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Impact of drought and normal monsoon scenarios on aerosol induced radiative forcing and atmospheric heating in Varanasi over middle Indo-Gangetic Plain

Manish Kumar[a], M.P. Raju[b], R.S. Singh[c,d], Tirthankar Banerjee[a,d,*]

[a] *Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India*
[b] *National Centre for Medium Range Weather Forecasting, Noida, India*
[c] *Department of Chemical Engineering and Technology, Indian Institute of Technology (BHU), Varanasi, India*
[d] *DST-Mahamana Centre of Excellence in Climate Change Research, Banaras Hindu University, Varanasi, India*

A R T I C L E I N F O

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A B S T R A C T

Observations on aerosols with specific emphasis to black carbon (BC) are reported for an urban site over middle Indo-Gangetic Plain (IGP), South Asia. Emphases are made to evaluate variation in BC concentrations during typical monsoon season (June-September, JJAS) from 2009 to 2011, and to recognize its impact on aerosol radiative forcing (ARF) and atmospheric heating. Almost entire Indian sub-continent experienced a drought year in 2009 before achieving a normal monsoon in 2010 and 2011. The ground monitoring station in Varanasi over middle-IGP experienced minimum monsoonal rain during 2009 drought year (total monsoon rain: 437.3 mm), which gradually increased during 2010 (deficit monsoon, 613.4 mm), before achieving a normal monsoon in year 2011 (1207.0 mm). The BC mass loading during drought year was relatively high (mean ± SD: 7.0 ± 3.3; range: 5.3–8.8 $\mu g\ m^{-3}$) compared to 2010 (4.9 ± 2.1, 3.7–5.8 $\mu g\ m^{-3}$) and 2011 (4.6 ± 2.1, 3.2–5.2 $\mu g\ m^{-3}$). The increase in BC aerosols especially during drought year was associated to lower wind speed and reduced rate of wet removal, which potentially enhanced BC loading in comparison to years with normal monsoon. Columnar aerosol loading in terms of aerosol optical depth (AOD) was retrieved from space-borne MODerate resolution Imaging Spectroradiometer (MODIS) sensor on-board Terra satellite. It has revealed high AOD over Varanasi during drought (2009: 1.03 ± 0.15) and deficit monsoon (2010: 1.07 ± 0.53) before being reduced during 2011 (0.89 ± 0.20). Conclusively, a radiative transfer model was run to estimate the ARF for composite aerosols for both surface (SUF), atmosphere (ATM) and top of the atmosphere (TOA). The 2009 drought year was found to have reasonably higher ATM and SUF forcing (ATM: 105; SUF: − 122 $W\ m^{-2}$) in comparison to deficit (ATM: 61; SUF: − 88 $W\ m^{-2}$) and normal (ATM: 67; SUF: − 89 $W\ m^{-2}$) monsoon scenarios. The lower atmosphere heating rates during 2009 monsoon was also recorded to be as high as 2.9 $K\ day^{-1}$ in comparison to 2010 (1.7 $K\ day^{-1}$) and 2011 (1.9 $K\ day^{-1}$). Such findings provide meaningful outcomes in terms of climatic effects of BC aerosols and their associated inference on Indian summer monsoon.

Capsule: BC induced aerosol radiative forcing during 2009 drought year was higher in comparison to deficit (2010) and normal (2011) monsoon scenarios over middle IGP.

* Corresponding author.
E-mail addresses: tb.iesd@bhu.ac.in, tirthankaronline@gmail.com (T. Banerjee).

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1. Introduction

Black carbon (BC), commonly referred as soot particle, is an integral part of combustion process and contributes significantly in absorbing visible solar radiation and thereby, pose potential in affecting thermal structure of atmosphere (Wang, 2004). The BC potentially modify the atmospheric stability within the boundary layer and free troposphere (Babu et al., 2011). It may also extend from surface to higher elevation, induce significant heating in mid-troposphere and perturbs large-scale modulations in atmospheric circulation (Lee & Kim, 2010). On the contrary, BC also induce strong extinction of solar radiation and thereby, leads to a reduction of insolation, and exhort a very complicated effect on regional hydrological cycle. Besides its direct role in atmospheric heating, there are experimental evidences of its indirect effects on modifying cloud microphysical properties and residence time. Aerosols could alter cloud properties both by microphysical interactions as well as on a more macroscopic scale including entire cloud systems. Aerosol-cloud interactions contribute single largest uncertainty in estimating Earth's energy budget by inducing rapid adjustment in aerosol-cloud-radiation interaction (Myhre et al., 2013). BC embedded in cloud droplets increases its potential absorption which simultaneously affects dissipation of cloud (Bond et al., 2013), while cloud cover is also expected to reduce in presence of BC embedded in the cloud layer (Koren, Kaufman, Remer, & Martins, 2004). Therefore, BC induced modification in atmospheric stability affects global atmospheric circulation and the hydrological cycle, which is often considered as a major challenge for 21st century.

The global BC emission has raised from 8 Tg Cyr^{-1} to 17 Tg Cyr^{-1} (Bond et al., 2004, 2013) with consequent amplifications in its global mean radiative forcing from + 0.20 (IPCC, 2007) to + 0.40 $W m^{-2}$ (IPCC, 2014). These multi wavelength light absorbing particles (Bond et al., 2013) of primary origin are emitted through incomplete combustion of fossil fuels, biomass/ wildfire and aircraft emissions. However, the BC emission vary greatly depending on the source strength. Nearly 60–80% of BC emission in Asian and African countries are contributed through coal and biomass burning while the scenarios in European countries is mostly dominated by automobiles (nearly 70%, Sanap & Pandithurai, 2015). The global budget of BC is contributed by the emissions from combustion of fossil fuels (38%), biofuels (20%), and open biomass burning (42%) (Bond et al., 2004). The BC emissions and its climatic effects are reported throughout the globe, but more extensively over few regional hotspots (e.g. Indo-Gangetic Plain, Eastern China; South-East Asia); regions affected by its trans-boundary movements (e.g. Arctic region) or due to the auxiliary effects of both (e.g. South-East Asia). Trans-boundary movement of BC facilitated by atmospheric circulation is attributed to their finer size and higher atmospheric life time (7–10 days) relative to other short-lived pollutants. The presence of BC aerosols even in pristine regions i.e. Svalbard Arctic Circle (Raju, Safai, Sonbawne, & Naidu, 2015) and Himalaya (Sarkar, Chatterjee, Singh, Ghosh, & Raha, 2015) emphasizes the role of its long range transport. The contributions of Asian region in the global BC budget have often been reported largest (Lamarque et al., 2010). However, scientific understanding on BC emissions and its climatic effects over Asia still consist large uncertainties, mainly due to availability of proper ground monitoring network.

Several hypotheses on the impacts of aerosols on Indian summer monsoon have been given with varying degrees of certainties. Lau and Kim (2006) emphasized the role of absorbing aerosols in enhancing premonsoon rainfall, and its reduction in monsoon period due to enhanced local meridional circulation. Lau, Kim, and Kim (2006) hypothesized that the absorbing aerosols (e.g. BC) can combine with mineral dust and increase the meridional temperature gradient, which further contribute to increased rainfall both during the pre- and summer monsoon. Ramanathan et al. (2005) using a global coupled climate model, recognized the implications of BC aerosols in reducing sea-surface temperature and thereby, reducing monsoonal rain over Indian subcontinent. Meehl, Arblaster, and Collins (2008) by twentieth-century simulations using BC aerosols in a global coupled climate model, hypothesized increased meridional tropospheric temperature gradient in the premonsoon months, which possibly contribute enhanced precipitation over India. However, during monsoon, the contribution of BC aerosols was reported to be negative. Bollasina, Nigam, and Lau (2008) speculated anomalous aerosol loading in late spring, which leads to large-scale variations in the evolution of monsoon over South Asia. Presence of massive aerosols during premonsoon lead to a decrease in cloudiness, thereby reduction in precipitation, increase in shortwave radiation at the surface, and subsequent heating of the ground. Overall, the effects of absorbing aerosols on monsoon was reported to be negative over much of the subcontinent. The contribution of active monsoon breaks (Manoj, Devara, Safai, & Goswami, 2010) characterized by higher anthropogenic aerosols can further modify the summer monsoon and augment the precipitation. In addition to the major source regions, the impacts of BC aerosols can also be extended to other areas and can influence precipitation and sea surface temperature (Wang, 2007). Recently, there are evidences of positive implications of local and remote absorbing dust aerosols (especially from Middle-East Asia) on Indian summer monsoon (Jin, Wei, & Yang, 2014; Jin, Wei, Yang, Pu, & Huang, 2015), while the degree of response is projected to be highly sensitive to the absorbing abilities of aerosols (Jin, Yang, & Wei, 2016). Using a high-resolution regional climate model coupled with online chemistry, Jin et al. (2016) concluded both the magnitude and direction of dust-induced monsoon rainfall changes are highly sensitive to aerosol absorptive properties, as dust aerosols with stronger absorption can result in larger increases of the monsoonal rainfall.

India contributes (0.41 Tg $(BC)yr^{-1}$) substantial proportion of global BC emission (8 Tg yr^{-1}, Bond et al., 2004) with a variety of sources based on different land-use pattern, burning of biofuels (0.17 Tg $(BC)yr^{-1}$), open biomass (0.14 Tg $(BC)yr^{-1}$) and fossil fuel (0.10 Tg $(BC)yr^{-1}$) (Venkataraman, Habib Fernandez, Miguel, & Friedlander, 2005). The explicit use of conventional fuels and less efficient combustion technologies in rural India contribute maximum BC emissions (Banerjee, Kumar, Mall, & Singh, 2017; Venkataraman et al., 2005). Despite of such huge burden, their associated impacts on precipitation and monsoon or vice-versa are sparsely documented. For the present submission, efforts are made to identify the impact of normal and drought monsoon scenarios on regional BC concentrations and associated radiative impacts for a typical urban station over middle-IGP. We have investigated both the diurnal and inter-annual variations of BC for different monsoon scenarios to recognize its radiative effects and its potential to modify the atmospheric thermal structure within the boundary layer. Note that, we have only investigated the radiative impacts of BC over different monsoon scenarios, but have not considered any microphysical effects of BC aerosols on the formation of cloud and