et al., 2005; Wang & Christopher, 2003). Satellite data indicate that Kanpur (MISR and MODIS) and Kolkata (MISR) AOD are significantly affected by a rise in the concentration of aerosol particles observed in the CPCB network data (Figs. 3 and 4).

3. Kanpur AERONET and validation of MISR-MODIS

The Kanpur AERONET station (26.45° N, 80.35° E, http://aeronet.gsfc.nasa.gov/) is located at the central region of the IG basin and has been operating since January 2001. We have used quality assured level 2 monthly mean AOD (550 nm) data from AERONET to validate level 3 monthly mean AOD available from MISR (558 nm) and MODIS Terra (550 nm) for the period January 2001 to December 2004. The MISR level 3 monthly average globally gridded data product (MIL3MAE, in HDF-EOS format) has been obtained in $0.5 \times 0.5°$ resolution. This is a “stage 2” validated product (http://www-misr.jpl.nasa.gov/) (Di Girolamo et al., 2004; Diner et al., 2001; Kahn et al., 2005). MODIS Terra AOD (MOD08_M3, in HDF format) has been obtained as a monthly gridded average in $1 \times 1°$ resolution (http://modis.gsfc.nasa.gov/) (Chu et al., 2002; Ichoku et al., 2002, 2004; Remer et al., 2005). For validation, monthly mean AOD from AERONET has been interpolated to a common wavelength of 550 nm using the power law,

$$\mathrm{AOD}_{550\mathrm{nm}} = \mathrm{AOD}_{500\mathrm{nm}}(550/500)^{-\alpha} \quad (1)$$

where α is the Angstrom exponent (440–870 nm).

The correlation between AERONET and MISR (or MODIS) has been computed for the summer (April–June) and winter

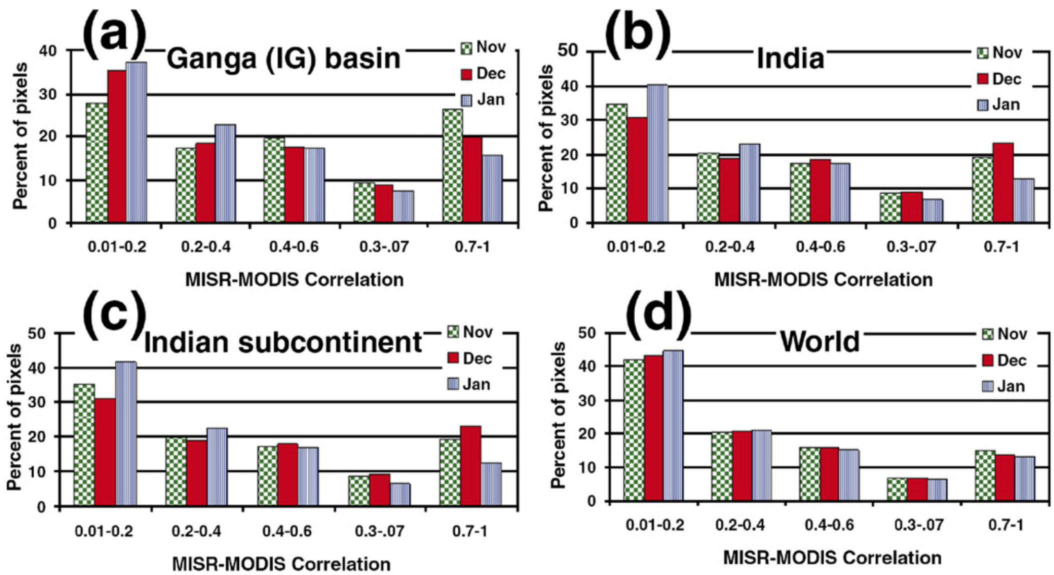

Fig. 7. Distribution of MISR-MODIS correlation (R^2) as frequency histogram of pixel count (in percent, %) over (a) the IG basin, (b) India, (c) Indian subcontinent including the Arabian Sea and the Bay of Bengal and (d) the world.

(November–January) seasons (Fig. 5). The correlation coefficient is found to be relatively high for AERONET-MISR during the summer season (0.64) compared to that of AERONET-MODIS (0.29), while the mean of absolute difference from the monthly average (AERONET minus MISR or MODIS) AOD is −0.01 for MISR and −0.16 for MODIS. This explains the systematically lower values of MISR AOD during the summer season (see Fig. 3) compared to that of MODIS over all major cities in the IG basin. In contrast, during the winter season, AERONET-MODIS shows a relatively higher correlation (0.47) compared to that of AERONET-MISR (0.34). The mean of absolute difference from monthly average AERONET AOD is found to be 0.23 for MISR and 0.27 for MODIS implying that MISR gives a slightly closer estimate of mean AOD with respect to AERONET during this season. However, the number of points is not sufficient to minimize error in the calculation of correlation coefficient due to large variance in the monthly dataset.

In summary, the MODIS AOD product shows higher values than AERONET during the summer and lower values during the winter. MISR also underestimates AOD during winter, but gives a slightly better estimate than MODIS, and gives superior results in the summer, when the IG basin is affected by a number of dust storms. We attribute the overall better performance of MISR, irrespective of its lower temporal sampling rate compared to MODIS, to its unique observing configuration of nine distinct view angles ranging from 70° aftward to 70° forward, and availability of four narrow spectral bands centered at 446, 558, 672, and 866 nm. MISR can retrieve aerosol optical properties over a variety of terrains, including highly reflecting desert areas, using its multiangular and multispectral viewing capability. The resulting algorithms permit aerosol retrievals to be independent of explicit radiometric surface properties (Diner et al., 2001; Martonchik et al., 2004).

4. Spatial correlation of MISR-MODIS (2000–2005, winter season)

We computed Pearson product moment correlation coefficients using monthly average level 3 MODIS (MOD08_M3) and MISR (MIL3MAE.004) data. Since the globally gridded product of MISR is of higher resolution (0.5 × 0.5°) compared to MODIS (1 × 1°), we have converted the spatial resolution of MODIS to that of MISR using nearest neighbor resampling. Each pixel in MODIS has been divided into 4 identical pixels of size 0.5 × 0.5° before applying the formula for computation of correlation coefficient. We used 5 years of monthly data from 2000–2004 (November, December) and 2001–2005 (January) from MISR and MODIS to calculate correlation coefficients for particular months. We masked all pixels for which data were absent or marked with a fill value for one or more annual samples of a particular month's interannual time series. We ensured that the correlation coefficient value computed for a particular pixel (see Fig. 6) has an equal number of months (over 5 years) available from both data sets. The time series for November and December includes data from 2000–2004, and for January includes data from 2001–2005. Therefore, the correlation coefficients shown in Fig. 6 (for each pixel) are based on 5 pairs of points obtained from MISR and MODIS. As shown in Fig. 6, the correlation coefficient for MISR-MODIS is found to be very high (>0.9) at some regions and moderate to low at other regions. A frequency histogram (Fig. 7) shows the percentage of pixels within a given area that fall in either the high (>0.7–1), moderate (0.6–0.7), low (0.4–0.6) and no reasonable correlation (0.01–0.2 and 0.2–0.4) classes.

For our MISR-MODIS correlation study, we choose the winter season, as the number of available data points is generally sufficient to obtain good results. Overall, high pixel counts (in the range 20–60) are found over India during this

Table 1
Distribution of pixel count (in percent, %) for MISR-MODIS spatial correlation (>0.6 and >0.7) over the IG basin, India, Indian subcontinent (including Arabian Sea and Bay of Bengal) and the world (winter season, 2000–2005)

Region	Correlation	Percentage (%) of pixels			
		Nov	Dec	Jan	Average
Ganga (IG) basin	>0.6	35.6	28.5	22.8	28.9
India	>0.6	27.8	32.2	19.7	26.6
Indian subcontinent	>0.6	27.7	31.9	18.8	26.2
World	>0.6	21.7	20.4	19.3	20.4
Ganga basin	>0.7	26.3	19.8	15.6	20.5
India	>0.7	19.3	23.2	13.0	18.5
Indian region	>0.7	19.1	22.9	12.4	18.1
World	>0.7	14.9	13.7	12.9	13.9

season. The level 3 MISR data show <10 pixel counts mostly along Himalayan and Tibet regions (primarily due to snow cover). During some winter months a small portion of the central Thar Desert also shows <10 pixel counts. By virtue of its faster revisit cycle, MODIS generally shows a high pixel count over the entire Indian region. During the summer, dust storms limit data availability over the Thar Desert. In addition, during the monsoon season (July–August–September), the pixel count is found to be relatively low over India for both MISR and MODIS. Using daily level 3 MODIS AOD at 1° spatial resolution over major cities of India to study daily variability of AOD over different parts of the IG basin, we found (see Fig. 3) that daily mean and standard deviation are lower in winter compared to the summer and monsoon seasons. Summer shows high variability in both mean and standard deviation due to influence of dust storms coming from western arid regions, and cloud cover affects daily AOD during the monsoon season. Thus, the winter season provides the best sampling with which to test the degree of MISR-MODIS correlation. Although the difference in sampling (particular day and number of days) that goes into the monthly mean product will cause some of the difference between MISR and MODIS AOD, analysis using multi-year data is expected to mitigate the effects of sampling.

Frequency histograms (Fig. 7) over the IG basin, India (political boundary), and the Indian subcontinent including the Arabian Sea and the Bay of Bengal show interesting features regarding MISR-MODIS correlation. During the winter season (November–January) over the IG basin, up to 26.3% (average

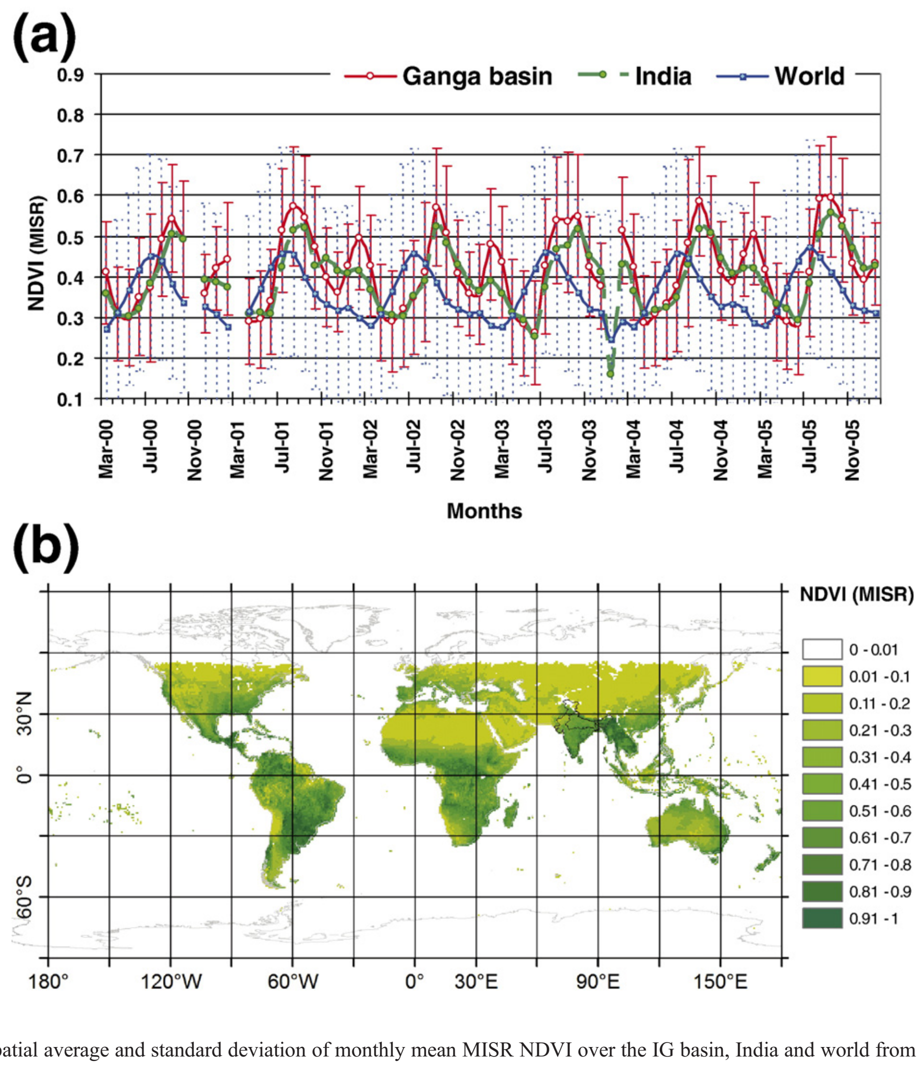

Fig. 8. (a) Time series of spatial average and standard deviation of monthly mean MISR NDVI over the IG basin, India and world from March 2000–January 2006. (b) Spatial distribution of multi-year average of vegetation cover (NDVI) obtained from monthly mean MISR NDVI (March 2000–January 2006).

Table 2
Mean MISR NDVI over the IG basin, India, Indian subcontinent (including Arabian Sea and Bay of Bengal) and the world (winter season, 2000–2006)

Region	Mean NDVI			
	Nov	Dec	Jan	Winter
Ganga (IG) basin	0.415	0.371	0.407	0.396
India	0.433	0.397	0.39	0.401
Indian subcontinent	0.267	0.242	0.241	0.244
World	0.286	0.276	0.268	0.25

20.5%) of pixels fall within the high correlation (>0.7–1) range. Similarly, over the India land mass (i.e., within the political land boundary), up to 23.2% (average 18.5%) of pixels fall within the high correlation (>0.7–1) range. The Indian subcontinent (area bounded by 5°–40°N latitude and 65°–100°E longitude) covering the Arabian Sea and the Bay of Bengal shows up to 22.9% of pixels (average 18.1%) falling within this range, while similar statistics for the whole world shows a relatively lower maximum of 14.9% (average 13.9%). The IG basin shows much higher number of pixels in the correlation range (>0.6–1), 28.9%, compared to India (land, political boundary) or the Indian subcontinent, and the smallest count occurs for the world. Table 1 summarizes the higher correlation between MISR-MODIS over the IG basin compared to other areas. The lower world average could be partly due to low pixel count statistics resulting from the higher percentage of desert and snow covered regions compared to India. In India, the western part is covered by desert, and snow cover is high in the Himalayan Mountains to the north. Thus, the higher correlation between MISR-MODIS AOD over the IG basin relative to India and the world could also be due to the greater proportion of vegetation cover. The aerosol retrieval algorithm used for MODIS is more accurate for densely vegetated regions (dark targets) as these areas have very low reflectance in the blue and red compared to the non-vegetated surfaces such as deserts, snow, and ice. MISR retrievals, on the other hand, are less sensitive to surface type in comparison to MODIS (e.g., Abdou et al., 2005). We have used monthly level 3 MISR Normalized Difference Vegetation Index (NDVI) with spatial resolution of 0.5° for the period March 2000 to January 2006 to study vegetation cover over the IG basin, India and the world. Monthly NDVI data in HDF format have been obtained from the NASA Langley Research Center MISR data archive (http://eosweb.larc.nasa.gov/). The monthly time series (2000–2006) showing spatial average of MISR NDVI is higher over the IG basin and India compared to the world during the monsoon and winter seasons (Fig. 8a). The mean NDVI of December, January and November months (for period 2000–2006) (see Table 2) is also much higher over the IG basin and India compared to the world. A higher vegetative cover over India (and IG basin) is also clearly visible in Fig. 8b (mean of winter season MISR NDVI, 2000–2006).

5. Conclusions

The south–north MISR AOD profile (Fig. 1a) (mean of 2000–2005) clearly demarcates the IG basin as a region of very high AOD during the summer and winter seasons. MISR AOD over the IG basin is found to be relatively higher in magnitude during the summer season (0.6–0.7) compared to the winter season (0.4–0.5). Growing anthropogenic activities due to rapid industrialization in the IG basin have led to increase in winter time aerosol loading favored by topography, wind and other meteorological conditions. The effect of increasing urbanization and industrialization is also observed in CPCB air quality data (2001–2005) collected at major cities of India. Using AERONET AOD as the standard, MISR performs better than MODIS during both summer and winter seasons owing to its unique multiangular and multispectral design. MODIS overestimates AOD during the summer whereas both sensors underestimate it during the winter. A multi-year validation exercise of MISR and MODIS using level 2 data (based on daily simultaneous satellite overpass and ground observation to achieve more sample points) is required to arrive at a precise figure of correlation between AERONET and MISR (or MODIS). We have found that a maximum of one-fourth and on an average one-fifth of the total area in the IG basin shows good MISR-MODIS correlation ($R^2>0.7$), which is relatively better than the world average of 13.9%. As aerosol optical depth retrieval is sensitive to the vegetation cover (dark and dense vegetation targets), particularly for MODIS, the relatively higher vegetation cover over the IG basin and India potentially explains the higher correlation between MISR and MODIS AOD over the IG basin and India compared to the world. The generally good correlation of MISR and MODIS over the IG basin indirectly increases confidence in the observation that aerosol loading has increased over the IG basin between 2000–2005. A similar exercise is required to test MISR-MODIS correlation and validation over different land surface types such as deserts, arid regions, and bare alluvial and vegetated land.

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