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Contrasting aerosol trends over South Asia during the last decade based on MODIS observations

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Abstract

Atmospheric aerosols over south Asia constitute a major environmental and climate issue. Thus, extensive land and cruise campaigns have been conducted over the area focusing on investigating the aerosol properties and climate implications. Except from the ground-based instrumentation, several studies dealt with analyzing the aerosol properties from space, focusing mainly on the spatial distribution of the aerosol optical depth (AOD) and possible feedbacks of aerosols on the monsoon system. However, except from some works using ground-based instrumentation or satellite observations over a specific region, there is lack of studies dealing with monitoring of the aerosol trend over south Asia. The present work analyzes the variations and trends in aerosol load over south Asia using Terra-MODIS AOD_{550} data in the period 2000–2009. Overall, an increasing trend of 10.17 % in AOD is found over whole south Asia, which exhibits large spatio-temporal variation. More specifically, the AOD_{550} increasing trend is more pronounced in winter, and especially over northern India. The present study shows an evidence of a decreasing AOD_{550} trend over the densely-populated Indo-Gangetic Plains (IGP) during the period April–September, which has never been reported before. This decreasing trend is not statistically significant and leads to an AOD change of −0.01 per year in June, when the dust activity is at its maximum. The AOD decrease seems to be attributed to weakness of dust activity in the northwest of India, closely associated with expansion of the vegetated areas and increase in precipitation over the Thar desert. Similarly, GOCART simulations over south Asia show a pronounced decreasing trend in dust AOD in accordance with MODIS. However, much more analysis and longer dataset are required for establishing this evidence.

1 Introduction

Atmospheric aerosols affect in many ways the global climatic system, i.e. by attenuating the solar radiation reaching the ground, modifying the solar spectrum, re-distributing

the earth-atmosphere energy budget and influencing cloud microphysics and hydrological cycle (IPCC, 2007). Although the aerosol optical properties have now been well known, large uncertainties still occur about the aerosol climate implications, and especially the aerosol indirect effect concerning the aerosol-cloud interactions, the changing in cloud microphysical properties, the re-distribution of the cloudiness and the modification of the hydrological cycle (Rosenfeld et al., 2008). Despite the great progress that has been achieved in the current knowledge about atmospheric aerosols via the systematic ground-based and satellite observations, the uncertainties in their direct and indirect effects still exist, mainly due to the variety of the aerosol types, the changing optical and physico-chemical properties, the influence of dynamic and synoptic meteorology and the mixing (internal and external) processes in the atmosphere (Satheesh and Moorthy, 2005).

Atmospheric aerosols have been recognized to constitute a vital parameter in climate change studies over south Asia that examine fluctuations in atmospheric temperature (e.g. Lau et al., 2006; Gautam et al., 2009a), radiative forcing (e.g. Ramachandran and Kedia, 2010; Satheesh et al., 2010) snow and ice-cover (e.g. Prasad and Singh, 2007), precipitation re-distribution (e.g. Prasad et al., 2007; Sarkar et al., 2007), frequency and intensity of tropical cyclones (e.g. Badarinath et al., 2009) and desertification (e.g. Prospero et al., 2002). Different types of aerosol are found over the Indian sub-continent, i.e. anthropogenic aerosols from the urban centers, biomass burning from seasonal forest fires or crop residue burning especially in the north-western part of India (Vadrevu et al., 2011), desert dust produced in the Thar desert or transported from the Arabia peninsula and marine aerosols from the surrounding oceans during the southwest summer monsoon (Dey et al., 2004; Ganguly et al., 2006a; Kaskaoutis et al., 2009). Due to large diversity in population density, regional emissions, land use and seasonally-changed air masses, the aerosol load, optical properties and their climate implications present large variations over India, both spatially and temporally (Lawrence and Lelieveld, 2010).

With the increase in population, urbanization, industrialization and demands for energy, the aerosol load in south Asia is gradually increasing having significant impact on continuation of solar dimming (Ohmura, 2009; Badarinath et al., 2010). Both ground-based measurements and satellite observations agree to an overall increase in AOD over the area (e.g. Massie et al., 2004; Sagar et al., 2006; Prasad and Singh 2007; Ramachandran and Cherian, 2008; Kharol et al., 2011). The increasing aerosol emissions, mainly from anthropogenic activities, are responsible for the presence of the atmospheric brown clouds (Ramanathan et al., 2005, 2007), which have significant climate implications in view of heating the middle and upper troposphere (Menon et al., 2002; Gautam et al., 2010). Sarkar et al. (2006) reported statistically significant increasing trends in AI over all major cities located in northern India during the period 1982–1993, while over the same region the aerosol radiative forcing (ARF) at the surface was much more negative from that observed over central and south India due to larger AOD and higher concentrations of absorbing aerosols. Prasad and Singh (2007) analyzed the AOD trends from MODIS, MISR and AERONET (at Kanpur) over five urban locations in northern India and found increasing trends in AOD on annual basis during the period 2000–2005. Ramachandran and Cherian (2008) analyzed the MODIS-AOD variations and trends over 35 locations spread uniformly over India and reported increasing trends in the yearly-mean AODs over all sites during the period 2001–2005. However, in the aforementioned studies there is lack of analysis of the monthly and/or seasonal trends of AOD over the different areas. More recently, Dey and Di Girolamo (2010) using MISR data over south Asia analyzed the seasonal differences in AOD and in anthropogenic and natural aerosol contributions, while Kharol et al. (2011) reported statistically significant aerosol increase (~20–34 %) over Hyderabad (2002–2008) detected both by ground based measurements and MODIS observations; however, the rainy monsoon season was not included in the analysis. Kishcha et al. (2011) found that the largest AOD increase is observed over the most densely populated areas over India, highlighting a ~2 % increase in AOD for regions with population density above 100 persons per km^2.

A detailed analysis of spatial distribution of the AOD trends over south Asia on monthly, or even on seasonal basis has not been carried out. Such studies are required to understand the nature of aerosols, monthly and seasonal dynamics of aerosols and their impact on the climate change. The present study aims to report the results of the spatial distribution of AOD trends over south Asia during the last decade (2000–2009), focusing mainly on specific regions, i.e. Arabian Sea (AS), Bay of Bengal (BoB), Northern Indian Ocean (NIO) and Indo-Gangetic Plains (IGP). The analysis is made on monthly basis basically using Terra-MODIS data and emphasizing further on AOD variations and trends over IGP, where a decreasing trend in AOD is found during late pre-monsoon and monsoon seasons. This decreasing trend is associated with land use/land cover changes over Thar desert, variations in precipitation and a general attenuation in the dust activity over south Asia as detected from GOCART simulations.

2 Data set and study regions

The main dataset used in the present study consists of Terra-MODIS AOD$_{550}$ observations over south Asia covering the period 2000–2009 on a monthly basis. The AOD$_{550}$ data used are from collection 5 (C005) Level 3 (1° × 1°) following the dark-target approach for aerosol retrievals over vegetated and oceanic surfaces with lack of data over the deserts (Levy et al., 2007). The spatio-temporal resolution of the dataset used is satisfactory for the scope of the study which is the climatology and variation of AOD over south Asia during the last decade. Numerous studies have been conducted over the globe aiming for validation of the MODIS data with ground-based sun photometers and other satellite sensors; satisfactory agreement between MODIS and AERONET AODs over Kanpur, India was found in several earlier publications (Jethva et al., 2007; Prasad and Singh, 2007; Ramachandran, 2007), thus rendering the satellite observations reliable for the aerosol monitoring over the area.

The Indian sub-continent exhibits a diverse topography with large variability in vegetation cover, ranging from the desert regions in the northwest to arid areas in the central-south and to dense vegetated areas along the southwestern coast and the northeastern part. More details concerning the climatology, land use, industrialization and aerosol emissions for different areas in India can be found elsewhere (Ramachandran and Cherian, 2008; Lawrence and Lelieveld, 2010). As far as the present analysis is concerned, the study region is defined by the co-ordinates 0–30° N and 58–95° E, including the Indian sub-continent (except the northernmost part), the AS, BoB and NIO. Since the analysis focuses on 4 specific regions with different weather conditions, aerosol characteristics and influences are discussed region wise.

2.1 Arabian Sea

In the present study, the AS is defined by the oceanic pixels above 8° N and west 67° E bounded by the Arabian peninsula in the northwest, Iran and Pakistan in the north and the western Indian coast in the east. The south-to-north movement of the Inter-Tropical Convergence Zone (ITCZ) mainly controls the meteorological and weather conditions over the area (Krishnamurthi et al., 1998). The AS is strong influenced by the local monsoon system, especially in summer when strong southwestern marine winds in the lower troposphere blow towards Indian mainland, while in the middle and upper troposphere westerlies bring large amounts of dust over the AS. The aerosol field over the area has been extensively investigated during several cruise campaigns (e.g. Indian Ocean Experiment, INDOEX; Arabian Sea Monsoon Experiment, ARMEX; Integration Campaign for Aerosols, gases and Radiation Budget, ICARB) which focused on region-specific characterization of the aerosol properties. Results from these campaigns have shown large amounts of wind-blown dust and anthropogenically-produced aerosols transported from the Asian landmass (e.g. Ramanathan et al., 2001; Moorthy et al., 2005; Kalapureddy et al., 2009; Kaskaoutis et al., 2010). Radiative forcing studies (Satheesh et al., 2006) have shown large attenuation of solar radiation in the surface and a negative (cooling effect) in the top of the atmosphere.

2.2 Bay of Bengal

The BoB has a unique weather pattern in terms of the Indian monsoon, being also under the influence of tropical cyclones (Badarinath et al., 2009). The region is surrounded by densely populated and industrialized regions from north, west and east, BoB provides an excellent environment for investigation of marine and continental aerosols, since pristine air masses from southern Indian Ocean and polluted air from the Indian sub-continent meet. The continental aerosols transported over BoB are of various origins (sea-salt production, dust particles, fossil-fuel combustion, biomass burning) and chemical compositions (e.g. Kumar et al., 2010), also present variable optical properties in spatial and temporal domains (e.g. Kaskaoutis et al., 2011). The western and northern BoB are strongly affected by the Indian landmass, while the eastern part is under the influence of the southeast Asia (Sinha et al., 2011). Some short term cruises (Ramachandran and Jayaraman, 2003; Vinoj et al., 2004; Ganguly et al., 2005) have been carried out in BoB focusing mainly in aerosols and pollutants in coastal waters, until ICARB (Moorthy et al., 2008) and W-ICARB (Raghavendra Kumar et al., 2011) explored the region in more detail during pre-monsoon and winter seasons, respectively. In the following, the BoB is defined as the oceanic area east from 80° E and north from 8° N.

2.3 Northern Indian Ocean

The aerosols over the NIO have initially been investigated in the framework of INDOEX (Ramanathan et al., 2001; Satheesh et al., 2002) and in some cruises starting from southern India to the premises of Antarctica (Vinoj et al., 2007). More recently, ICARB and W-ICARB campaigns also focused on aerosol field in parts of NIO, around 3° N. The oceanic region is characterized by more transparent atmospheric conditions, where the ITCZ plays a major role in long-range aerosol transport from Indian mainland. Although, the AOD is, in general, below 0.25, a large anthropogenic component was found over the northern parts of the NIO (Nair et al., 2010). In the present study, we have considered the NIO as the whole oceanic area south of 8° N.

2.4 Indo-Gangetic Plains

The northern part of India is crossed by the Ganges river; on the north side the region is surrounded by the towering Himalaya, the Thar desert in the west, Vindhayan hill in the south and the Bay of Bengal in the east. This area is known as Indo-Gangetic Plains (IGP) accounting for ~21 % of the land area of the Indian sub-continent and holding nearly 40 % of the total population (Badarinath et al., 2011). During the winter season, the area suffers from severe fog and haze conditions causing pollution smog environment, which was first time observed by the ADEOS POLDER satellite (Goloub et al., 2001). Numerous studies during the last decade examined the aerosol load and optical properties over the IGP focusing mainly in the winter season, due to foggy conditions and large black carbon (BC) concentrations, and pre-monsoon and early monsoon due to frequent dust outbreaks from the Thar desert (Dey et al., 2004; Singh et al., 2004; Jethva et al., 2005; Ganguly et al., 2006b; Ramachandran et al., 2006; Prasad et al., 2004, 2006, 2007; Das et al., 2008; Gautam et al., 2009a, b). Several industries and thermal power plants are located in the IGP contributing to significant aerosol and pollution emissions (Reddy and Venkataraman, 2002; Prasad et al., 2006; Singh, 2011). We have considered IGP area bounded by 21.5–30° N and 74–91° E, excluding the pixels over Nepal and Himalaya in the analysis.

3 Results and discussion

3.1 Seasonal variation of the AOD_{550} over south Asia

In this section a description regarding the aerosol field over south Asia based on MODIS observations during the period 2000–2009 is given. Figure 1 shows the monthly mean AOD_{550} spatial distribution over south Asia during the last decade for four representative months. The AOD seasonality, despite some differences observed from region-to-region, in general, exhibits an annual pattern of lower values during post-monsoon and winter and higher during pre-monsoon and monsoon, depending on the location. All studies conducted over the area show larger BC concentrations and

the presence of anthropogenic aerosols during winter season. Anthropogenic aerosols are the dominant type over south Asia since they contribute about 70–80 % to the total AOD (Chung et al., 2005), being also the dominant type both over urban locations (Kaskaoutis et al., 2009) and downwind oceanic areas (Ramachandran et al., 2004). In rural and agricultural areas the fine-mode aerosols mainly originate from burning of bio-fuels, while in urban areas from fossil-fuel combustion.

In the month of January, during peak winter season, a narrow belt of very large AOD is observed along the IGP, mainly over its eastern part, also influencing the western and the northern BoB. Pronounced continental influence is seen along the coastal AS, while northern AS, NIO and southern India exhibit AOD_{550} values below 0.2. In April the AOD is gradually increasing over continental India and adjoining oceanic areas, with an evidence of decrease in the eastern IGP. From April onwards the dust activity over the northwestern arid regions starts (note the large AOD over Pakistan) spreading dust aerosols over the northern and central parts of India (e.g. Dey et al., 2004; El-Askary et al., 2006); the dust activity is strengthened and shifts towards north AS during the monsoon season, while the Indian landmass is under the influence of oceanic air masses. Long-range dust transport from the Arabian peninsula and the Middle East in the middle and upper troposphere (up to 5 km, Gautam et al., 2010) consist a significant contribution to the high AOD over central-north AS and western India in July relative to the other months. In October, the dust activity disappears and the AOD range is observed similar to the range observed during January and April. The main characteristic is the increased AOD over the northwestern IGP in the month of October associated with crop residue burning (Sharma et al., 2010). However, apart from the large aerosol emissions produced over Indian mainland, trans-boundary aerosol and pollution transport from southeast Asia and Middle East also affects the study region. More detailed analysis of the seasonal mean AOD spatial distribution over the area is given by Dey and Di Girolamo (2010) using MISR data, which follows the pattern of MODIS-AOD spatial distribution.

Figure 2 presents the annual variation of AOD_{550} in box chart view over the four distinct areas in south Asia revealing, except from the monthly mean and median values, the 25 % and 75 % percentiles as well as the spread of the AOD_{550} distribution. AS presents a pronounced annual variation in AOD_{550} with increased values during June-August. Although the spatial and temporal variability is very large during the monsoon, in post-monsoon and winter seasons, the AOD_{550} is about 0.22 representing a rather homogeneous atmosphere. The mean AOD_{550} (0.35 ± 0.17) is larger than that found over BoB (0.30 ± 0.08), although ICARB and other previous cruise campaigns reported larger AODs over BoB compared to AS. The larger AOD over AS is attributed to the very high values during the monsoon season, since the area is under the influence of the arid regions in the west and north, whereas such an influence is very limited over BoB. However, during the winter season and March-April when the W-ICARB and ICARB campaigns took place, the MODIS-AOD_{550} over BoB is higher. There is also a shift in the maximum monthly AOD_{550} over BoB observed during May–June, while the spread of the data and the annual variation are significantly lower than those over AS. The most transparent and homogeneous area is NIO (mean $AOD_{550} = 0.18 \pm 0.03$), also presenting the lowest annual variability. The latter is mainly controlled by long-range aerosol transport, i.e. dust particles from the west in May-July and continental outflows in the winter, when the anthropogenic contribution over NIO was found to be 80 ± 10 % (Ramanathan et al., 2001). The large amount of anthropogenic aerosols during the winter season, in combination with dust aerosols during April–July and crop-residue burning in post-monsoon, cause high AOD_{550} values (0.50 ± 0.15) throughout the year over IGP. Both dust and biomass burning have a pronounced signal in AI over the area, especially in the dry season when their atmospheric lifetime is larger (Habib et al., 2006). Aerosols over IGP undergo a pronounced annual variation in both load and type with very large AODs (mean ∼0.7) in May–July (dust aerosols mixed with anthropogenic ones) and moderate-to-high AOD (∼0.4–0.45) during the winter season (anthropogenic aerosols and BC).

The IGP has been well recognized to constitute the main anthropogenic-pollution aerosol source region in India (Di Girolamo et al., 2004; Eck et al., 2010; Lawrence and Lelieveld, 2010; Giles et al., 2011). Under favorable wind conditions the aerosols are spreading over the whole Indian mainland, surrounding oceans and the foothills of the Himalaya. To this respect, Fig. 3 shows the correlation of the monthly-mean area-averaged AOD_{550} between IGP and the three oceanic regions. The correlation is statistically significant regarding the co-variance between AODs over IGP and BoB, since the latter is in the downwind region of aerosol outflow especially in winter and early pre-monsoon (Nair et al., 2009; Moorthy et al., 2010). It should be noted that considering as BoB the oceanic region north of 15° the R^2 value goes up to 0.75. On the other hand, pronounced positive correlation is shown between IGP and AS, but with lower coefficient of determination. Note that in some months (monsoon period) the AODs over AS are larger, directly influenced by dust outflow from Arabia and Middle East and not from aerosols coming from IGP; AS is in the downwind region of western IGP mainly in post-monsoon and winter. Finally, the aerosol field over NIO does not seem to be influenced by IGP aerosols on monthly basis. The slight positive correlation is attributed to the co-variance of the annual AOD pattern (Fig. 2), but the larger AODs over NIO in monsoon are mainly controlled by marine particles and air masses coming from the west. However, for establishing the IGP effect in controlling the aerosol variations over various locations in south Asia the analysis has to be carried out on daily basis examining the air-mass trajectories, over Himalaya (Gobbi et al., 2010), northeastern India (Pathak et al., 2010; Gogoi et al., 2011), BoB (Moorthy et al., 2003) and AS (Vinoj et al., 2010).

3.2 Temporal variation and trend of AOD_{550} over south Asia in the last decade

In this section the decadal (2000–2009) changes in MODIS-AOD_{550} values over south Asia are examined. The AOD variation is quantified via the slope values of the linear regressions and the (%) differences in AOD on monthly basis. The spatial distribution (1° × 1° resolution) of the slope values is shown in Fig. 4. During the winter months

(December to February) a pronounced increasing trend in AOD_{550} is observed over south Asia, especially over the Indian mainland and IGP, while over NIO and the southern parts of BoB and AS the trend is rather neutral. The increasing aerosol load over northern India seems to affect the northern BoB and eastern coastal AS due to increased outflows. The overall increasing trend in the region is reported by many as cited in the introduction. On the other hand, a slight statistically insignificant decreasing trend in AOD_{550} (-0.01 per year, or even less) is observed over southwestern India in January, which must be examined from ground-based instruments for defining its reliability.

In March the trend starts changing; either similar or even slight by declining AOD trends are observed over northwestern India, NIO and southern BoB. On the other hand, the increasing AOD trend remains over eastern IGP, Bangladesh and northern BoB. In April, the situation is significantly changed with the AS exhibiting on increasing trend, while central and northern India constant or declining trend. A reliable explanation about this feature is rather difficult to be established taking also into account the reverse situation in May (neutral or slight decreasing trend over AS and increasing over BoB). Thus, to attribute the increase in AOD over AS in April to enhancement in dust activity over the Arabia peninsula may be not the real scenario, since in May the AOD trend is negative over the same region. Similarly, the increasing AOD over BoB in May cannot be attributed to increased emissions from IGP (the results show decreasing trends), and changes in other aerosol sources must be examined, i.e. biomass burning in southeast Asia. Examining the yearly variation of the area-averaged values (not shown), we found that over AS in April the mean AOD_{550} was nearly steady to ~0.275 during the period 2000–2006, while in 2007–2009 the AOD_{550} increased to 0.35–0.4, thus leading to the increasing trend. Similarly, the pronounced increasing AOD trend over the whole BoB in May is controlled by the increased area-averaged value (0.6) in May 2008 against the mean of 0.4 for this month during the period 2000–2009. This suggests that the spatial distribution of the AOD trends are strongly influenced by yearly variations and, therefore, the results (Fig. 4) can be assumed rather qualitative and not

quantitative. On the other hand, a longer period must be considered for such analysis and the MODIS retrievals have to be compared with ground-based measurements in order to examine any agreement or disagreement in the spatial distributions presented here.

In monsoon months (June–September) the spatial distribution of the slope presents large deviations from region-to-region (for areas above 15° N), and it is difficult to conclude about the trend. Furthermore, the AOD trends are much more intense than the rest of the year. This may be attributed to the extensive cloud cover in this season reducing the number of valid MODIS observations and leading to sharper spatio-temporal variation. Quite interesting is the pronounced increasing AOD trend over AS in June and the decreasing one over coastal western India. This can be partly explained by large variations in cloudiness and precipitation over western India, where the rainfall monsoon season starts in the beginning of June (Kishcha et al., 2011). Northwestern India is affected by monsoon by the end of June, and as a consequence, the MODIS retrievals in July and August are limited due to extensive cloudiness. So, there is possibility of lack of data in some years over specific pixels in this area leading to the observed complicated pattern as regards the AOD trends. Similar feature is shown over central India and the northern BoB attributed to the same reason. The observed trends, even over specific locations, are difficult to be verified using ground-based sun-photometers due to extensive cloudiness in this season, suggesting the use of longer-term satellite observations as absolutely necessary. Nevertheless, an overall decreasing trend in AOD is observed over IGP in the monsoon months.

In post-monsoon months (October–November), the spatial distribution shows neutral-to-increasing AOD trends over the oceanic regions, which are larger over the coastal BoB and the AS in October. The slightly decreasing AOD trend over IGP in October shifts to increasing in northwestern parts of this region in November, probably due to increased biomass-burning activities. An indication for the latter is the increasing CO and NO_2 emissions over Punjab state, an agricultural area in northwestern India, during the last years (not shown).

Figure 5a shows the monthly mean variation and trends of the area-averaged AOD_{550} over the four sub-regions during the period 2000–2009. Significant annual and year-to-year variations are observed especially over IGP and AS directly influenced by the dust activity during May–July. Gautam et al. (2009c) found that dust frequency and intensity during pre-monsoon over northern India depend on rainfall amount, soil moisture, wind speed and monsoon onset. Thus, during the weak monsoon years (2002, 2004, 2008) the dust activities were higher, thus the aerosol loading was higher over northern AS and IGP; the AOD peak was observed during May–July of 2008 compared to 2007, which was a normal year (Gautam et al., 2009c). The AOD_{550} trends obtained from the linear regression of the monthly-mean values reveal a large increase of about 20.9 % over AS and 22.1 % over BoB, while the increase over NIO seems to be low (5.2 %). In contrast, Kishcha et al. (2009) using MODIS and MISR data for the period 2000–2008 do not find any significant AOD trend over the oceanic regions if the anthropogenic sources are far away. Very surprisingly and opposite to the general thought, the MODIS data show a negligible AOD trend over IGP on annual basis, attributed to the decreasing trend in late pre-monsoon and monsoon (Fig. 4). The majority of the published works limited the examined period to 2000–2005 and analyzed the AOD trends on annual basis or only in the winter period. Due to lack of AOD trend studies over BoB and AS it is not possible to compare the presented results.

The AOD_{550} variation regarding the whole south Asia shows an increase of ∼10.17 % (Fig. 5b), which is considered one of the largest AOD increasing trends over the globe (Mishchenko et al., 2009). This increase is believed to be mainly due to increase in anthropogenic aerosols, since Novakov et al. (2003) reported increasing soot and sulfate aerosols as well as greenhouse gases over India since the 1930s, Ramanathan et al. (2007) estimated a mean tropospheric (<5 km) warming rate of 0.24 °C/decade over the Himalayan region from 1950s. Figure 5b shows the monthly variation of the slope values (*100) (lower panel) and the respective AOD_{550} (%) variation (upper panel) in the whole south Asia. As we earlier noted these values may be considered rather qualitative and not quantitative, since large deviation in the monthly values may occur

depending on the yearly AOD variation. It was found that the trends are statistically significant at 95 % level showing AOD variations up to ∼20 %. Figure 5b shows pronounced increase (>20 %) in AOD_{550} values during winter, while a slight decrease is observed in August and September although not statistically significant.

The trends and (%) variations are much more sensitive to yearly AOD fluctuations when the study area is limited (Fig. 6). This is the case for the period April-July over AS and for May and October over BoB as shown in Fig. 4. On the other hand, both oceanic regions show increasing AOD_{550} trends throughout the year, which are more intense during the winter season, as also observed over NIO. NIO shows large monthly deviations in slope values and % variations, not allowing any safe conclusion except from post-monsoon and winter. Very contrasting AOD trends are observed over IGP during winter and monsoon. Thus, the following section focuses on AOD variations and trends over IGP aiming at giving some explanations about the observed decreasing trend in monsoon.

Since the slope values in the linear regressions and the % differences in AODs are strongly dependent on the yearly AOD variation, the AOD_{550} over south Asia is obtained for two periods 2000–2005 and 2006–2009 in order to reduce the sensitivity of the trends on the yearly AOD variation. Three seasons were considered for analyzing the AOD differences, (i) winter (January–February), (ii) summer (April–June) and, (iii) rainy season (July–September). The mean AOD_{550} over each region in the two periods as well as the differences (ΔAOD_{550}) are summarized in Table 1 for the three seasons considered. The oceanic regions show increased AOD_{550} during the second half of 2000s, which can be up to 0.05 over AS (rainy season) and BoB (winter) corresponding to differences of 10–15 %. Statistically significant increase in AOD_{550} over NIO is observed only in the winter season, while IGP shows large deviation in AOD_{550} variation, where the increase of 16.5 % during the winter season reverses to −17.1 % in the rainy season. However, the mean ΔAOD values during summer and rainy seasons are associated with large standard deviations and must be considered as qualitative.

3.3 AOD_{550} variations and trends over IGP

Initially, we start the analysis of AOD over IGP by showing the longitudinal variation of the latitude-averaged AOD_{550} values on monthly basis (Fig. 7). During winter season a pronounced eastwards increasing AOD is observed highlighting the topographic low eastern IGP as the most aerosol-laden region in the south Asia. Di Girolamo et al. (2004) characterized this region as "the Bihar pollution pool" strongly influencing the aerosol load and properties over the northern BoB. Pre-monsoon seems to be a transition season since in March and April the situation is somewhat similar to that during winter season whereas in the month of May the variation in AOD shows a neutral pattern. The northern part of India has been recognized to be influenced by seasonal (pre-monsoon and monsoon) dust transport from the Thar desert (Singh et al., 2005) strongly affecting the AOD values and variations. This is evident from the large standard deviations during the May–July period where dust activity is at its maximum. The larger AODs in western IGP in late pre-monsoon and early monsoon are attributed to the dust transport vertically distributed up to 4–5 km influencing the aerosol properties over the Himalayas (Gobbi et al., 2010; Duchi et al., 2011). During the post-monsoon months, the AOD longitudinal variation is rather constant showing larger AOD in the western part in October attributed to extensive crop residue burning in the northwestern IGP (Sharma et al., 2010), while by the end of the post-monsoon the AOD over the eastern IGP again increases.

The analysis of the longitudinal variation of the AOD trends over the IGP during the last decade is shown in Fig. 8. The increasing trend of positive values (increase in AOD) towards eastern IGP in winter season (Kar et al., 2010) suggests that the aerosols over this area, except of the large values, exhibit the largest increasing trend over the whole south Asia, thus enhancing further the "Bihar pollution pool". A similar trend is observed in March, while from April onwards evidence of decreasing AOD is observed, especially for latitudes western from the 80° E. During May and monsoon months, the AOD trend is always negative, while in view of the large standard deviations

it is difficult to conclude the trend of the longitudinal variation of the slope values. However, in general, the western part of the region along the longitudes exhibits larger negative values indicating the overall pronounced decreasing AOD trend.

Figure 9 shows the yearly AOD_{550} trends during the winter and summer seasons over four cities located in IGP from northwest to southeast, Amritsar to Kolkata, respectively. These locations closely follow the main pattern in the AOD trend along longitude (Figs. 7 and 8), since the increasing AOD during the winter is more pronounced in the east (Kolkata), while the respective decrease in the summer is much more intense in the west (Amritsar). Decreasing AOD trends over specific locations in IGP during pre-monsoon and monsoon seasons have never been noticed, even using Kanpur AERONET data. The contrasting trends in AOD between these seasons result in vanishing of AOD seasonality by the end of the 2000s, a feature that has never been investigated over IGP. Thus, such analysis of the data observed at the Kanpur AERONET station operating since 2001 will constitute a real challenge, also aiming to justify the MODIS results.

3.4 Reasons for the declining AOD over IGP

The larger AODs in the western IGP in April–August and the neighboring Thar desert suggest that the AOD over the area is mainly composed of dust particles during this period. This was also the result of numerous studies performed over northwestern India (e.g. Ganguly et al., 2006b; Kedia and Ramachandran, 2011). Therefore, any AOD variation during pre-monsoon and monsoon months may be related mainly to variation in dust load (Gautam et al., 2009c); the decreasing AOD trend presumes attenuation in dust frequency or intensity, which may be attributed to land use/land cover changes over the Thar desert, variation in soil moisture and/or changes in weather conditions and precipitation.

Land use/land cover changes have been recognized to affect the atmospheric dynamics as well as cloudiness, cloud properties and precipitation (Ray et al., 2006; Douglas et al., 2009). The construction of an irrigation canal carrying water to the desert (western) and semi-arid (eastern) Rajastan State (northwestern India) resulted in increasing essentially the vegetated areas, the crop production and, subsequently, the economic development (Pandya et al., 2004). The irrigation facility provided by the "Indira Gandhi Canal" has transformed the deserts in to green and greenery and changed the feature of Rajasthan's desert. The analysis of LANDSAT MSS and IRS-P6 AWiFS satellite data sets over Rajasthan (paper under preparation) shows that the crop area has increased by ~57 % and ~68 % in eastern and western Rajasthan during the period 1972–1973 to 2006–2007. Douglas et al. (2006) analyzed the changes in water-vapor and energy fluxes between a pre-agricultural and a contemporary agricultural area in India and found 17 % increase in mean annual water-vapor fluxes with an increase in rainfall of 7 % during the period July–December and 55 % during January–May, indicating a pronounced influence of agriculture on atmospheric moisture and energy fluxes. The expansion of the vegetated areas in Rajasthan has a direct effect on relative humidity and soil moisture over the area and a negative feedback in dust activity. The opposite was found to occur over sub-Sahel savanna, where the drought conditions have expanded the desert areas with a linkage to increasing dust outflow and loading (Engelstaedter et al., 2006).

Figure 10 shows the rainfall amount (a) and the total number of rainy days (b) during the period April–September 1997–2007 over western and eastern Rajastan. The precipitation amount consists of daily gridded rainfall data at 1° × 1° spatial resolution obtained from the Indian Meteorological Department (IMD) (Rajeevan et al., 2006). The IMD product uses gauge data from 1803 stations to estimate daily accumulated rainfall; the Shepard (1968) interpolation technique was used for gridding data from individual stations over the Indian sub-continent (6.5° N to 37.5° N, 66.5° E to 101.5° E). The gridded daily rainfall data over Rajasthan were analyzed to identify the number of rainfall days for each year, which were detected as the days with rainfall amount above "0". Both the rainfall amount and total number of rainy days present an increasing trend over eastern and western Rajasthan, especially during the period 2000–2007 (MODIS observations), maybe as a consequence of the increase in vegetation cover

and atmospheric moisture. The results show that the increasing trends are more pronounced over western Rajasthan which is located well within the Thar desert. It was also found (not presented) that the expansion of the crop areas was also larger over western Rajasthan limiting the dust source regions.

On the other hand, the role of aerosols in the rainfall variability over northern India cannot be ignored, since Gautam et al. (2010) have shown that the radiative heating by absorbing aerosols over IGP may accelerate the pre-monsoon warming and influence the evolution of summer monsoon. Furthermore, modeling studies have suggested the importance of absorbing aerosols in modulating the rainfall re-distribution (Randles and Ramaswamy, 2008). However, the dust activity over IGP can partly be controlled by the changes in land use/land cover over Thar desert and/or changes in precipitation, since the dust source regions that affect northern India are extended further to west, in the Arabian Peninsula and Middle East (Prospero et al., 2002). The dust activity over the region is also controlled by the intensity of the monsoon, synoptic meteorology and wind field. To this respect, the AOD over AS does not follow the decreasing trend found over IGP during May–August. However, IGP is mainly influenced by the Thar desert, while AS is in the downwind region of the Iran-Pakistan dust outflows (Levar winds) and the Arabian peninsula.

3.5 GOCART simulations

The aerosol and dust simulations from Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model are obtained over south Asia during 2000–2007 for the months April–September when the dust activity is at its maximum and a decreasing trend in the AOD over northern India was observed. In the GOCART simulations south Asia corresponds to a greater area including the Iranian and Pakistan deserts as well as the Arabian peninsula. Earlier studies (Chin et al., 2002, 2004; Yu et al., 2003) have shown considerable consistency between GOCART simulations and observations (i.e. AERONET, MODIS) over the globe, while recently Chin et al. (2009) analyzed the GOCART simulations and AERONET retrievals over Kanpur showing satisfactory regarding the aerosol properties. The GOCART simulations of the total and dust AOD_{550} obtained via Giovanni (http://disc.sci.gsfc.nasa.gov/giovanni) are used in the present study with a spatial resolution of $2^\circ \times 2.5^\circ$. Detailed information about aerosol types included in the GOCART simulations, emission inventories, errors and uncertainties in the simulations can be found elsewhere (Chin et al., 2009).

Figure 11 shows the GOCART simulations of the monthly variation of the total and dust AOD_{550} (lower panel) and of the dust contribution (%) to the total AOD_{550} (upper panel) for the months April to September covering the period 2000–2007. The monthly values correspond to the area (4–35° N, 45–95° E) and the linear regressions as well as the % variation of each parameter are shown. The results show that the GOCART simulations are in accordance with MODIS observations for decreasing AOD_{550} over the region suggesting a pronounced decrease of the dust component (-25.9 ± 17.8 %). Furthermore, the dust contribution to the total AOD_{550} exhibits a considerable decrease over the area (-26.9 ± 15.2 %), supporting the declining trend in AOD_{550} over northern India attributed to the attenuation of dust activity. However, the GOCART simulations are limited to 2007, but except of that, the decreasing trend of dust AOD_{550} can be considered as real.

Furthermore, the spatial distributions of the monthly mean and the % variation of the dust AOD_{550} are presented in Fig. 12 in order to reveal the regions of enhanced dust load and significant variations. Starting from the dust AOD_{550} the GOCART simulations show increased values over the Arabian Peninsula, Iran and Pakistan deserts, also extended to northwestern India; another region of large dust AOD_{550} is the Taklimakan desert, while the rest of the area presents very low dust AOD_{550} (<0.15). Focusing on the areas with higher dust load, the model simulations show gradually decreasing dust from May to August, while September reveals only limited dust over the Arabian peninsula. This is somewhat opposite to MODIS observations, which show increased AOD till July over the northern part of AS and western IGP, while COGART shows rather similar amounts of dust during April and July over northern AS and significantly lower dust load in the monsoon over the northwestern India. Regarding the dust-AOD_{550}

trends (right panels) a wide range of % variation is observed in each month. It should be noted that in areas with very low dust load, small trends in the 8-yr period (2000–2007) can lead to very large % variations, as the case over NIO in April and over Tibetan Plateau in June. However, these areas are meaningless for examination of the dust variability and we focus our discussions on large dust-affected areas. Thus, the dust load presents an increasing trend over the Arabian peninsula and Middle East during May–July, and partly in September, while over northwestern India a decreasing dust-AOD_{550} trend (-10 to -50 %) is observed, which is in general agreement with the MODIS observations.

As far as the total AOD_{550} is concerned, the mean GOCART simulations for the months April–September show increased values over the Arabian peninsula and northern India, especially in the eastern IGP (Fig. 13a), a feature that is more characteristic during the winter season (see Fig. 1 and Dey and Di Girolamo, 2010). Regarding the % variations of the total AOD_{550} and emphasizing over northern India (Fig. 13b), GOCART simulations reveal a decreasing (increasing) trend in the western (eastern) IGP. Although MODIS observations show a decreasing AOD_{550} trend over all northern India, one can see a general accordance from the GOCART simulations regarding the negative trends over northwestern India. As expected, the dust contribution to the total AOD_{550} (Fig. 13c) is much larger over the desert regions gradually decreasing towards east and south. The most important finding from the GOCART simulations is the negative trend of the dust contribution (Fig. 13d), especially over the Indian sub-continent, giving support to our suggestions for attenuation of dust over the region during the period April–September in the last decade.

4 Conclusions

This study focused on analyzing the AOD variations and trends over south Asia based on Terra-MODIS observations during the last decade (2000–2009) aiming further at investigating the reasons for such decadal changes. The MODIS observations show considerable spatio-temporal variations in AOD as well as in its decadal changes, mainly consisted of a general increasing trend over the whole south Asia, which is more intense during winter season, and a pronounced decreasing AOD trend over IGP during late pre-monsoon and monsoon months (April to September). Since several earlier studies highlighted the increasing aerosol load over south Asia, we focused on the monsoon decreasing trend over IGP aiming to reveal some reasons for that. Since the main aerosol type over northern India in late pre-monsoon and monsoon is dust transported mainly from the Thar desert, we showed its variations in order to explain the decreasing AOD trend over the region. Thus, the decrease in AOD may be closely related to the attenuation of dust activity and the fact that the decreasing AOD trend was more intense in the western rather than eastern IGP justifies such attenuation. The construction of an irrigation canal carrying water in the semi-arid Rajastan state has changed the feature of the Thar desert and extended the crop-land areas. As a consequence, the desert areas in northwestern India have been reduced and the higher air moisture due to vegetated areas led to increase in precipitation, both constitute negative feedbacks for the dust outflows. The GOCART simulations also showed considerable reduction of dust-AOD and its contribution to the total AOD over south Asia during 2000–2007, which are in general agreement with the MODIS observations.

However, the AOD trends as well as their spatial distribution over south Asia, either from MODIS observations or GOCART simulations, may be considered rather qualitatively and not quantitatively due to the short period used for such applications. Thus, the monthly variations of the slope values and (%) changes in AOD_{550}, especially for the four sub-regions, may be strongly modified depending on the yearly AOD variation. Nevertheless, the results showed a pronounced increasing trend in AOD over the whole south Asia, mainly during winter season, and an evidence of decrease in AOD over northern India and IGP during summer, which requires further investigations from ground-based measurements.

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Table 1. Mean area-averaged AOD_{550} values for the periods 2000–2005 and 2006–2009 in four regions over south Asia and ΔAOD_{550} in absolute and percentage values between the two periods for winter (December–February), summer (April–June) and rainy (July–September) seasons.

Region	Season	Mean AOD (2000–2005)	Mean AOD (2006–2009)	ΔAOD	ΔAOD (%)
AS	winter	0.209 ± 0.038	0.249 ± 0.043	0.040 ± 0.015	15.74 ± 5.37
	summer	0.376 ± 0.068	0.425 ± 0.088	0.048 ± 0.040	10.53 ± 7.84
	rainy	0.502 ± 0.151	0.553 ± 0.151	0.051 ± 0.050	9.29 ± 8.16
BoB	winter	0.242 ± 0.062	0.291 ± 0.088	0.049 ± 0.028	15.81 ± 5.28
	summer	0.348 ± 0.097	0.383 ± 0.110	0.035 ± 0.043	7.92 ± 11.09
	rainy	0.300 ± 0.041	0.335 ± 0.056	0.035 ± 0.039	9.56 ± 9.83
NIO	winter	0.164 ± 0.036	0.186 ± 0.039	0.023 ± 0.014	12.01 ± 7.09
	summer	0.184 ± 0.052	0.181 ± 0.058	−0.003 ± 0.018	−2.76 ± 9.31
	rainy	0.188 ± 0.044	0.194 ± 0.046	0.006 ± 0.012	2.85 ± 6.31
IGP	winter	0.407 ± 0.142	0.489 ± 0.173	0.082 ± 0.046	16.49 ± 6.74
	summer	0.619 ± 0.159	0.567 ± 0.141	−0.042 ± 0.041	−7.19 ± 6.49
	rainy	0.567 ± 0.153	0.499 ± 0.145	−0.068 ± 0.085	−17.14 ± 22.67

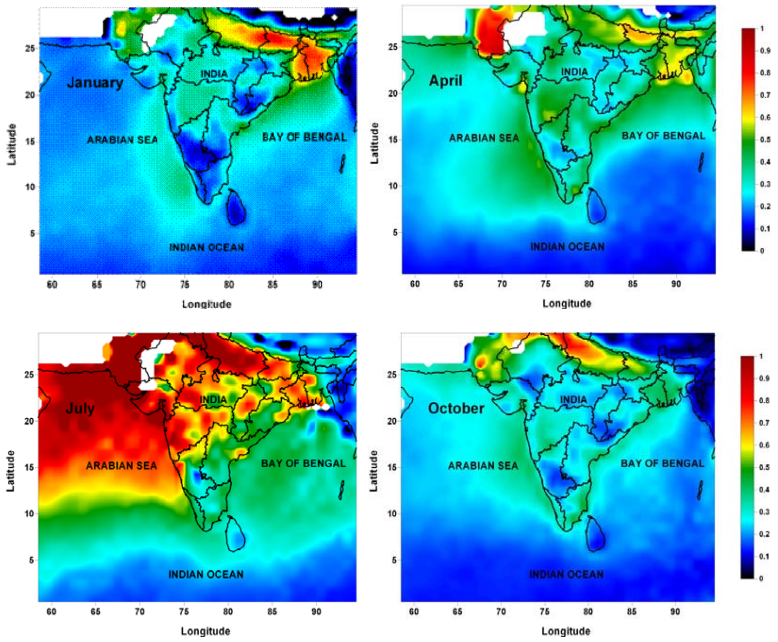

Fig. 1. Monthly-mean spatial distribution of the Terra-MODIS AOD_{550} over south Asia during the period 2000–2009 for characteristic months in each season (January for winter, April for pre-monsoon, July for monsoon, October for post-monsoon).

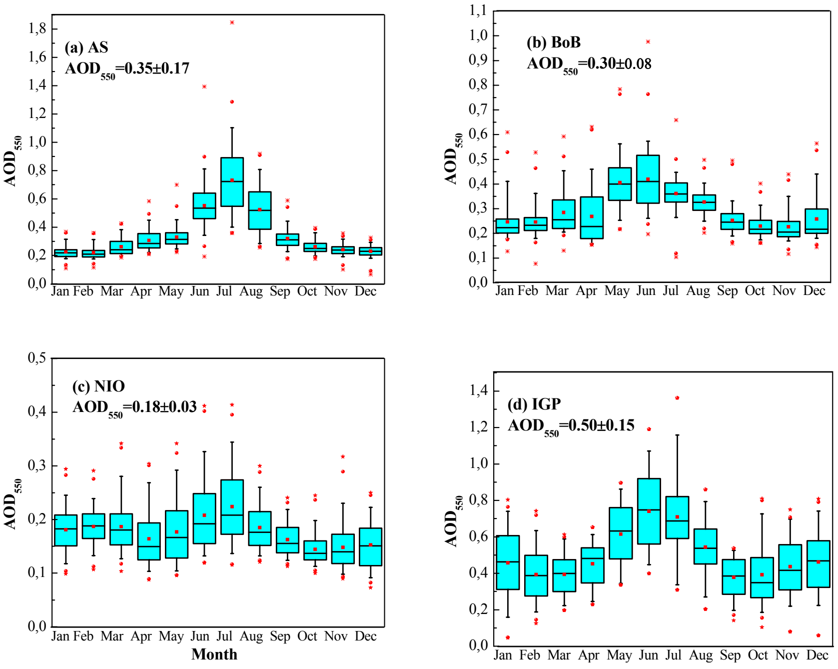

Fig. 2. Monthly variation of the area-averaged Terra-MODIS AOD_{550} values over 4 sub-regions in south Asia **(a)** AS, **(b)** BoB, **(c)** NIO and **(d)** IGP. Box: 25–75%, λ: 1 %, 99 % percentile, ↔: min, max value. ν: mean value.

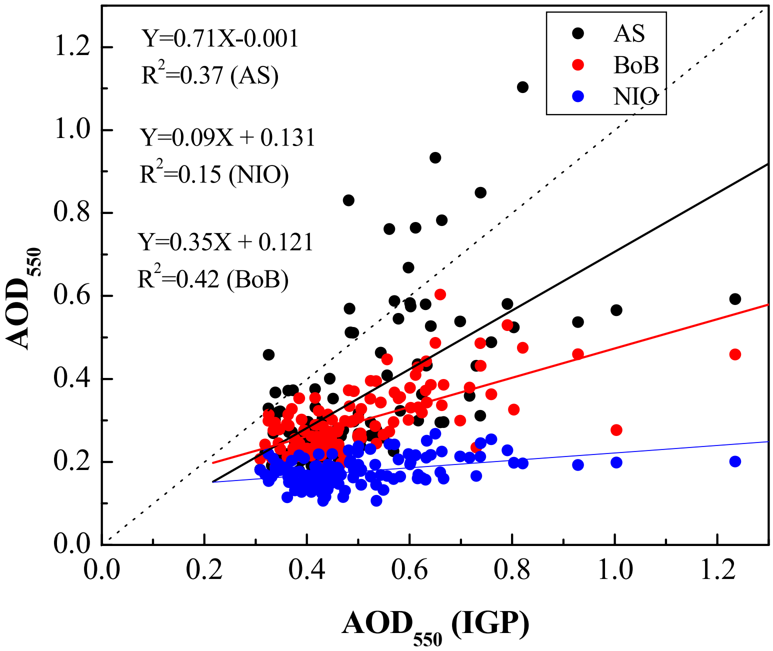

Fig. 3. Correlation between the area-averaged monthly mean MODIS-AOD_{550} values over IGP with those obtained over AS, BoB and NIO.

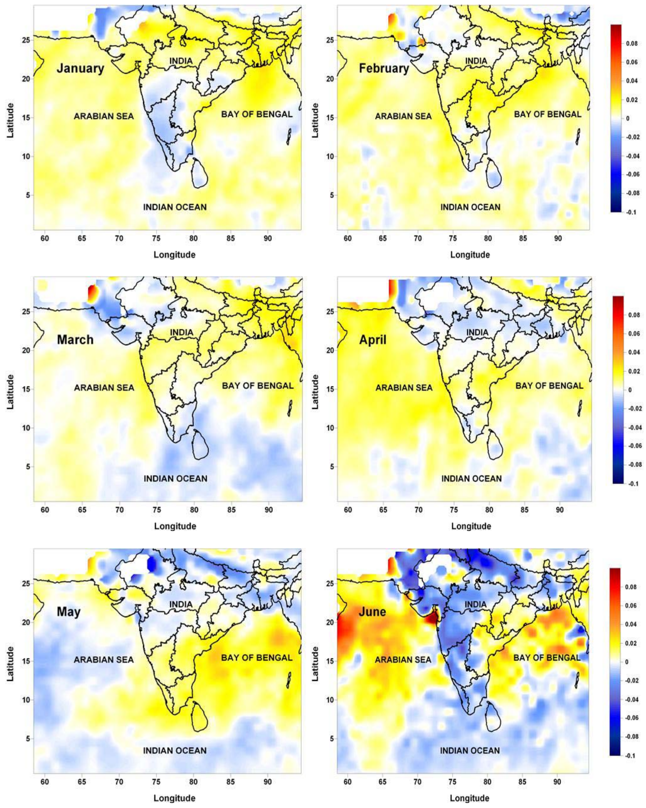

Fig. 4a. Caption on next page.

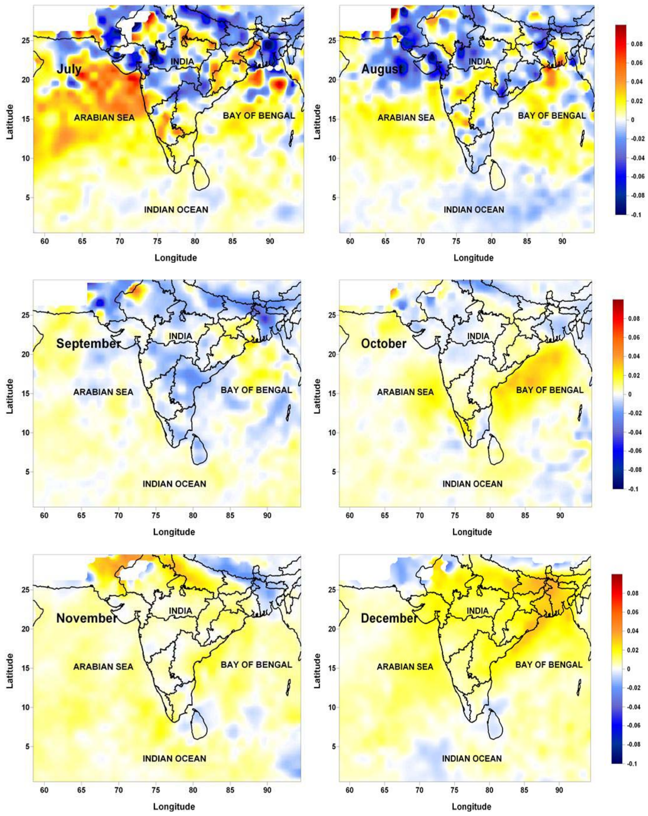

Fig. 4b. Spatial distribution of the trends in MODIS-AOD$_{550}$ during the period 2000–2009. The trend values correspond to the slope of the linear regression analysis.

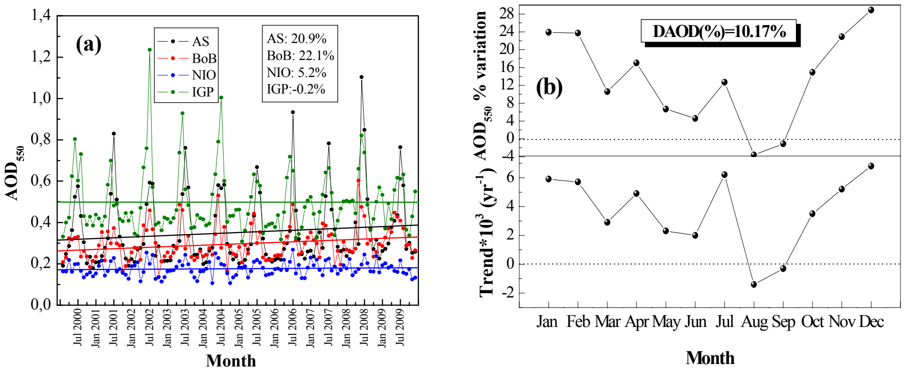

Fig. 5. Monthly-mean variation and trends for the area-averaged MODIS-AOD$_{550}$ in the four sub-regions during the period 2000–2009 **(a)**. Trend values*10^3 and % variations in AOD$_{550}$ calculated from the linear regression of the monthly mean AOD$_{550}$ averaged over the whole south Asia during the period 2000–2009 **(b)**.

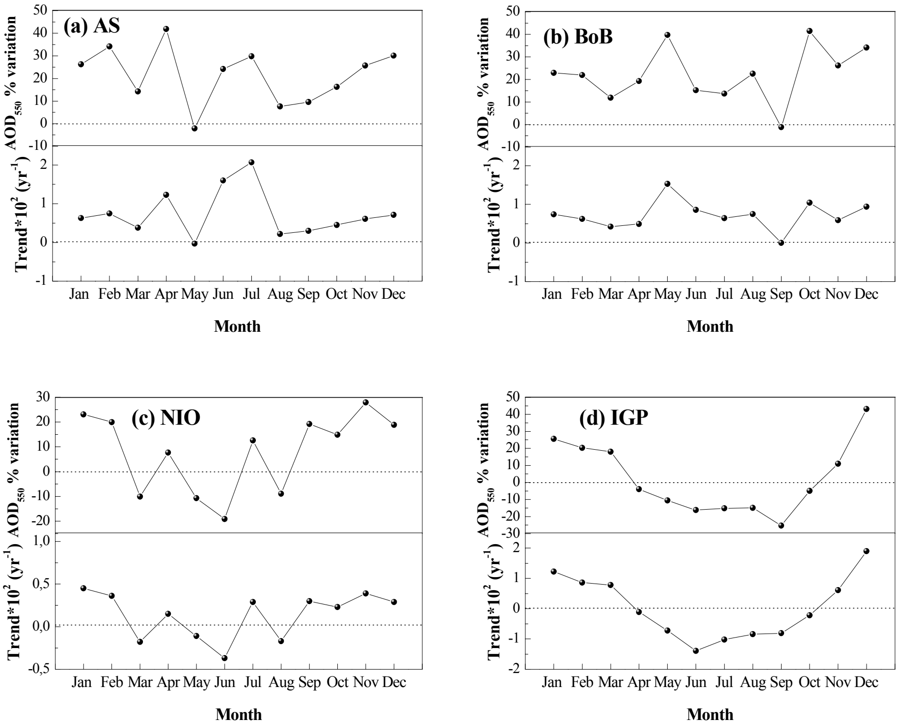

Fig. 6. Trend values*10^2 and % variations in the monthly mean MODIS-AOD$_{550}$ averaged over **(a)** AS, **(b)** BoB, **(c)** NIO and **(d)** IGP in the period 2000–2009.

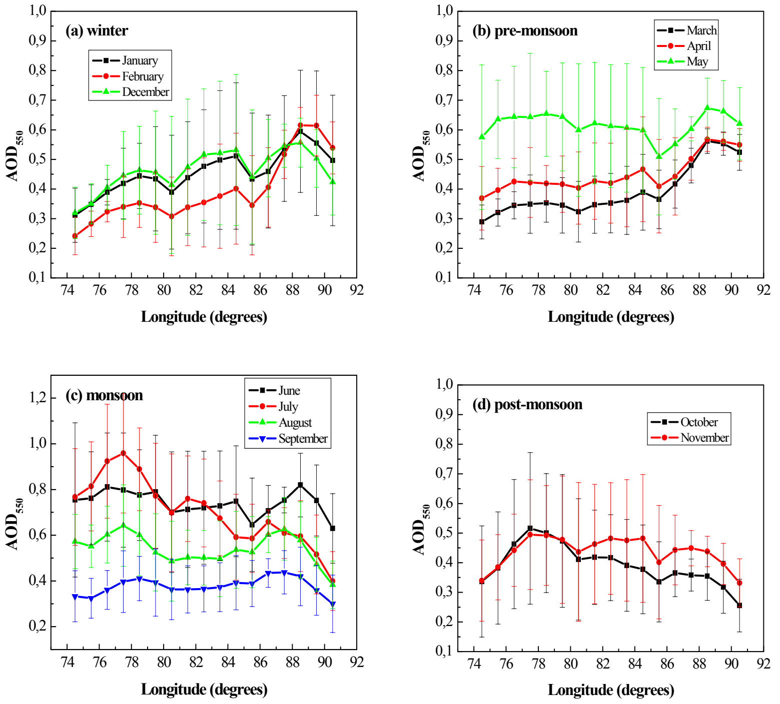

Fig. 7. Monthly mean longitudinal variation of the MODIS-AOD$_{550}$ over IGP during the period 2000–2009. The vertical bars express one standard deviation from the latitudinal mean value.

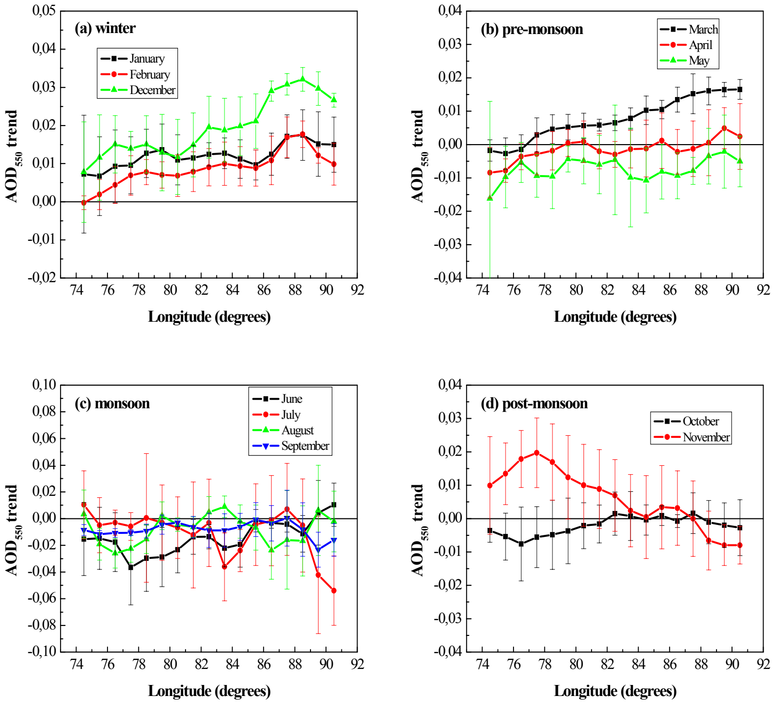

Fig. 8. Monthly mean longitudinal variation of the slope values indicating the MODIS-AOD$_{550}$ trend over IGP during the period 2000–2009.

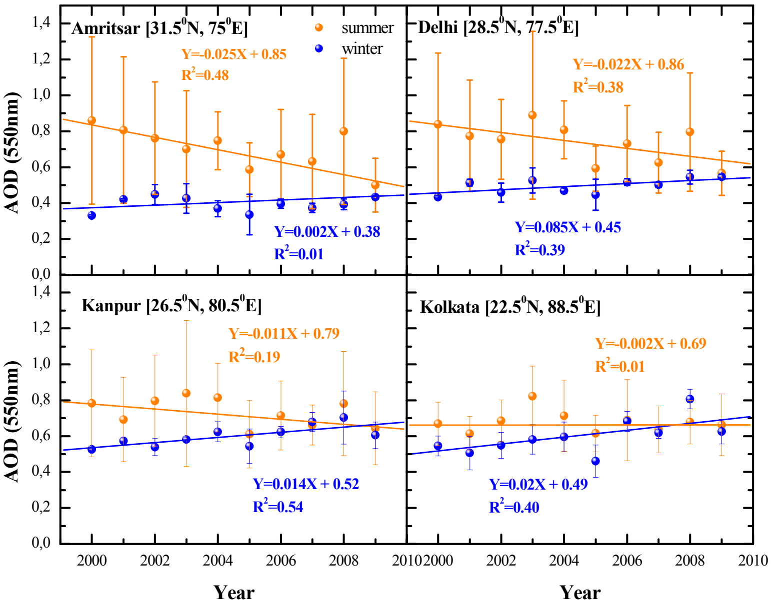

Fig. 9. Decadal variation of the yearly MODIS-AOD$_{550}$ values in winter (December–January) and summer (April–June) seasons over four urban locations in IGP. The vertical bars express one standard deviation from the seasonal mean.

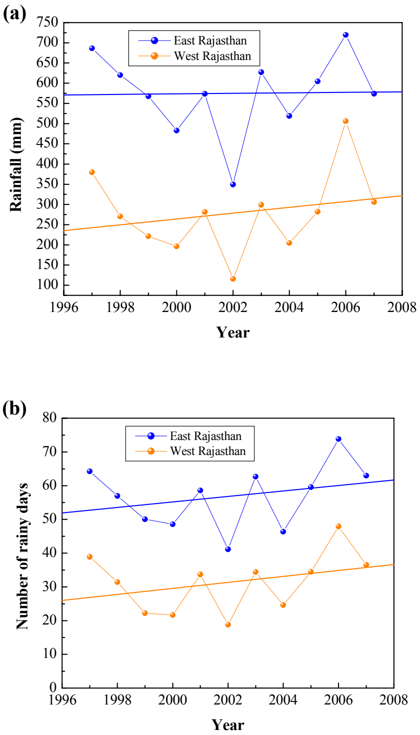

Fig. 10. Variation in the rainfall amount **(a)** and total number of rainy days **(b)** over east and west Rajsthan during the period April–September for the years 1997–2007. Data obtained from IMD (see text for details).

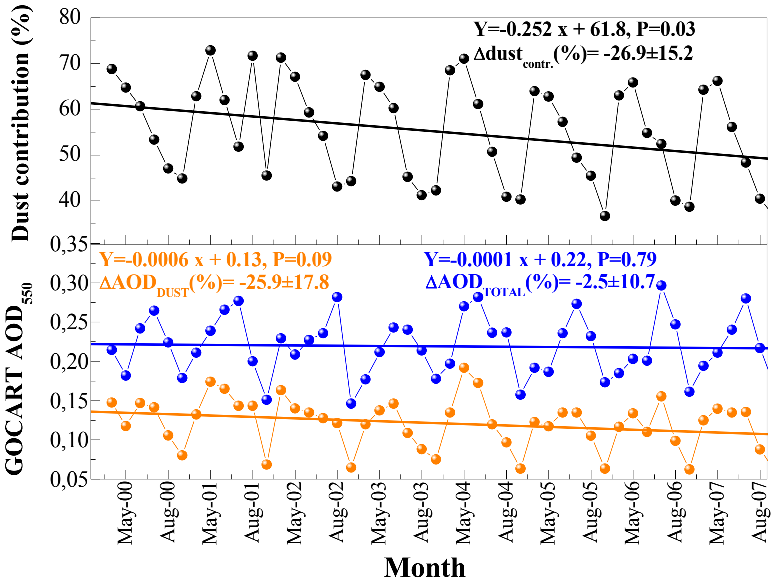

Fig. 11. Monthly variation and linear regression trends for total and dust AOD$_{550}$ (lower panel) and for dust contribution (%) in the total AOD$_{550}$(upper panel) via GOCART simulations over south Asia for April–September in the period 2000–2007.

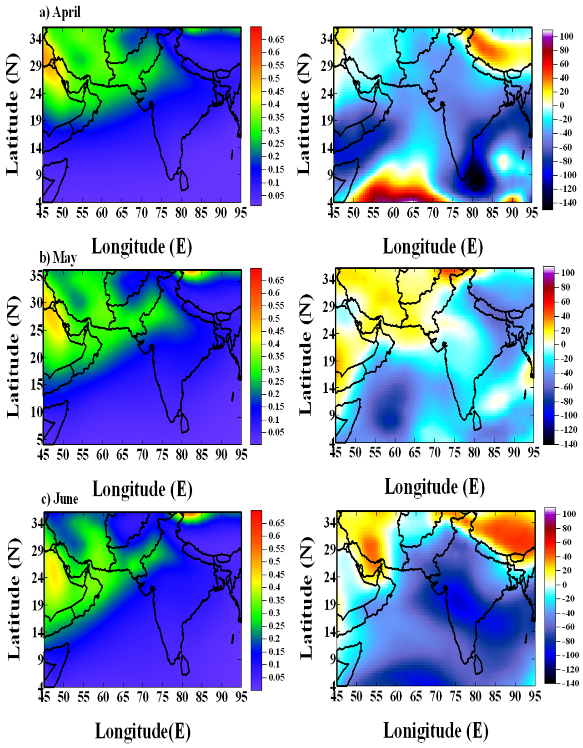

Fig. 12a. Caption on next page.

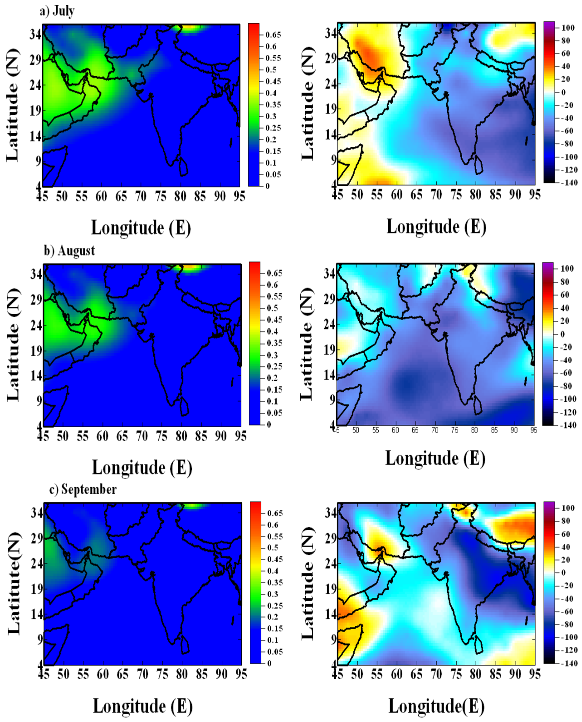

Fig. 12b. Mean values (left column) and % variation (right column) of the dust AOD_{550} over south Asia during April–September in the period 2000–2007 according to GOCART simulations.

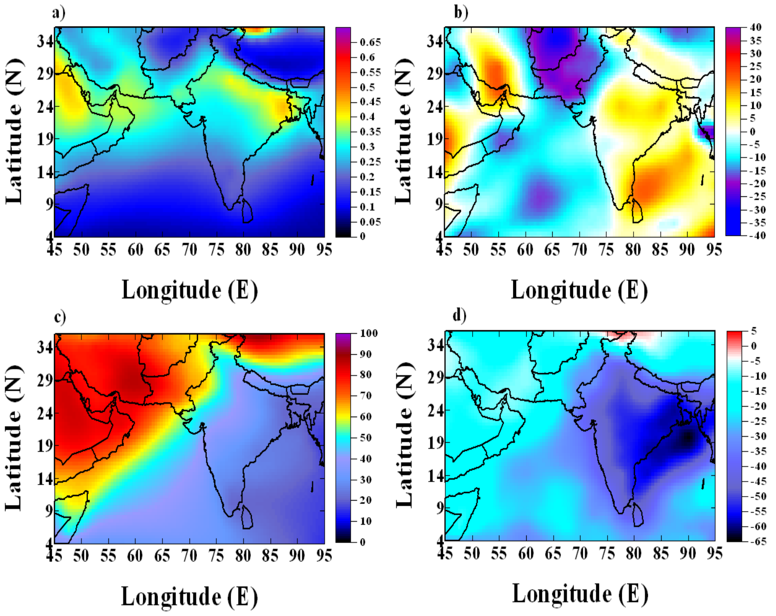

Fig. 13. Mean values and % variation for the total AOD_{550} (**(a)**, **(b)**, respectively) and for the dust contribution to the total AOD_{550} (**(c)**, **(d)**, respectively) over south Asia during April–September in the period 2000–2007 according to GOCART simulations.