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Aerosol indirect effect over Indo-Gangetic plain

S.N. Tripathi*, A. Pattnaik, Sagnik Dey

Department of Civil Engineering, Indian Institute of Technology, Kanpur 208016, India

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Abstract

Moderate resolution imaging spectroradiometer (MODIS) data are analyzed over the Indo-Gangetic plain (IGP) to study the effect of aerosol optical depth (AOD) on the water ($R_{eff,w}$) and ice ($R_{eff,i}$) cloud effective radius for the period 2001–2005. The temporal variation of $R_{eff,w}$ and $R_{eff,i}$ shows reverse trend as that of AOD for most of the time. The intensity of positive indirect effect (i.e. increase of $R_{eff,w/i}$ with decrease of AOD and vice versa) is the highest in winter ($\Delta R_{eff,w}/\Delta AOD \sim -9.67\,\mu m$ and $\Delta R_{eff,i}/\Delta AOD \sim -12.15\,\mu m$), when the role of meteorology is the least. The positive indirect effect is significant in 43%, 37%, 68% and 54% of area for water clouds in winter, pre-monsoon, monsoon and post-monsoon seasons, respectively, whereas the corresponding values for ice clouds are 42%, 35%, 53% and 53% for the four seasons, respectively. On the contrast, $R_{eff,i}$ in some locations shows increment with the increase in AOD (negative indirect effect). The negative indirect effect is significant at 95% confidence level in 7%, 18%, 9% and 6% grids for winter, pre-monsoon, monsoon and post-monsoon seasons, respectively. The restricted spatial distribution of negative indirect effect in IGP shows that the cloud microphysical processes are very complex. Our analyses clearly identify the contrasting indirect effect, which requires further *in situ* investigations for better understanding of the aerosol–cloud interaction in the region.

Keywords: Indo-Gangetic plain; Aerosol indirect effect; Clouds

1. Introduction

Aerosols indirectly affect the climate by acting as cloud condensation nuclei (CCN) and ice nuclei (IN) and thereby modify the cloud properties (Lohmann and Feichter, 2005; Koren et al., 2005). The Intergovernmental Panel on Climate Change report (Ramaswamy et al., 2001) has emphasized the importance of quantifying the indirect effect on water and ice clouds in regional scale to minimize the uncertainty in the global estimate of indirect forcing. The Twomey effect (or the 'first' indirect effect, Twomey, 1959) refers to enhanced reflection by smaller cloud droplets with fixed liquid water content, thus increasing cloud albedo. Subsequently, the more but smaller cloud droplets reduce the precipitation efficiency and increase the cloud lifetime ('second' indirect effect). Another effect (semi-direct effect) results from the absorption of solar radiation by aerosols, which heats up the atmosphere and evaporates the cloud droplets. The indirect aerosol effect has been investigated through observational as well as modeling studies in many parts of the world (Lohmann and Feichter, 2005

*Corresponding author. Tel.: +91 512 259 7845; fax: +91 512 259 7395.
E-mail address: snt@iitk.ac.in (S.N. Tripathi).

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and references therein; Myhre et al., 2006). In Indian subcontinent, during the Indian Ocean Experiment, this issue was addressed for the Indian Ocean (Ramanathan et al., 2001), where the polluted clouds have aerosol number density three times larger than that in the pristine clouds. Subsequently, Vinoj and Satheesh (2004) have studied the indirect effect of sea salt aerosols on the cloud microphysical properties over the Arabian Sea using the empirical relations developed from the INDOEX measurements. But no previous study was focused to the Indo-Gangetic plain (IGP), where the aerosol characteristics are complex due to mixing of anthropogenic and natural aerosols (Chinnam et al., 2006).

Here, we focus on IGP, which is the most polluted region in the Indian sub-continent (Singh et al., 2004; Tripathi et al., 2005a, b) and contribute to the wintertime pollution observed over the adjacent oceans. The most striking feature of the IGP is that mineral dust adds to the anthropogenic pollution load in the pre-monsoon and monsoon seasons (Dey et al., 2004; Chinnam et al., 2006). The effect of the increasing pollution load on the water and ice clouds could be different, as observed recently by Chylek et al. (2006) using moderate resolution imaging spectroradiometer (MODIS) data over the Indian Ocean during the winter months. In this paper, spatial and temporal inter-relationship between aerosol optical depth (AOD, quantifying the pollution load) and effective radius of water ($R_{\mathrm{eff,w}}$) and ice clouds ($R_{\mathrm{eff,i}}$) has been explored to study the aerosol indirect effect in the IGP. However, aerosol–cloud interaction is not straightforward; as aerosols and clouds are related also other than through microphysics, most notably through their dependence on meteorological conditions. The meteorological effect has been decoupled from the aerosol effect using the NCEP vertical wind data (Koren et al., 2005). The main objectives of this paper are to investigate the intensity and spatial extent of the indirect effect in the IGP and to identify if the indirect effects for water and ice clouds show any contrasting behavior.

2. Study area and data analysis

In our analysis, to account the spatial variation, the IGP has been divided into four regions (Fig. 1a). First region (70–76°E and 22–32°N) represents the western part of IGP which includes the Thar desert region, which is the major dust producing area

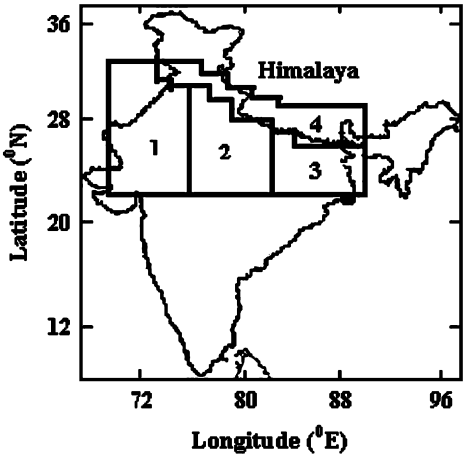

Fig. 1. The area covered under the four regions in the IGP chosen in the present study.

(Chinnam et al., 2006). Second region (76–82°E and 22–30°N) covers the central part of the IGP and third region (82–91°E and 22–28°N) comprises the eastern part of IGP. A fourth region is separated from the main IGP and defined as the foothills of the Himalayas. Each region is further sub-divided into grids of $1^{\circ}\times 1^{\circ}$ and analysis has been performed for each grid. The current analysis in larger spatial grids is able to capture the general trend and indicates some interesting discrepancies, which indicates the necessity to perform similar analysis in much finer spatial scale along with *in situ* data to have more accurate quantification of the indirect effect in this region. Also, it should be kept in mind that clouds observed in a particular grid might have been transported from another location, which is not possible to account for using the satellite data and is a limitation of this study. However, we have considered five year time period and statistically significant correlation between AOD and cloud effective radius would indicate that this could not be an artifact. The grids covering the Himalayan mountainous region in the north of IGP and the fourth region are excluded from the statistical analyses, as they do not represent the basin and the topographic nature of the terrain along with the orographic influence would make the aerosol–cloud interaction study using the satellite data problematic.

The aerosol and cloud parameters are extracted from the level-3 MODIS-Terra gridded atmosphere monthly global product (Kaufman et al., 1997; Platnick et al., 2003) for each grid for a period of 5