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Variability of aerosol optical depth and aerosol forcing over India

S. Sarkar, R. Chokngamwong, G. Cervone, R.P. Singh *, M. Kafatos

Centre for Earth Observing and Space Research, School of Computational Sciences, George Mason University, 4400 University Drive MS 5C3, Fairfax, VA 22030-4444, USA

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Abstract

Over the Indian continent, population is growing day by day and it is expected that soon India will become one of the world's most populated countries. With the growing population, industrialization and urbanization, the aerosol loading in India is increasing that has significant impact on the weather/climatic conditions. The present paper discusses the analysis of the temporal and spatial variations of aerosol and aerosol forcing for major populated and industrial cities in India.

Keywords: India; Aerosol loading; Aerosol forcing; MODIS; TOMS; Remote sensing

1. Introduction

The aerosols represent the nature of atmosphere and play an important role in climate processes. The aerosol particles have strong influence on the climate system by reflecting, absorbing and scattering radiation, where reflection and scattering mostly predominates. The presence of aerosols controls the cooling/heating effect on the earth surface and in turn warming/cooling of the atmosphere.

Numerous studies on aerosols have shown that the aerosols have effect on our climate system. The radiative forcing by the presence of black carbon aerosols is forced to contribute to global warming (Hansen et al., 2000; Jacobson, 2001). Penner et al. (2003) have found that the aerosols have indirect effects on cloud brightness and cloud cover. The presence of black carbon aerosols is found to be responsible to increase rainfall in the southern part of China and drought in the northern part of China (Menon et al., 2002). Hansen and Nazarenko (2004) have also found decrease in albedo of snow and ice surfaces that play a key role in reducing the effect of these aerosols. Consequently, this effect is likely to play global warming and the melting of worldwide glaciers and sea-ice.

Efforts have been made by Indian scientists to carry out annual and inter-annual variability of aerosol parameters using multi wavelength radiometer since 1980 under the Indian Space Research Organization Geosphere Biosphere Program (ISRO-GBP) (Moorthy et al., 1999). Since last 20 years, efforts were made to monitor aerosol parameters in the southern and central parts of India. Not much efforts were made to study the aerosol parameters and its variability in the northern part of India especially in the Indo-Gangetic basin region which is one of the largest populated basins in the world. This basin suffers with severe fog, dense haze and smog which are the causes of population growth in the basin and also due to increasing anthropogenic activities. The first time dense pollution was mapped by the ADEOS POLDAR data (Goloub et al., 2001) and attracted the attention of Indian scientists and a CIMEL sun/sky radiometer was deployed under the part of NASA–AERONET program in Kanpur which is centrally located in the Indo-Gangetic basin. Recently, Singh et al. (2004) have discussed the annual and seasonal characteristics of aerosol parameters measured in Kanpur during 2001–2003. Higher aerosol optical depth was found during pre-monsoon and summer seasons higher AOD was observed over Kanpur due to the transport of dust from

* Corresponding author. Tel.: +1 703 993 8409; fax: +1 703 993 1993.
E-mail addresses: rsingh3@gmu.edu, rpalka425@gmail.com (R.P. Singh).

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western Thar Desert (Dey et al., 2004) and during winter season high AOD is attributed to the biofuel cooking and anthropogenic activities (Singh et al., 2004). Recently, Prasad et al. (2004, 2005) have carried out seasonal study of AOD over Indian sub-continent and have found that the Indo-Gangetic basin suffers with very high AOD. Di Girolamo et al. (2004) have recently observed high pool of aerosol over the Bihar province (north-eastern region in the Indo-Gangetic basin) using MISR data in India during winter season. Massie et al. (2004) analyzed TOMS data from 1979 to 2000 for the winter season (November–February) and have found large AOD over the IG basin.

In the present paper, we show the trend of AOD using TOMS data over numerous major cities and also the characteristics of aerosol optical depth in recent years (2000–2004) using MODIS data over India and its annual variability.

2. Data used

The aerosol concentration retrieved in terms of aerosol index (AI) from TOMS (http://toms.gsfc.nasa.gov) and MODIS data are analyzed over various Indian cities. The AI data from TOMS is globally available with $1° \times 1.25°$ resolution and monthly averaged values are used for this study for the period January, 1982–May, 1993 from the Nimbus TOMS.

The recent monthly average aerosol optical depth (AOD) has been taken from the MODIS instrument onboard the Terra platform. The monthly mean of AOD at 0.55 μ for both ocean (best) and land (corrected) are retrieved from the MODIS Level 3 atmosphere monthly product. The present study is based on 46 months of AOD data from MODIS from March, 2000 to December, 2003 which are downloaded from EOS Gateway (http://redhook.gsfc.nasa.gov/~imswww/pub/imswelcome/).

The $2.5° \times 2.5°$ CERES Earth Radiation budget data is taken from the NASA Langley DAAC (LARC) (http://eosweb.larc.nasa.gov/PRODOCS/ceres/tableceres.html) and are monthly averages of different radiation parameters (Clear-sky and Total-sky Fluxes, Clear-sky and Total-sky Solar Incidence, and Clear-sky and Total-sky Albedo) from the Terra sensor (ES-4). The CERES data is used for calculation of the top of atmosphere flux for two years from January, 2001 to December, 2002.

3. Aerosol concentration over India

The population growth in India and increasing urbanization and industrialization, the aerosol concentration over

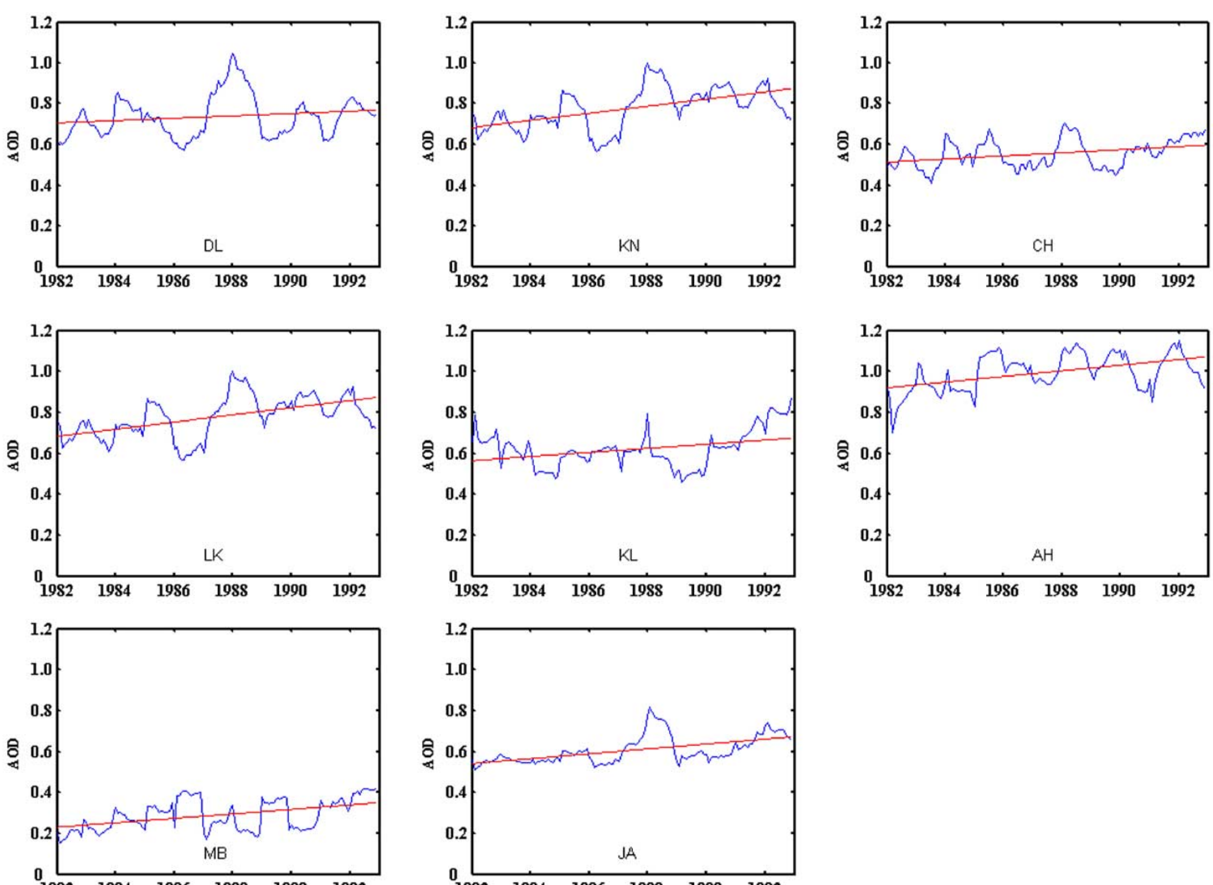

Fig. 1. The trend in AI over major cities (Delhi – DL, Kanpur – KN, Chandigarh – CH, Lucknow – LK, Kolkata – KL, Ahmedabad – AH, Mumbai – MB and Jaipur – JA) in Northern India. All trends shown here are significant at 99%, conducted through a two tailed Student's t test with α set at 0.01.

the Indian sub-continent is found to increase in general (Singh et al., 2004). The increase of aerosol pollution over the Indo-Gangetic (IG) plain is especially prominent that has been mapped by the ADEOS-Polder data (Goloub et al., 2001). Fig. 1 shows the variation of AI over some of industrial and populated cities in the northern part of India for 12 years from 1982 to 1993. All these cities show substantial increasing trend in AI compared to cities located in the southern part of India where the increasing trend is found to be insignificant. This increasing trend is significant based upon rejection of null hypotheses of the slope being not significantly different from zero at $\alpha = 0.01$, through a Student's t test. This increasing trend is found to be significant in recent years 2000–2003 using MODIS AOD (not shown).

3.1. Seasonal variation of AOD from MODIS

During the summer months from June to August, AOD is found to be significant which is attributed to the observed dust events in the northern part of India from the Saharan desert and from the north western dust bowls in Pakistan (Dey et al., 2004). Fig. 2 shows the seasonal variations of AOD. The AOD is found to increase from the month of March with maxima peak in the month of June over the mainland India, though strong AOD persists over neighboring Pakistan and the Arabian sea until August. The maximum AOD is observed over the northern parts of India, specifically over the IG plain and over the south the AOD is found to be low throughout the year.

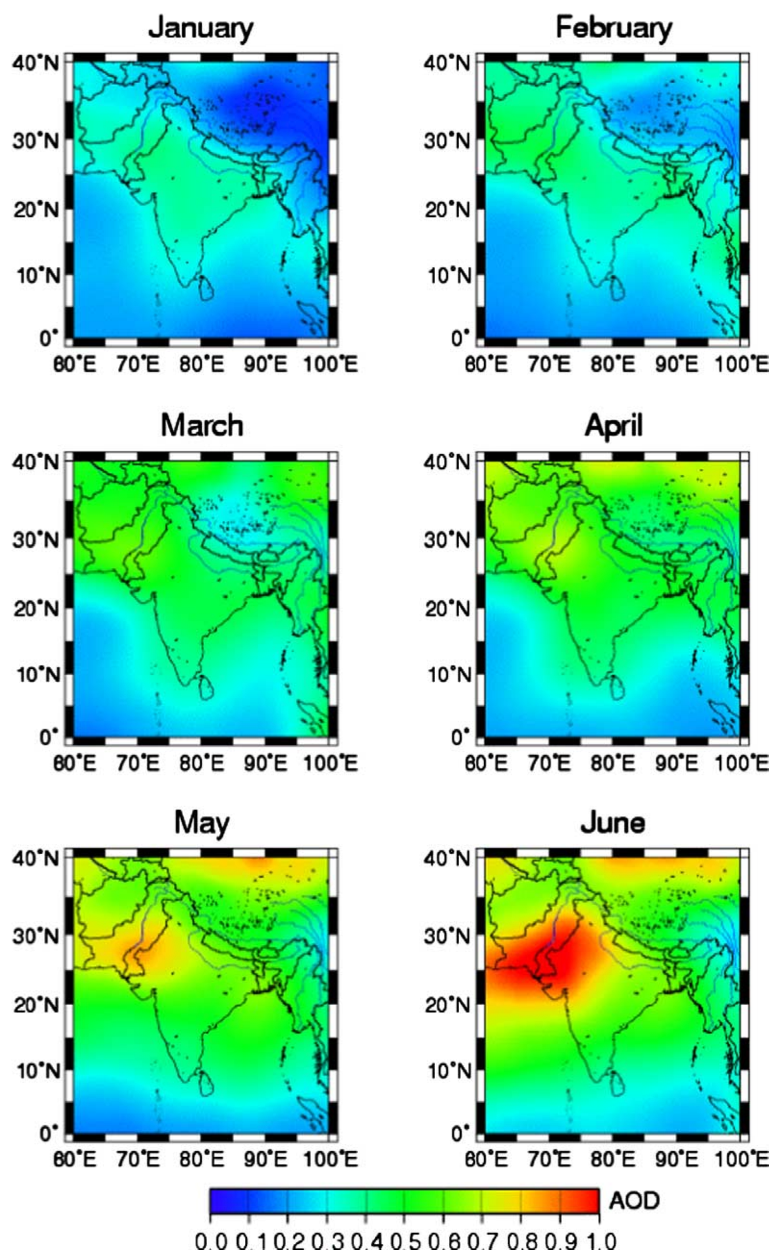

Fig. 2. Monthly variation of AOD, derived from MODIS, over the Indian sub-continent.

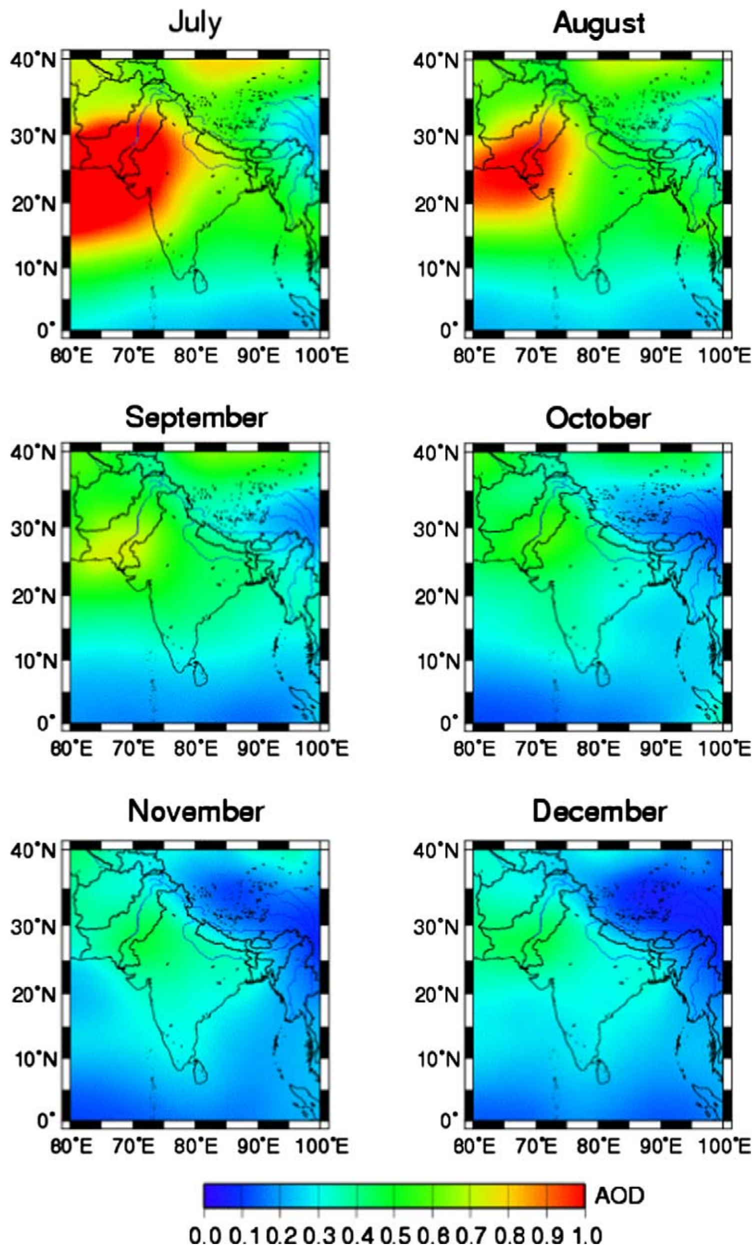

Fig 2. (*continued*)

4. Aerosol forcing

The knowledge of aerosol loading is important as it can change the weather and climate patterns by perturbing the radiation budget over any region. In order to understand the aerosol loading on regional radiation flux distribution, we have carried out numerical aerosol forcing calculations.

The top of the atmosphere (TOA) and surface radiative forcing are defined as the perturbation in the upscattered solar radiation flux (F_{up}) and surface reaching solar intensity (F_{down}), respectively, with change in the AOD. The surface radiative forcing has been calculated from the following equation (Charlson et al., 1992):

$$F_{\mathrm{Surf}} = -0.5 F_{\mathrm{T}} T^2 (1 - A_{\mathrm{c}})(1 - \bar{R}_{\mathrm{s}})^2 \bar{\beta} \tau,$$

where F_{T} is the solar constant (1370 W/m^2), T is surface temperature, A_{c} is the fractional cloud cover, $\bar{R}_{\mathrm{s}}$ is the mean albedo of the underlying surface, $\bar{\beta}$ is the fraction of the radiation scattered upward by the aerosol column and τ is the aerial mean optical depth of the aerosol. This formula has been shown to be quite effective in the vicinity of the Indian sub-continent by Dey et al. (2004). The TOA forcing is given as $F_{\mathrm{TOA}} = F_{\mathrm{CLR}} - F_{\mathrm{AERO}}$, where F_{CLR} is aerosol free flux estimate; F_{AERO} is the flux estimate over aerosol laden areas. The atmospheric forcing is given by the difference $F_{\mathrm{Atm}} = F_{\mathrm{TOA}} - F_{\mathrm{Surf}}$. The TOA forcing has been estimated using the CERES earth radiation budget data and the AOD data from MODIS data. Clear sky TOA shortwave (SW) flux from the CERES has been taken as an estimate of cloud free aerosol forcing (F_{AERO}) over dusty

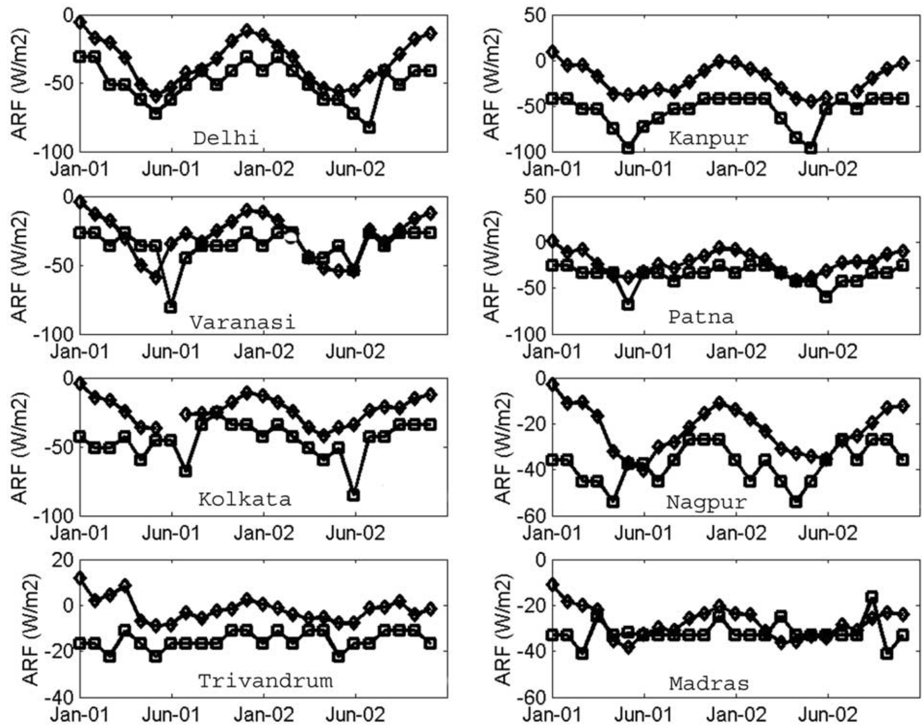

Fig. 3. TOA and surface forcing for the selected locations over the Indian sub-continent. The curves with diamond symbols are the TOA estimates and surface forcing is represented by the square symbols.

areas, while the aerosol free estimates of SW flux (F_{CLR}) comes from the observations from CERES where the collocated MODIS AOD is found to be <0.02 (Christopher and Zhang, 2002).

The global albedo and cloud cover fraction has been estimated from the climatological 2.5° × 2.5° values available as part of the International Satellite Cloud Climatology Project (ISCCP). The cloud fraction over India increases markedly during the summer months from July to August and thus biases the calculation for surface forcing. Hence, a single cloud fraction estimate derived by averaging the climatological values for one year is used for each location. The single scattering albedo (SSA) for the aerosol has been estimated to be 0.67 from an aerosol model comprising a mixture of soot, coarse minerals, transported minerals and sulphate particles using the optical properties and clouds (OPAC) database (Hess et al., 1998). Our aerosol mixture composition model is supported by observations of aerosol composition over the Indian Ocean by Krishnamurthi et al. (1998) and Satheesh and Ramanathan (2000).

The surface forcing is generally found to be higher compared to those of the TOA forcing for all the locations over the Indian sub-continent (Fig. 3). The AOD is found to be highest over India during summer season, as a result the surface forcing is found to be significantly higher over northern cities (Delhi, Kanpur, Kolkata, and Varanasi) which are located in the IG basin, whereas the surface and TOA forcing are almost the same over the southern locations (Trivandrum and Chennai) throughout the year. In contrast, atmospheric forcing on the contrary becomes lower during the summer season over the northern part of the IG basin. The high AOD during summer months also causes a higher TOA forcing over the north, thus making the difference between the surface and atmospheric forcing smaller (Table 1).

Fig. 4 shows the climatology of surface aerosol forcing over India and adjoining regions and shows the seasonal buildup of aerosols due to dust events in Sahara during summer seasons. It is seen that dust events start around March–April and culminate around August–September, with the maximum surface forcing over India due to transport of dust in the months June–July. During the winter months, the surface forcing is lower but still considerable and mainly restricted to the north Indian plain (IG). The winter aerosols are largely consist of sulphates and NO_x

Table 1
The mean atmospheric and surface forcing pattern over major Indian cities during summer and winter

Cities	Atmospheric forcing (W/m^2)		Surface forcing (W/m^2)	
	Winter	Summer	Winter	Summer
Delhi	19.09	15.27	−36.92	−67.18
Kanpur	39.79	38.27	−44.37	−70.97
Varanasi	14.83	3.62	−29.48	−46.36
Patna	18.38	15.85	−27.92	−46.73
Kolkata	28.10	23.47	−42.61	−56.29
Nagpur	24.32	5.26	−37.29	−38.05
Trivandrum	15.36	11.98	−16.01	−18.67
Madras	1.16	−9.97	−22.56	−22.43

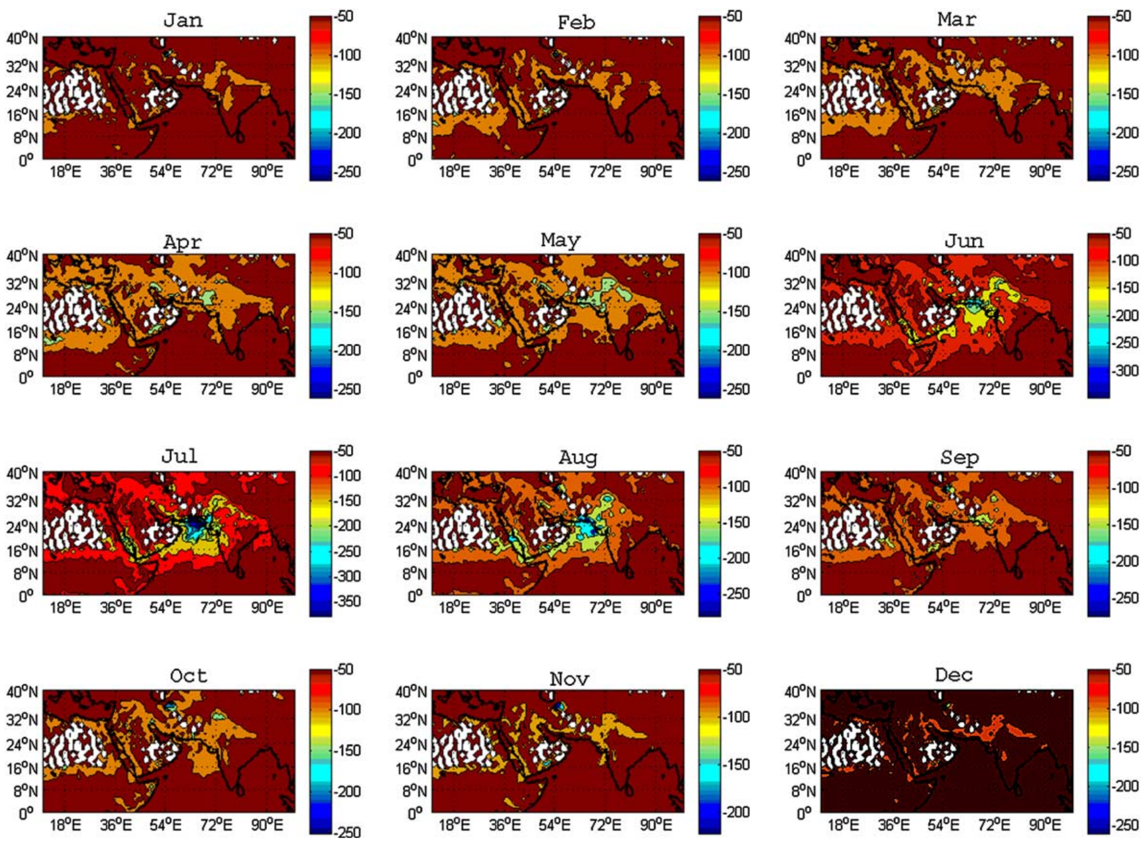

Fig. 4. Climatology of surface forcing pattern (in W/m^2) over South Asia and adjoining regions. The blank spaces in the figures are areas where calculation could not be extended because of missing values in CERES radiation data.

that are responsible for smog and haze, which are common over the IG plain during winter.

5. Conclusion

The results clearly show that the aerosol loading over the major cities in India has increased significantly in the recent years. Due to increasing population, urbanization and industralization, the AOD over the northern part of India is higher compared to southern part of India. The AOD shows contrast annual variability with higher aerosol loading due to dust events in the northern part of India. The surface and TOA forcing are found to be higher in the northern part compared to those of southern part of India which is attributed to the higher aerosol loading in the northern part. Due to higher AOD loading as a result of dust events, the higher TOA forcing over the north is found to be higher that leads to reduce the difference between the surface and atmospheric forcing smaller. The present results show the spatial pattern of dust loading and aerosol forcing over Indian region.

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