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Effect of the growing population on the air pollution, climatic variability and hydrological regime of the Ganga basin, India

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Abstract The Ganga basin constitutes a major part of northern India and is a part of the Ganga–Brahmputra–Meghna basin. The basin has a population of over 460 million. With growing population, urbanization and industrialization, the climatic conditions are found to change significantly, which has a direct impact on agricultural productivity. The hydrological regime of the basin is interrelated with the climatic conditions. In the present paper, we have studied the effect of the growing population on satellite deduced parameters (normalized difference vegetation index—NDVI, soil moisture—SM, aerosol optical depth—AOD, and rainfall during 2000–2004). Efforts have been made to study the relationship between NDVI and AOD. The percentage rise in AOD during the summer season (2004) compared to 2000 is found to be very high. The western and the eastern parts of the basin are found to show contrasting seasonal behaviours.

Key words aerosol optical depth; climate; Ganga basin; India; NDVI; rainfall; soil moisture

INTRODUCTION

The Ganga basin is a part of the composite Ganga–Brahmputra–Meghna basin (ASIA: International River Basin Register, 2004). Large-scale and rapid urbanization and industrial development in this region have caused high pollution levels in air, water and land. The Ganga basin is bounded by the Himalayas in the north, the Aravalli in the west, the Vindhyans and Chhotanagpur Plateau in the south and the Brahmaputra ridge in the east. The Ganga is the major river flowing in this basin which covers about one-third of the agricultural land of India with a major portion of the agricultural yield (Sarkar *et al.*, 2003). About 460 million people live in the basin out of a total population of one billion. Numerous industrial cities (New Delhi, Kanpur, Banaras, Patna and Kolkata) are located in the basin. Most of these cities are situated along the Ganga River. Increasing aerosol loading has been observed for this region in recent years. Satellite data have been used that provide information about the air quality in terms of aerosol optical depth (AOD) (Chu *et al.*, 2003; King *et al.*, 2003; Engel-Cox *et al.*, 2004; Hutchison *et al.*, 2004). The effect of population density on the long-term effect of aerosols and its impact on the normalized difference vegetation index (NDVI)

is highly important for the Ganga basin. Indo-Asian aerosols have an impact on radiative forcing causing negative forcing (cooling) on the surface and a positive effect (warming) at the top of the atmosphere (Satheesh & Ramanathan, 2000; Ramanathan *et al.*, 2001b; Kaufman *et al.*, 2002; Kulmala *et al.*, 2004). Interaction between aerosols, rainfall and its impact on regional climate was recently discussed extensively by Liao & Seinfeld (1998), Rotstayn *et al.* (2000), Ramanathan *et al.* (2001a) and Chung & Ramanathan (2004). The Ganga basin experiences high AOD values and reduced NDVI that have potential effects on crop yield, besides impact on human health such as respiratory diseases. Efforts have been made to study the effect of AOD on NDVI in conjunction with others factors that affect NDVI. The monthly average of 100 km × 100 km area around major cities has been used to study trends in recent years of AOD, NDVI, rainfall and soil moisture (SM). The percentage increase of AOD in recent years reveals drastic changes over vegetation in the Ganga basin.

DATA USED

Aerosol optical depth data were obtained from Level-3 MODIS gridded atmosphere monthly global product "MOD08_M3" (ESDT Long Name: MODIS/Terra Aerosol Cloud Water Vapor Ozone Monthly L3 Global 1Deg CMG). The monthly average MOD08_M3 product files are available in Hierarchical Data Format (HDF-EOS) at a spatial resolution of 1° × 1° (MODIS, 2004). The population density data for the years 2000 and 1990 (units: persons per km^2) were obtained from the *Gridded Population of the World* (GPW) data set available from the Center for International Earth Science Information Network (CIESIN, 2004). NDVI data for the period 2000–2004 were obtained from SPOT Vegetation having spatial resolution of 1 km^2 (SPOT, 2004). Satellite-based rainfall data were used for the analysis of rainfall patterns between 2000 and 2004. Rainfall data (units: mm) were obtained from TRMM Precipitation Product 3B43 (V6) (TRMM, 2004). The soil moisture (SM) data (units: mm) were taken from NOAA NCEP CPC Global Monthly Soil Moisture Dataset (NOAA NCEP CPC, 2004).

OBSERVATION AND DISCUSSION

The aerosol optical depth (AOD), NDVI, rainfall and SM anomaly trends were studied for major cities in the Ganga basin since the year 2000. The effects of rainfall and SM patterns were also studied to explain their combined effect on the reduction of NDVI values in recent years. An effort was made to explain the increase of AOD and the decrease of NDVI along with other variables influencing both AOD and NDVI, such as rainfall. The whole basin was divided into three zones (western, central and eastern) to study spatial distribution patterns during different seasons. Aerosol optical depth spatial maps were prepared for four distinct seasons observed in a year for the Ganga basin: (a) the summer season (April–June); (b) the monsoon season (July–October); (c) the winter season (November–February); and (d) the spring season (March).

The population density (in 2000) had increased to a large extent since 1990 (Fig. 1). Most of the increase can be seen along the Ganga River. Distinct seasonal

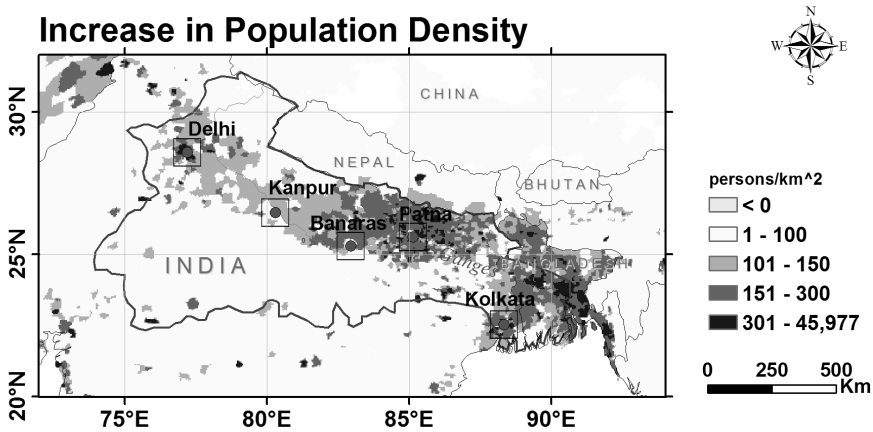

Fig. 1 Increase in population density (2000) since year 1990. The major growth in population can be seen concentrated along the course of the Ganga river. Variables studied have been averaged for 100 km × 100 km areas (square box) around New Delhi, Kanpur, Banaras, Patna and Kolkata cities.

patterns of AOD distributions in the Ganga basin were observed (Fig. 2). The AOD was very high for the whole region during summer 2004 compared to 2000 (Fig. 3, percent increase during summer 2004). Aerosol loading was found to be very high (>0.6) during the summer season for all three zones (Fig. 2, summer 2004). In the monsoon season, an increase in gradient of AOD from east to west was observed (Fig. 2, monsoon 2003); this is very high (>0.6) in the western part and gradually reduces to 0.4–0.5 in the eastern part. The percentage rise in monsoon AOD (for 2003) compared to 2000 was found to show no change except for southern parts of the basin (south of the cities Kanpur and Banaras) (Fig. 3, percentage increase in monsoon AOD). The influence of westerly winds on AOD content around the Delhi region is clearly visible. The rainfall distribution pattern was found to be higher in the eastern part of India, which also controls the aerosol loading. The higher rainfall and longer rainy days reduce the aerosol loading further (Saha & Moorthy, 2004) in the eastern part compared to the western part of the basin. Dust storms also increase AOD in the western part, especially at the beginning of the monsoon season. The AOD was generally found to be low in all parts of the basin during the winter season compared to other seasons. An opposite trend in aerosol loading was observed during the winter season compared to the monsoon season. In the winter season, higher AOD was found in the eastern part compared to the western part (Fig. 2, winter 2003). The rise in winter AOD for 2003 was found to be around 1–10% compared to 2000 in the western part of the basin and near Kolkata. The AOD was found to increase by 10–20% near Delhi and Kanpur cities, which can explain the dense fog observed around Delhi and Kanpur during winter seasons (Fig. 3, percentage rise during winter AOD). The spring season shows more or less low AOD in all parts of the basin similar to the winter season (Fig. 1, spring 2004).

An increase in aerosol optical depth for cities in recent years was studied with its effect on NDVI (vegetation). Averages of the variables for 100 km × 100 km around the cities were computed. A negative correlation was found for AOD and NDVI. The Kanpur region shows 16.7% increase in AOD since 2000 with a decrease of 8.1% in NDVI for the same area over the same time period. Similarly, the aerosol loading was

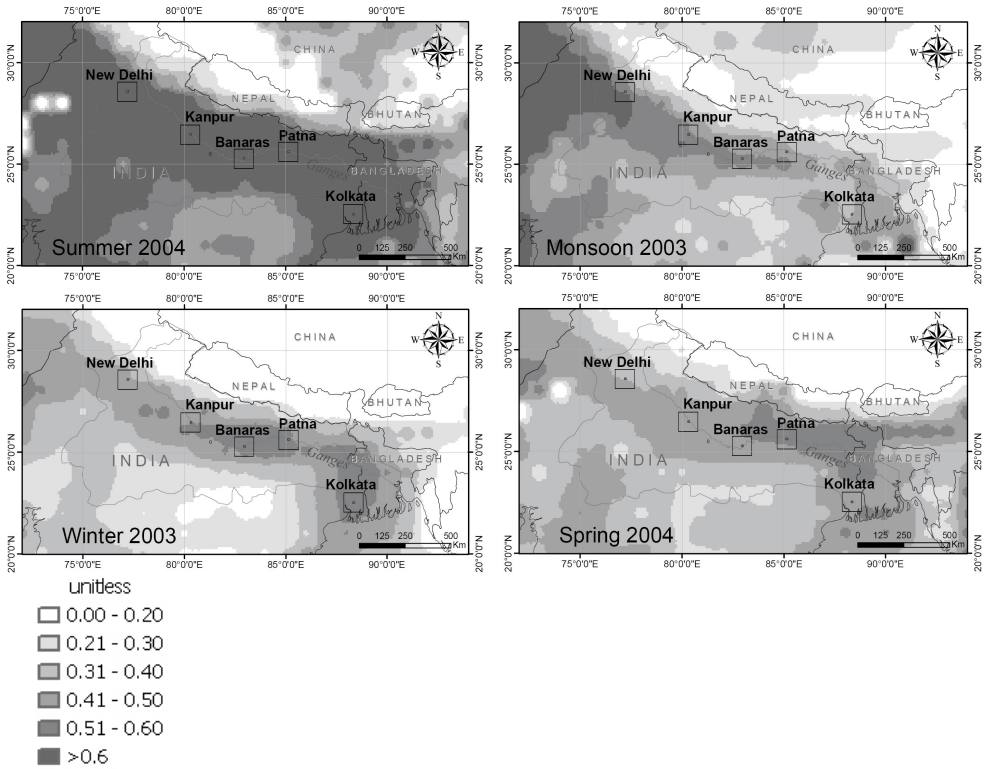

Fig. 2 AOD spatial distribution in the Ganga basin for the summer, monsoon, winter and spring seasons.

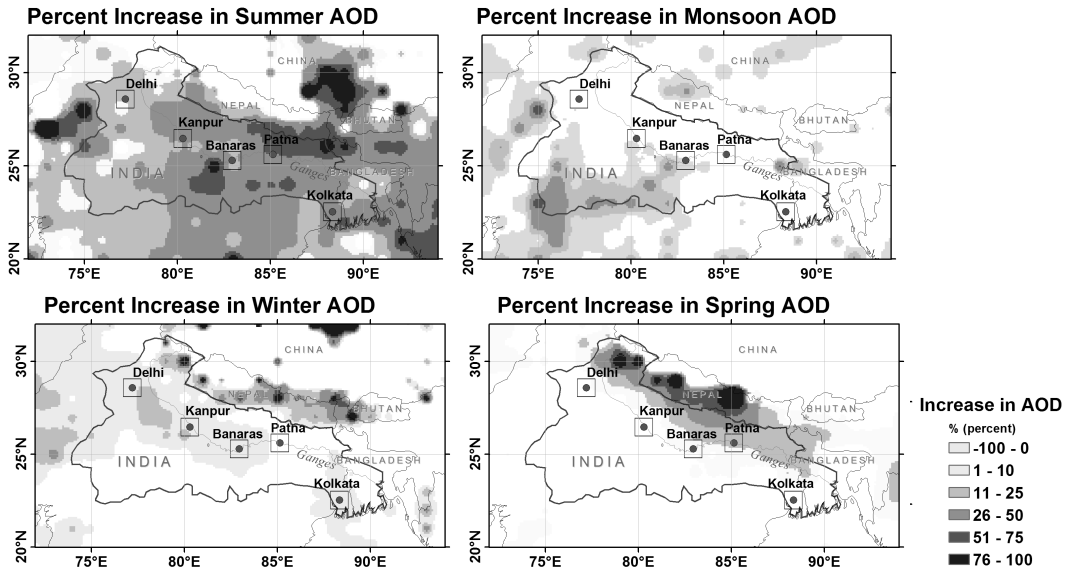

Fig. 3 Percentage increase in AOD over the Ganga basin in different seasons.

found to have increased by 37% in Banaras since 2000 with a corresponding 5.5% decline in NDVI (Fig. 4, Kanpur and Banaras). The increase in AOD was found to be associated with the decrease in NDVI. However, the negative effect of AOD over NDVI was found to be different in different regions (Fig. 4, Kanpur, Banaras,

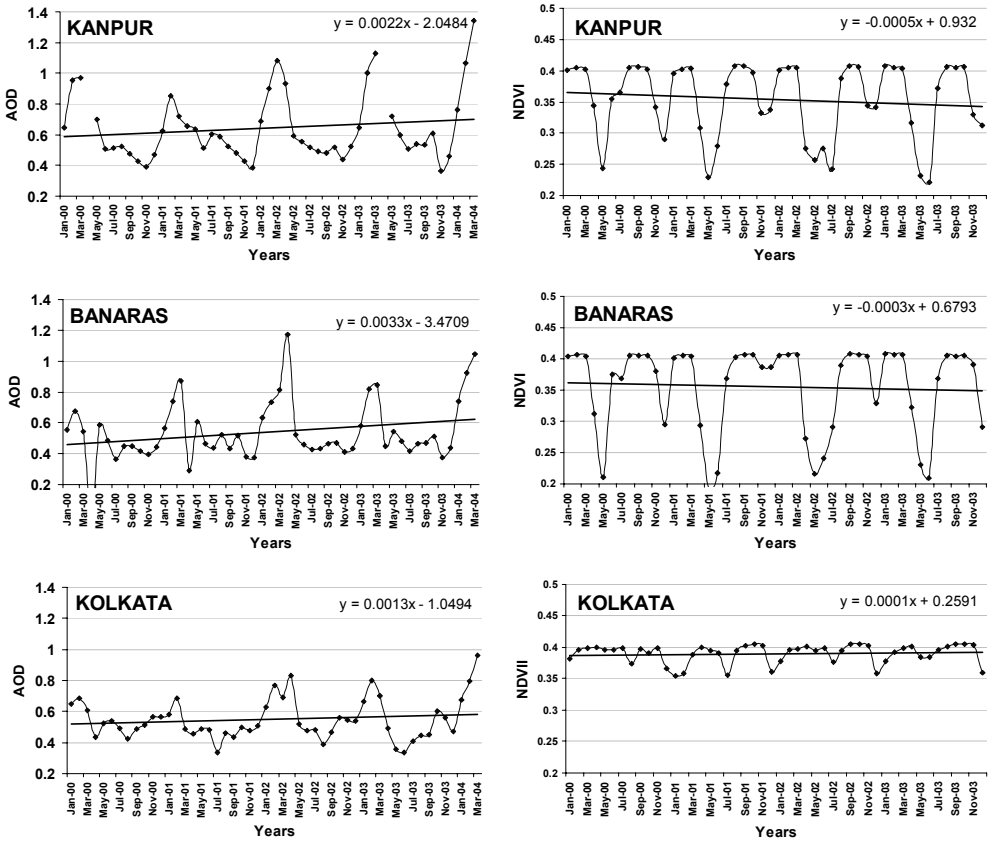

Fig. 4 Aerosol optical depth (AOD) and NDVI for major cities in the Ganga basin (average of 100 by 100 km^2 area). A negative relationship exists between AOD and NDVI with varying magnitude.

Kolkata). The AOD also increased significantly near Kolkata but a corresponding decline in NDVI was found to be negligible. In this context it is important to note that Kolkata shows an increasing trend in soil moisture since 1982 compared to Kanpur and Patna (Fig. 4, Kolkata). Soil moisture also influences the negative relationship between NDVI and AOD. The NDVI is found to be affected by an increase in AOD. The magnitude of the effect on the AOD and NDVI relationship is different as the roles played by rainfall and SM in vegetation growth vary significantly between regions. The effect of aerosols on NDVI measured through satellites is important (Trishchenko *et al.*, 2002; Liu *et al.*, 2004). A modified vegetation index, namely Aerosol Free Vegetation Index (AFRI) can help in reducing the direct effect of aerosols on sensor level measurement of NDVI (Karnieli *et al.*, 2001). The AFRI can be used in future to study the relationship between AOD and NDVI.

Generally, an increase in AOD was found with a corresponding decline in NDVI with varying response over the Ganga basin. The higher AOD level is cutting a substantial portion of sunlight reaching the Earth; hence, there is a decrease in the Photosynthetically Active Radiation (PAR) influx used by plants for growth (Bergin *et al.*, 2001). Droughts and floods drastically affect the NDVI values compared to normal years, irrespective of AOD level. Hence a comprehensive approach is required which is quite complex to evaluate. Efforts have been made in this study to understand the

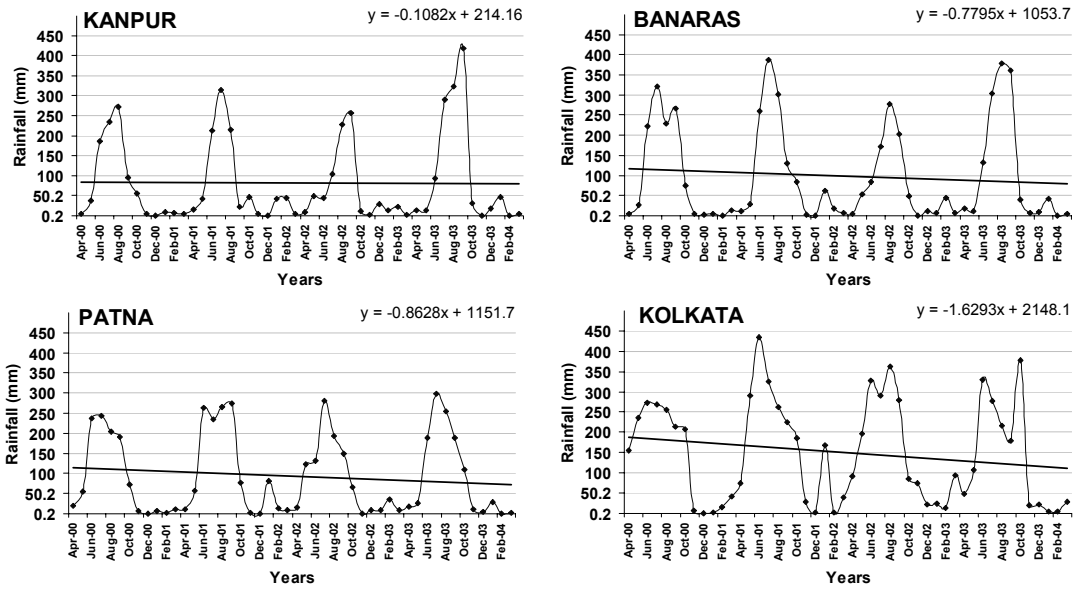

Fig. 5 Rainfall (mm) for major cities in the Ganga basin (average of 100 km × 100 km area) since 2000. Short-term trend of rainfall shows a decline in rainfall received by Kolkata, Patna and Banaras cities and their surroundings.

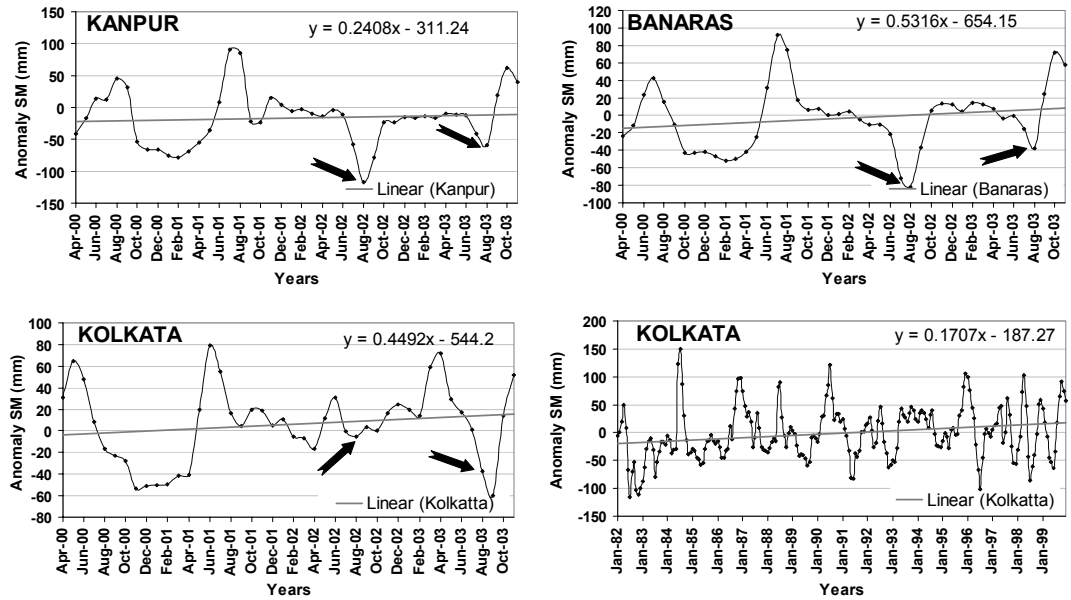

Fig. 6 Soil moisture (SM) anomaly for major cities in the Ganga basin (average of 100 km × 100 km area) since 2000 (for Kanpur, Banaras and Kolkata) and 1982 (for Kolkata). Arrows mark the SM during drought year 2002 and normal rainfall year 2003.

effect of all variables. In recent years a decrease in total rainfall has been observed for Kolkata, Patna and Banaras cities and an increase in SM observed for all cities (Figs 5 and 6). A decrease in NDVI for Kanpur and Banaras is unlikely to be due to the effect of decreasing rainfall alone. The negative effect of AOD on NDVI is found to be prominent in the central part of the Ganga basin.

CONCLUSION

The MODIS-derived AOD data clearly show the increase in AOD over the Ganga basin during the years 2000–2004, which also confirms the observations of ADEOS POLDER data. An increased level of aerosols is partially cutting out solar radiation (PAR) which is therefore not reaching the vegetation and causing a reduction in photosynthetic activity which is seen in the SPOT NDVI data. The Kanpur region shows a high level of AOD (>0.7). Aerosol optical depth seems to be the direct cause of a reduction in NDVI, as rainfall and SM data for recent years are almost constant for Kanpur. In the Banaras region, a decrease in rainfall and an increase in AOD is causing a decrease in NDVI. Both Kanpur and Banaras lie in the central part of the Ganga basin and are highly affected by an increase in aerosols in the atmosphere. The Ganga basin is very fertile and contains major agricultural resources. The long-term impact of aerosols and the corresponding decrease in NDVI is alarming.

The AOD in the Delhi region was found to be stable since 2000, unlike other cities, which is attributed to the use of CNG and also the positive effect of reducing vehicular pollution in the Delhi region. The implementation of measures to reduce aerosols especially in the central part of the basin is urgently needed. A strong negative relationship between the increase and high levels of AOD and its effect on photosynthetic activity (NDVI) is established especially for the central zone of the Ganga basin. The Ganga basin as a whole shows an excessive percentage increase in summer AOD in 2004 with respect to the base year 2000. The percentage increase in AOD during winter 2003 with respect to 2000 shows extremely high values (11–25% rise) near Delhi and Kanpur that can explain the dense fog observed in this region during the winter season.

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