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Aerosol optical thickness trends and population growth in the Indian subcontinent

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The Indian subcontinent occupies 2.4% of the world land mass and is home to ~17% of the world population. It is characterized by a wide range of population density (*P*), significant population growth and high levels of air pollution. The quantification of the effect of urbanization on aerosol optical thickness (AOT) trends was carried out by analysing 8-year (March 2000 to February 2008) Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR) satellite data. Here we show that over extensive areas with differing population densities, which are significant parts of the Indian subcontinent, (1) the higher the averaged population density the bigger the averaged AOT and (2) the larger the population growth the stronger the increasing trends in AOT. Over the regions with $P > 100$ persons km^{-2} (more than 70% of the territory), a population growth of ~1.5% year^{-1} was accompanied by increasing AOT trends of over 2% year^{-1}. The presence of the aforementioned AOT trends is evidence of air quality deterioration, in particular in highly populated areas with $P > 500$ persons km^{-2}. This situation could worsen with the continued growth of the Indian population.

1. Introduction

The anthropogenic aerosol concentrations have peaks in the densely populated regions, many of which are concentrated in Asia (Ramaswamy 2009). This study was aimed at finding evidence that links urbanization to aerosol optical thickness (AOT) and its trends over the Indian subcontinent, based on the 8-year National Aeronautics and Space Administration (NASA) databases of Multiangle Imaging SpectroRadiometer (MISR) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite retrievals, from March 2000 to February 2008. The subcontinent is characterized by high levels of air pollution due to intensively developing industries and mass fuel consumption for domestic purposes (Di Girolamo *et al*. 2004, Ramanathan and Ramana 2005, Tripathi *et al*. 2005, Prasad and Singh 2007). Furthermore, it has a wide range of population density (persons km^{-2}), from zero in remote sites to thousands in the Ganges basin. The aforementioned factors give us the

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opportunity to quantify the effects of urbanization on AOT, averaged separately over regions with differing population densities. Currently available satellite measurements with global coverage provide us with evenly distributed AOT data (Kaufman *et al*. 2002). This makes it possible to estimate aerosol effects on AOT trends over highly populated areas.

There are many factors, however, which could play a role in the relationship between urbanization and AOT. Ramanathan *et al*. (2007) analysed the relationship between population in the top 26 megacities around the world and AOT retrieved from MODIS data from 2001 to 2003. Their study included three megacities in India: Calcutta, New Delhi and Mumbai, with population (including suburbs) approximately 15, 20 and 20 million people, respectively. AOT was estimated to be equal to approximately 0.57, 0.54 and 0.39, respectively. This shows that there was no correspondence between population and AOT for these megacities. Similarly, there was no correspondence between population and AOT in other megacities around the globe. This demonstrates that the relationship between population figures and AOT is not obvious and depends on many factors.

In our approach to estimating the effect of urbanization on AOT, we used AOT averaging over extensive territories which are significant parts of the Indian subcontinent with differing population densities. After averaging over the extensive territories, the effects of some specific sites on AOT could be local and do not contribute significantly to the total dependence of AOT on population density.

2. Data

Our approach to estimating the effect of urbanization on AOT over the Indian subcontinent was based on analysing seasonal and long-term variations of AOT, averaged separately over the regions with population densities (P, persons km^{-2}) within the following four groups: $1 \leq P < 100$; $100 \leq P < 250$; $250 \leq P < 500$; and $P \geq 500$. The Gridded global population density of World Version 3 (GPWv3) $2.5' \times 2.5'$ data set of the year 2000, from Socioeconomic Data and Applications Center (SEDAC) of Columbia University, was used (figure 1(*a*)) (http://sedac.ciesin.columbia.edu/gpw/). As estimated on the basis of the GPWv3 data set of the year 2000, the four aforementioned regions with different population densities occupy approximately 19%, 37%, 21% and 16% of the Indian subcontinent, respectively. The rest of the territory ($\sim$7%) with population density less than 1 person km^{-2} is mostly the Himalayas region and the Thar Desert. One can see that, in the Indian subcontinent, regions with $P > 100$ persons km^{-2} occupy over 70% of its territory (figure 1(*a*)).

In order to compare AOT trends for the period under consideration with a population density growth in each of the four regions with differing population density, the P growth (% year^{-1}) was estimated by using the GPWv3 data sets (http://sedac.ciesin.columbia.edu/gpw/) of the years 2008 and 2000, respectively, with resolution $1° \times 1°$. In particular, the P growth was estimated to be approximately 1.7%, 1.5% and 1.4% year^{-1} for the regions with $100 \leq P < 250$; $250 \leq P < 500$; and $P \geq 500$ persons km^{-2}, respectively. The P growth over the Indian subcontinent where $P > 100$ persons km^{-2} was estimated to be approximately 1.5% year^{-1}.

To analyse the effect of urbanization on AOT, we have used the 8-year level-3 monthly gridded data with horizontal resolution $1° \times 1°$, from March 2000 to February 2008, from MISR and MODIS sensors on board the NASA Terra spacecraft

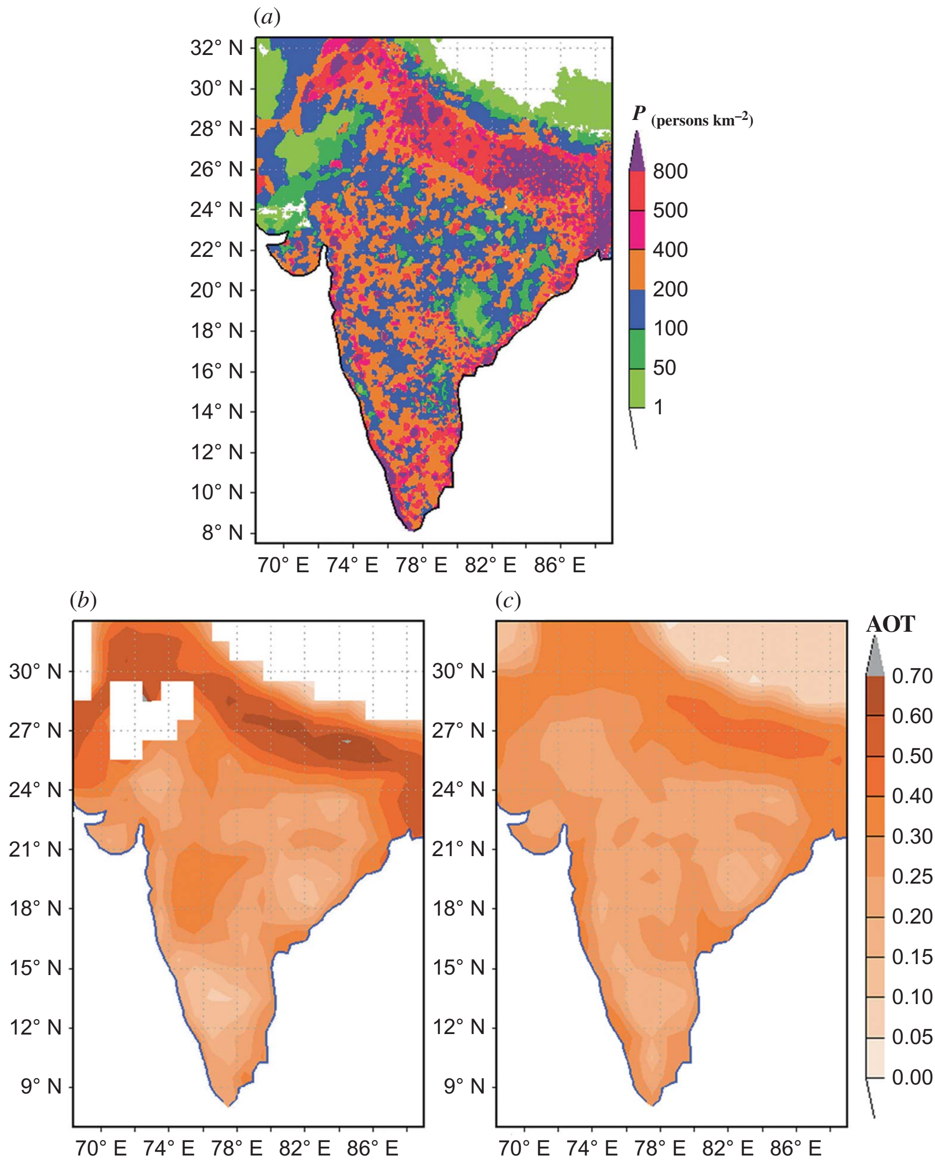

Figure 1. (*a*) The study area with a population density (persons km^{-2}) distribution over the Indian subcontinent. (*b*) and (*c*) The 8-year (2000–2008) mean distributions of (*b*) Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical thickness (AOT) and (*c*) Multiangle Imaging SpectroRadiometer (MISR) AOT for the months from October to February.

orbiting the Earth since December 1999, with daytime equator crossings at 10:30 local time (LT). The MODIS aerosol product is increasingly being used in conjunction with MISR, as the greater MODIS coverage and shorter revisit time complement the retrievals provided by MISR over bright surfaces (Kalashnikova and Kahn 2008, Kahn *et al*. 2009).

Collection 5 (MOD08_M3-005) of MODIS-Terra level-3 monthly aerosol data was used. MODIS with its 2330 km viewing swath provides almost daily global coverage. The MODIS AOT uncertainty is $\pm 0.05 \pm 0.15 \times$ (AOT) over the land (Remer *et al*. 2005, Levy *et al*. 2007). MISR is a multiangle (nine view) imaging instrument operating on four spectral bands centred at 446, 558, 672 and 867 nm, respectively (Diner *et al*. 1998). The fore–aft–nadir cameras acquire images with view angles relative to the Earth's surface at 0°, 26°, 46°, 60° and 70°. The swath width is about 380 km and global coverage is obtained every 9 days. MISR AOT has been extensively validated against AErosol RObotic NETwork (AERONET) Sun photometer measurements over different regions. It was estimated that overall about two-thirds of the MISR-retrieved AOT values fall within ± 0.5 or $\pm 0.2 \times$ (AOT) of the value of AERONET AOT (Kahn *et al*. 2005). Shown in figure 1(*b*) and (*c*), the 8-year mean distributions of AOT for the months from October to February, based on MISR and MODIS data, display that the two sensors show high AOT over the Ganges basin in the northern part of India. This is in line with Di Girolamo *et al.* (2004). Over the Ganges basin, MODIS AOT is noticeably higher than MISR AOT (figure 1(*b*) and (*c*)).

In order to illustrate the effects of cloudiness during the monsoon period on the accuracy of satellite AOT retrievals, Collection 5 MODIS-Terra monthly $1° \times 1°$ data of cloud fraction, together with the Global Precipitation Climatology Project (GPCP) monthly $1° \times 1°$ precipitation data product, was also used for the 8-year period under consideration (http://disc.sci.gsfc.nasa.gov/giovanni).

3. Results

Shown in figure 2(*a*), the 8-year mean distribution of cloud fraction in the summer (monsoon) months (June–August) revealed that the major part of the Indian subcontinent is characterized by high cloud presence with a cloud fraction value exceeding 0.9, with the exception of the Thar Desert and northern regions. MODIS and MISR have quite a limited opportunity to view aerosols if cloud cover is so significant (Tripathi *et al*. 2005, Zhang *et al*. 2005, Koren *et al*. 2007, Prasad and Singh 2007, Remer *et al*. 2008). It means that satellite aerosol retrievals obtained under such overcast conditions, during most of the days in the summer months, are less accurate than AOT obtained in the winter months (November–January), when cloud presence is rather low (figure 2(*b*)). Moreover, in accordance with Remer *et al*. (2008) and Zhang *et al.* (2005), it is possible that, when cloud fraction exceeds 0.8, satellite aerosol retrievals are overestimated because of cloud contamination: the aerosol retrievals interpret, in error, cloud droplets as coarse mode particles. Therefore, the summer (monsoon) season with high cloud presence over the Indian subcontinent is unfavourable for studying relationships between urbanization and satellite-based AOT. By contrast, the months from October to April are characterized by minimal cloud presence, in accordance with seasonal variations of MODIS cloud fraction averaged over the 8-year period under consideration (figure 2(*c*)).

The effects of urbanization on AOT are connected with a high level of anthropogenic aerosol emissions. Due to the mixing of aerosols loaded by natural and anthropogenic sources, satellite measurements cannot distinguish between natural and anthropogenic aerosols. Previous studies of aerosols over the Indian subcontinent (Dey *et al*. 2004, Singh *et al*. 2004, Tripathi *et al*. 2005, Prasad *et al*. 2006) showed that desert dust transport from the Sahara, the Middle East deserts and the Indian Thar Desert is observed from March to August. However, in the winter months, when

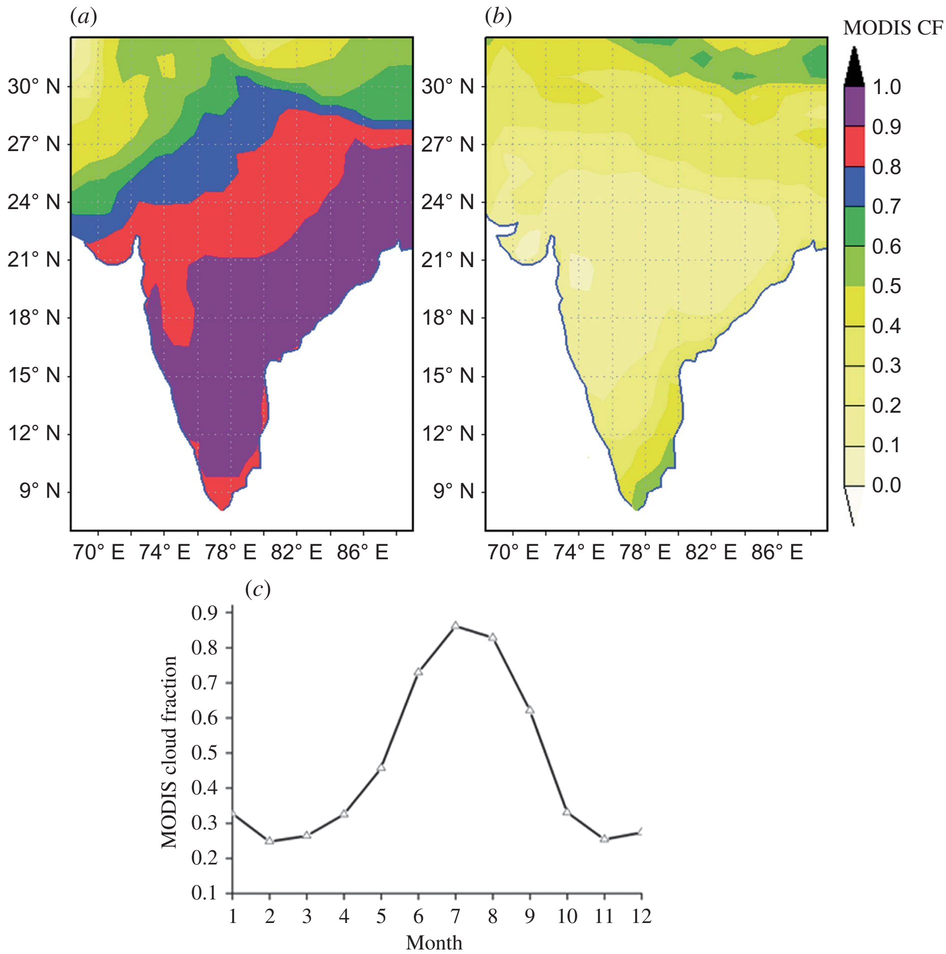

Figure 2. (*a*) and (*b*) The 8-year mean distributions of Moderate Resolution Imaging Spectroradiometer (MODIS)-Terra cloud fraction for (*a*) the summer months, from June to August, and for (*b*) the winter months, from November to January. (*c*) Seasonal variations of MODIS-Terra cloud fraction averaged over the Indian subcontinent during the 8-year period under consideration. CF, cloud fraction.

desert dust activity is minimal and anthropogenic aerosols dominate (Di Girolamo *et al*. 2004, Singh *et al*. 2004, Prasad and Singh 2007), it is easier to determine the relationship between AOT and population density.

Figure 3(*a*) and (*b*) show month-to-month variations of 8-year mean MISR AOT (figure 3(*a*)) and MODIS AOT (figure 3(*b*)) averaged over the regions with differing population densities from October to February: this is a season with minimal cloud fraction and minimal desert dust activity. In this season, the orderly relationship between AOT and population density is noticeable (figure 3(*a*) and (*b*)). It is clearly seen that, on average for the months from October to February for both sensors, the dependence of AOT on population density is monotonic: an increase in population density is accompanied by an increase in AOT (figure 3(*c*) and (*d*)). In particular, MODIS (MISR) AOT values range from a low of 0.19 ± 0.03 (0.20 ± 0.03)

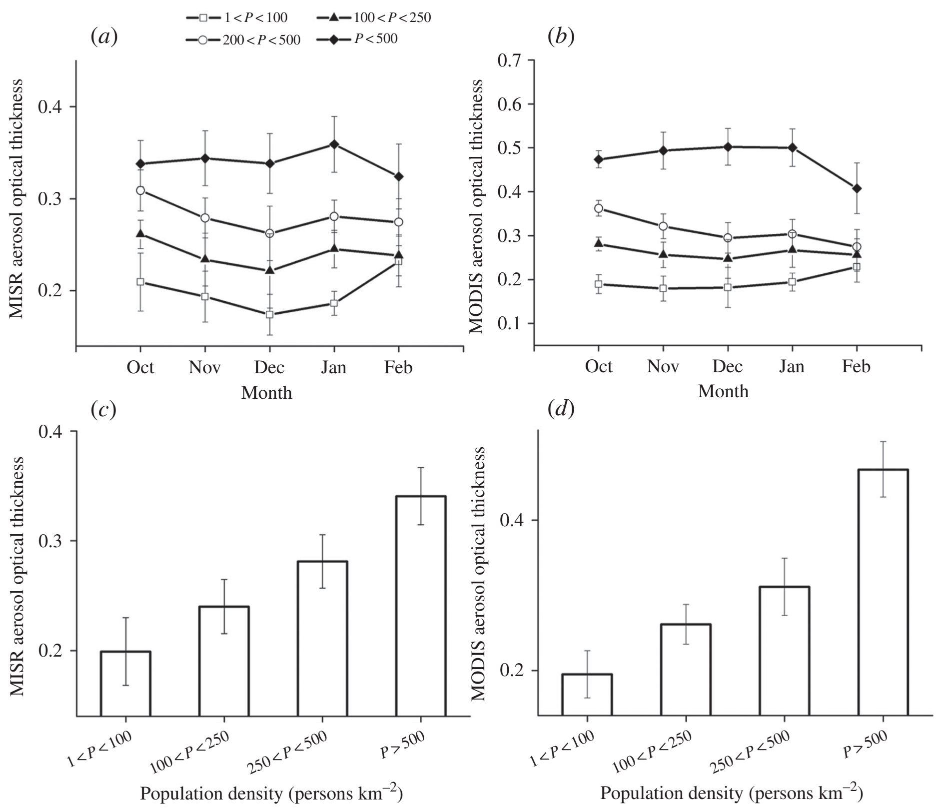

Figure 3. (*a*) and (*b*) The 8-year mean month-to-month variations, from October to February, of (*a*) Multiangle Imaging SpectroRadiometer (MISR) aerosol optical thickness (AOT) and (*b*) Moderate Resolution Imaging Spectroradiometer (MODIS) AOT averaged over the regions with differing population densities (persons km^{-2}). (*c*) and (*d*) The 8-year mean AOT averaged for the months from October to February over the regions with differing population densities, based on (*c*) MISR and (*d*) MODIS data. Standard deviation bars are shown by the *vertical* lines.

for $1 < P < 100$ persons km^{-2} to a high of 0.47 ± 0.04 (0.34 ± 0.03) for $P > 500$ persons km^{-2} (table 1). Assuming approximately the same level of natural aerosols over regions with different population densities, the AOT rise can be attributed to significant anthropogenic aerosol emissions over the highly populated areas, including megacities and main industrial centres.

In this study, the 8-year time series of MISR–MODIS AOT over the Indian subcontinent for the months from October to February, averaged over the specified population areas, was analysed with the purpose of obtaining aerosol tendencies during the whole period under consideration (figure 4). It was found that over the Indian subcontinent there was a minimum of AOT in winter 2005–2006 according to both sensors (figure 4(*a*)). Moreover, figure 4(*b*) and (*c*) represents the time series of both MODIS AOT and MISR AOT for the months from October to February, averaged over regions with differing population densities for the whole period under consideration including the winter 2005–2006. The AOT minimum in winter 2005–2006 is seen on each graph of both sensors.

Table 1. The 8-year mean aerosol optical thickness (AOT), its standard deviation (SD) and resulting trends (α), obtained from the long-term variations (March 2000 to February 2008) of AOT, averaged for the months from October to February over the regions with differing population densities (P).

P (persons km^{-2}; % of the territory)	AOT ± SD	α, (% year^{-1})	R^2	p-Value
MISR AOT				
$P \geq 1$ (93)	0.26 ± 0.02	2.2 (1.9)	0.91 (0.63)	<0.05 (<0.05)
$P \geq 500$ (16)	0.34 ± 0.03	2.2 (1.9)	0.92 (0.63)	<0.05 (<0.05)
$250 \leq P < 500$ (21)	0.28 ± 0.02	2.1 (1.9)	0.83 (0.68)	<0.05 (<0.05)
$100 \leq P < 250$ (37)	0.24 ± 0.02	2.5 (2.0)	0.89 (0.51)	<0.05 (<0.05)
$1 \leq P < 100$ (19)	0.20 ± 0.03	– (–)	0.40 (0.34)	Not significant (not significant)
MODIS AOT				
$P \geq 1$ (93)	0.31 ± 0.02	2.2 (–)	0.69 (0.31)	<0.05 (not significant)
$P \geq 500$ (16)	0.47 ± 0.04	2.3 (1.9)	0.85 (0.54)	<0.05 (<0.05)
$250 \leq P < 500$ (21)	0.31 ± 0.04	2.1 (–)	0.61 (0.33)	<0.05 (not significant)
$100 \leq P < 250$ (37)	0.26 ± 0.03	2.5 (–)	0.62 (0.22)	<0.05 (not significant)
$1 \leq P < 100$ (19)	0.19 ± 0.03	– (–)	0.19 (0.04)	Not significant (not significant)

Notes: The unit of α-values is % year^{-1} in reference to the corresponding average AOT. The coefficient of determination (R^2) and the p-values, characterizing how linear trends fit the long-term variations, are also displayed. α, R^2 and p are given without taking into account the winter 2005–2006 and (in parentheses) with this winter included.

The 8-year time series of GPCP precipitation data over the Indian subcontinent showed that the winter 2005–2006 was characterized by anomalously high precipitation (figure 4(*a*)). Figure 5 represents spatial distributions of precipitation and AOT anomalies (in %) in winter 2005–2006, in relation to their corresponding 8-year means. Figure 5(*a*) illustrates that positive precipitation anomalies up to 25–100% were observed over a significant part of the Indian subcontinent. These positive precipitation anomalies were accompanied by negative AOT anomalies over regions with differing population densities (figure 5(*b*) and (*c*)). The aforementioned anomalous precipitation in winter 2005–2006 manifests itself differently through MODIS and MISR data: MODIS AOT anomalies (up to 20–30%) (figure 5(*b*)) were more pronounced than MISR AOT anomalies (≤20%) (figure 5(*c*)). Therefore, in winter 2005–2006, MODIS AOT data were influenced more strongly than those of MISR by the anomalous precipitation.

It is reasonable to suggest that MODIS AOT trends were also affected by precipitation in winter 2005–2006 more significantly than MISR AOT trends. Indeed, as estimated, MISR-based AOT trends were mainly statistically significant, whereas the corresponding MODIS-based AOT trends were mainly insignificant (table 1). Specifically, MODIS AOT trends were only statistically significant over the highly populated region with $P \geq 500$ persons km^{-2}. This region includes the highly populated Ganges basin, where the precipitation anomalies in winter 2005–2006 were minimal (<25%) (figure 5(*a*)). A possible explanation is that MODIS provides global coverage daily, while MISR provides it only every 9 days (see §2). Because of its daily coverage, MODIS aerosol data might have been influenced more significantly than MISR data by anomalous precipitation in winter

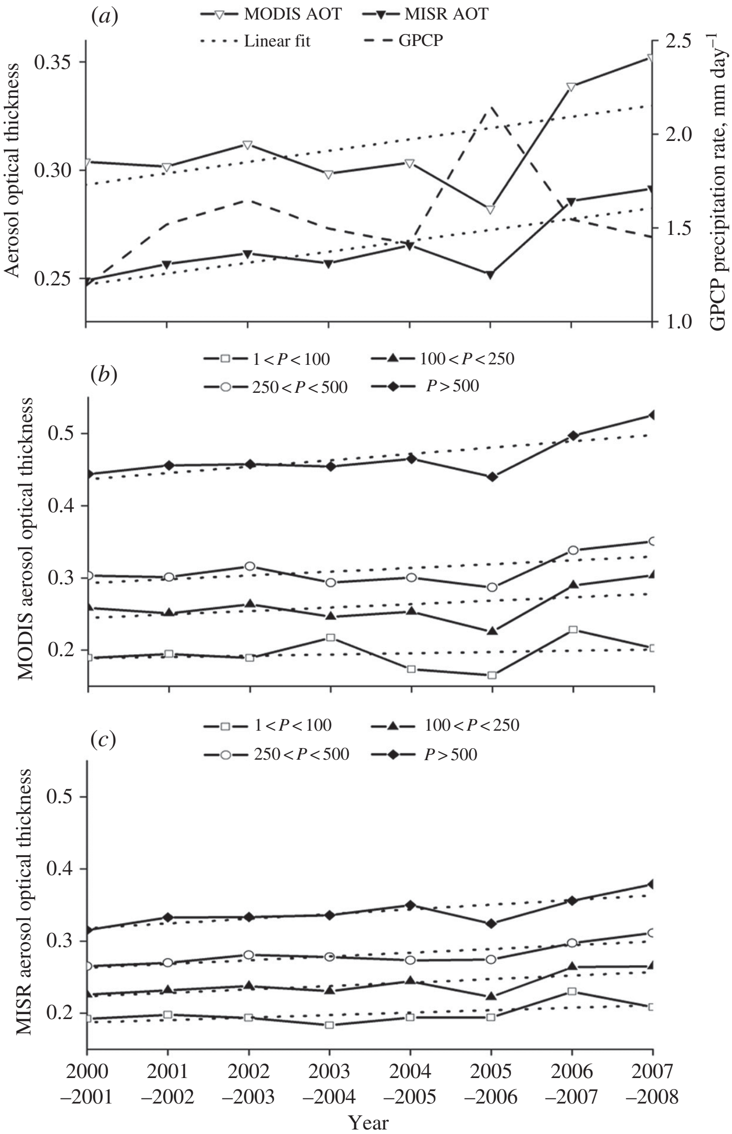

Figure 4. (*a*) The time series of aerosol optical thickness (AOT) averaged over the Indian subcontinent where $P > 1$ person km^{-2} for the months from October to February during the whole period under consideration (2000–2008), based on Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR) data. The dashed line designates the time series of GPCP precipitation rate averaged for the same months over the Indian subcontinent. (*b*) and (*c*) The time series of AOT averaged for the months from October to February over the regions with differing population densities (persons km^{-2}) (*solid lines*), based on (*b*) MODIS and (*c*) MISR data. The *dotted* lines designate linear trends.

2005–2006. For both sensors, however, the 8-year mean AOT, for the months from October to February (figure 3(*c*) and (*d*)), did not differ substantially when the data of 2005–2006 with anomalous precipitation were included or excluded.

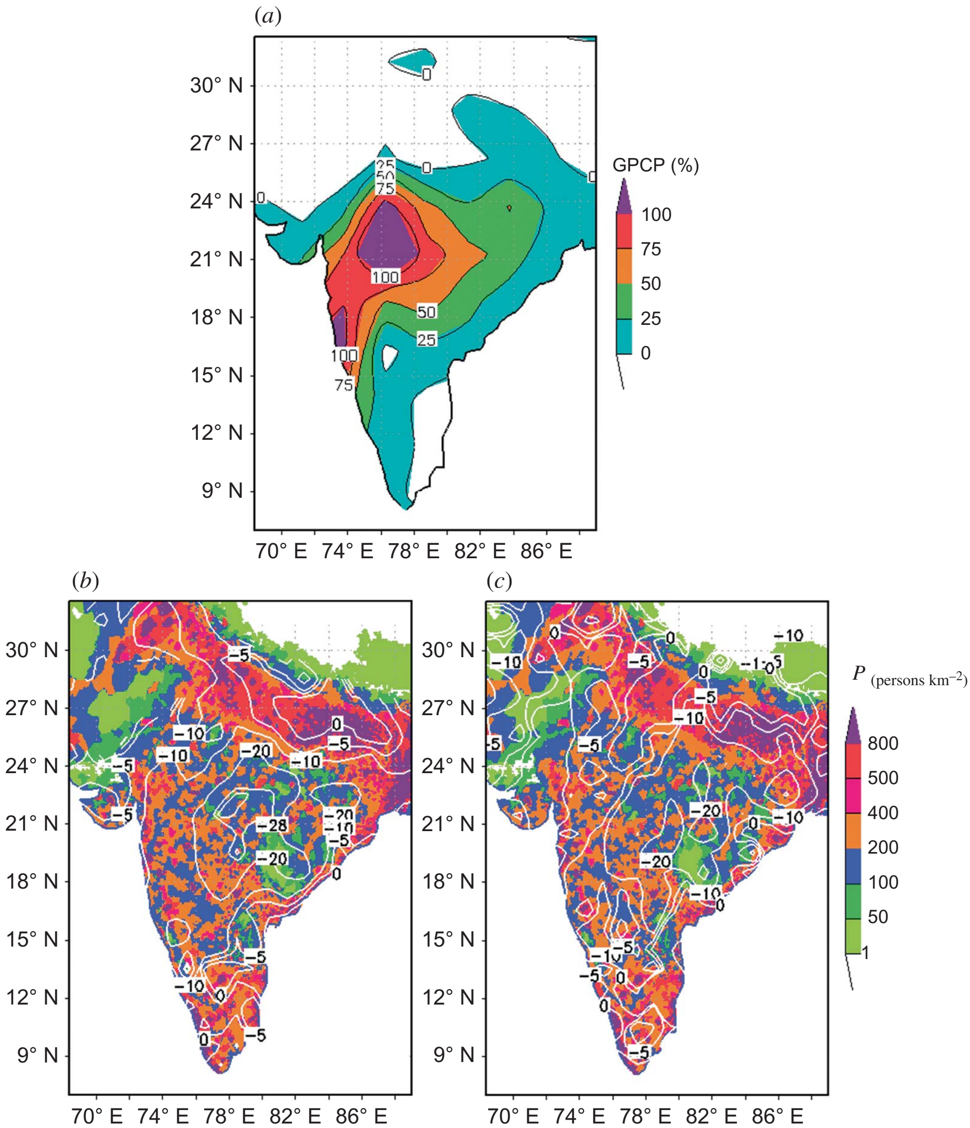

Figure 5. Spatial distributions of (*a*) GPCP precipitation anomalies and (*b*) and (*c*) aerosol optical thickness (AOT) anomalies (in %) in winter 2005–2006, in relation to their corresponding 8-year means. The AOT anomalies are based on (*b*) Moderate Resolution Imaging Spectroradiometer (MODIS) and (*c*) Multiangle Imaging SpectroRadiometer (MISR) data. In the bottom panels of (*b*) and (*c*), the colours designate population density distributions, while the contours designate AOT anomaly distributions.

Because the anomalous precipitation in winter 2005–2006 concealed the true effect of urbanization on AOT, we excluded this winter from our analysis of aerosol tendencies. After the elimination of winter 2005–2006, similar results for AOT tendencies from both sensors were obtained (table 1). Figure 6(*a*) and (*b*) represents AOT tendencies based on MODIS and MISR data after the elimination of winter 2005–2006. Significant AOT trends (over 2% year^{-1}) were observed over the Indian subcontinent

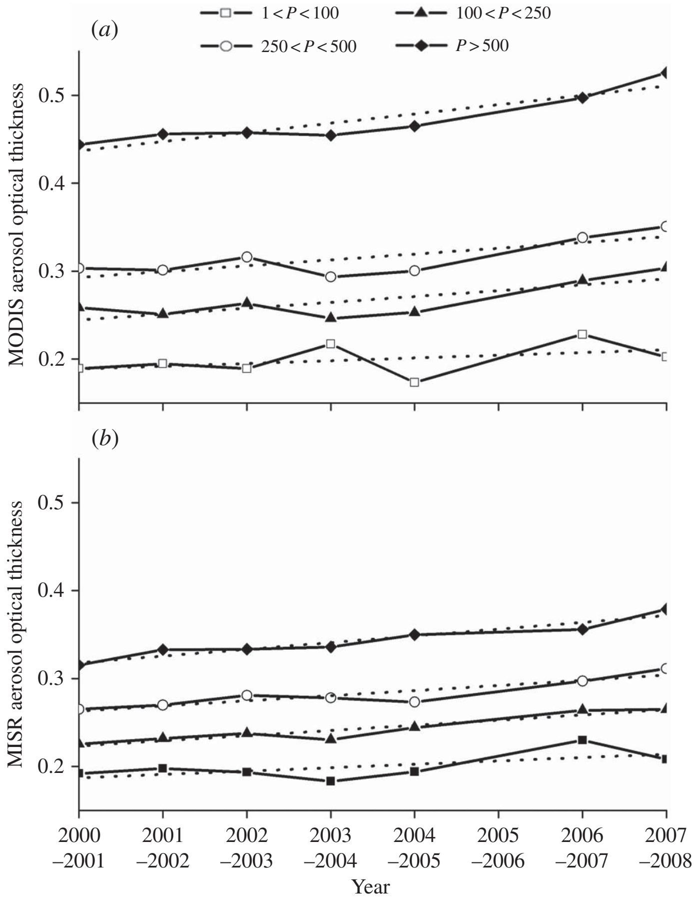

Figure 6. Time series of aerosol optical thickness (AOT) averaged for the months from October to February over the regions with differing population densities (persons km^{-2}) (*solid lines*), after the elimination of winter 2005–2006 with anomalous precipitation: (*a*) Moderate Resolution Imaging Spectroradiometer (MODIS) and (*b*) Multiangle Imaging SpectroRadiometer (MISR). The *dotted* lines designate linear trends.

where $P > 100$ persons km^{-2} (more than 70% of the territory) (table 1). Over the regions with $P > 500$ persons km^{-2}, which occupy 16% of the entire territory, including megacities with maximum industrial pollution, an increasing trend of ~2.2% year^{-1} was obtained (table 1). The mainly rural region with population densities of $100 \leq P < 250$ persons km^{-2}, which occupies more than one-third of the Indian subcontinent, was characterized by the maximum AOT trend of 2.5% year^{-1}.

In contrast to the regions with $P > 100$ persons km^{-2}, over the areas with population densities $1 \leq P < 100$ persons km^{-2} (19% of the entire territory), aerosol trends were not statistically significant. This is based on the data of both sensors (table 1) and suggests that those regions did not experience enough anthropogenic influence. This result is in line with our previous study (Kishcha *et al*. 2009), which was also based on the same 8-year (2000–2008) MODIS and MISR satellite data sets. As found in that study, AOT trends over ocean areas, remote from sources of anthropogenic aerosol emissions, were not observed.

Taking into account the aforementioned relationship between averaged AOT and population density in a particulate region, it is plausible to assume a connection between AOT trends and population density trends in that region. Indeed, over the regions with $P > 100$ persons km^{-2} (more than 70% of the territory), a population growth of ~1.5% year^{-1} was accompanied by an increasing AOT trend of over 2% year^{-1}. According to table 1, over the mainly rural region with $100 \leq P < 250$ persons km^{-2} (37% of the Indian subcontinent), an AOT trend ~ 2.5% year^{-1} was estimated, which was accompanied by a population growth of ~1.7 % year^{-1}. Over the region with $250 \leq P < 500$ persons km^{-2} (21% of the Indian subcontinent), an AOT trend of ~2.1% year^{-1} was estimated, which was accompanied by a population growth of ~1.5% year^{-1}. Over the region with $P \geq 500$ persons km^{-2} (16% of the Indian subcontinent including megacities), an AOT trend ~2.2–2.3% year^{-1} was estimated, which was accompanied by a population growth of ~1.4% year^{-1}. Therefore, the maximum AOT trend (~2.5% year^{-1}) over the mainly rural region with $100 \leq P < 250$ persons km^{-2} was accompanied by a higher population growth (1.7% year^{-1}) than the population growth in the region with $P \geq 500$ persons km^{-2}. Therefore, there is a connection between increasing AOT trends and population growth. It could be explained by the fact that a growing population needs support, such as increasing transportation, mass fuel consumption and industrial development. This results in increasing anthropogenic aerosol emissions.

4. Conclusions

Our study was aimed at quantifying the effects of urbanization on AOT connected with a high level of anthropogenic aerosols. To estimate the effect of urbanization on AOT, we used averaging over extensive territories, which are significant parts of the Indian subcontinent, with differing population densities. In the Indian subcontinent, there are sites where there is no direct relationship between population growth and AOT trends. After averaging over extensive territories, the effects of such specific sites on AOT could be local and do not contribute significantly to the total dependence of AOT on population density.

Furthermore, in our study, we removed, as much as possible, the factors which influence AOT, but do not depend on population density: these factors are natural aerosols (desert dust), the effects of cloudiness during the monsoon period on the accuracy of satellite AOT and the anomalous precipitation in winter 2005–2006 associated with increased wet removal of atmospheric aerosols. These factors interfere with determining the relationship between AOT, associated with anthropogenic activities, and population densities, and between AOT trends and population growth.

Our analysis has led us to the conclusion that, over the specified regions in the Indian subcontinent with differing population densities, (1) the higher the averaged population density the bigger the averaged AOT and (2) the larger the population growth the stronger the increasing trends in AOT.

During the season of minimal cloud presence and desert dust activity, from October to February, an increase in averaged P from dozens to several hundreds of persons km^{-2} was accompanied by an increase in averaged AOT from 0.19 to 0.47 and from 0.20 to 0.34, based on MODIS and MISR data, respectively. Similar results obtained by the two different data sets support each other. This rise in averaged AOT can be attributed to significant anthropogenic aerosol emissions over the highly populated areas, including megacities and main industrial centres.

Over the regions with $P > 100$ persons km^{-2} (more than 70% of the territory), a population growth of ~1.5% year^{-1} was accompanied by increasing AOT trends of over 2% year^{-1}. The presence of the aforementioned significant AOT trends is evidence of the current worsening air quality, in particular in the highly populated areas with $P > 500$ persons km^{-2}. The population of the Indian subcontinent is already witnessing air quality deterioration and relating health problems due to anthropogenic aerosol emissions. This situation could become even worse with the projected population growth: India will become the most populated country in the world by the year 2030 with a population of over 1.4 billion, compared with approximately 1.2 billion now (US Census Bureau).

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