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Invited review article

The effect of absorbing aerosols on Indian monsoon circulation and rainfall: A review

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ABSTRACT

Aerosol, an uncertain component of the climate system, has attracted wide attention among the researchers due to its role in hydrological cycle and radiation budget in a changing climate. According to IPCC 5th assessment report, current understanding of aerosol–cloud–precipitation interaction is low to moderate, as a result they are not well represented in the climate models, and in turn are recognized as major uncertainties in the future climate projections. In South Asian monsoon regions, the aerosol forcing response to water cycle is even more complicated. Substantial amount of transported dust from Middle East countries and adjacent deserts get accumulated over Indian subcontinent (mainly North India and Indo Gangetic Plains; IGP) and further coated with black carbon (BC) produced from local emission, which make the atmospheric physics and chemistry of the aerosol more complex over the region. Here we review earlier studies and recapitulate our current understanding of absorbing aerosols on Indian monsoon circulation and rainfall from observational evidences and variety of numerical model simulations. This review begins with current understanding of the absorbing aerosols and interactions with Indian summer monsoon, followed by discussion on various working hypotheses, observational and modeling perspective, local and remote impacts. The key open questions and suggestions for future research priorities are delineated to improve the current understanding about the relationship between absorbing aerosols and Indian summer monsoon.

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1. Introduction

Atmospheric aerosols are highly variable in space and time with their physical, chemical, optical and radiative properties. Though most aerosols scatter the incoming solar radiation, some also absorb it. An aerosol effect on light depends mainly on the composition and size of the particles. In general, bright-colored particles tend to reflect radiation back to space. Dark aerosols can absorb considerable amounts of incoming solar radiation. Scattering aerosols like sulfates, nitrate, and sea salt reflect nearly all radiation they encounter and in turn cool the atmosphere as well as the Earth's surface. On the contrary, absorbing aerosols (e.g., black carbon; BC, dust, and brown carbon) absorb the incoming solar radiation, not only warming the atmosphere but also dimming the surface. The main sources of BC aerosols are diesel engines, industries, and residential solid fuels and open burning. The largest global

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BC sources are open burning of forest savannas. Other BC sources are location dependent. For e.g., coal and biomass burning contributes 60–80% of the Asian and African BC emission. On the other hand, diesel engine contributes about 70% of the BC emission (on road and off road) in Europe. Residential coal burning is a significant source of BC in China (Bond et al., 2013). Basic characteristics of BC as discussed in Bond et al. (2013) are as follows: i) The BC strongly absorbs the visible light (with mass absorption ~5 $m^2\ g^{-1}$), (ii) it retains its basic form at very high temperature (~4000 K), (iii) it is insoluble in water and organic solvents, and (iv) it is found as an aggregate of small carbon spherules. The absorption properties of BC highly depend on combustion temperature and carbon emission during the combustion process (Bond and Bergstrom, 2006). No other substance with such high light absorption per unit mass is present in the atmosphere. BC also has very low chemical reactivity; therefore it is removed from the atmosphere by dry deposition or wet removal due to rain. Brown carbon, a part of organic aerosols also considered as the one of the significant contributor for absorption of the light. Light absorption by brown carbon is relatively weak as compared to BC. Unlike BC, brown carbon absorption is wavelength dependent (Kirchstetter et al., 2004) and it is soluble in some of the organic compounds (Andreae and Gelencsér, 2006). The recent laboratory experiment by Liu et al. (2013) demonstrated that the single scattering albedo (SSA) for fresh biomass burning aerosols varies strongly with fire integrated combustion efficiency. They clarify that, higher fire integrated combustion efficiency results in lower SSA values and greater spectral dependence of SSA.

In addition to BC and organic/brown carbon, dust also absorbs light in visible radiation. Large amount of the atmospheric dust originates from deserts (Chin et al., 2009) and smaller amounts come from construction, road traffic, agriculture etc. Dust particle absorption per unit mass is weaker than that of the BC (Clarke et al., 2004). They are larger in size and abundant in the atmosphere as compared to other absorbing aerosols. Absorbing aerosols supplement the global warming in addition to green house gases (GHG). However, unlike the GHGs, understanding the effect of absorbing aerosol on climate is critical due its high temporal–spatial variability and to insufficiency of the high resolution (space and time) data. Soot also known as BC is highly absorbing type of aerosols (Bond and Bergstrom, 2006) with estimated climate forcing $+0.71$ ($+0.09$ to $+1.26$) Wm^{-2} (Bond et al., 2013), snow/albedo forcing ~$+0.05\ Wm^{-2}$. Lack of knowledge about cloud interaction with BC contributes to the major uncertainties in net climate forcing due to BC (Forster et al., 2007; Bond et al., 2013; IPCC, 2014). Climate projection study on mitigation effect of short lived climate pollutants (e.g., methane, tropospheric ozone, hydro-fluorocarbons and black carbon) on sea level rise has been discussed by Hu et al. (2013). According to their analysis, the mitigation of short lived climate pollutants can reduce the sea level rise rate by 24–50% and cumulative sea level rise by 21–44% by year 2100. The comprehensive assessment study on role of anthropogenic absorbing aerosols on precipitation and clouds is explained by Wang (2013). While, Wang (2013) focuses on global effects of absorbing aerosols on clouds and precipitation, here we concentrate on the studies on the effect of absorbing aerosols on Indian summer monsoon.

Indian subcontinent is one of the densely populated, industrialized and developing regions of the world. Aerosol over the region affects not only the monsoon system, but also the global climate (Ramanathan and Carmichael, 2008). The BC observations over various Indian cities in the past shows high BC loadings (Babu and M.K.K., 2002; Ganguly et al., 2006; Ramachandran and Cherian, 2008; Safai et al., 2007). Latitudinal variation of the aerosol distribution over Indian region shows that aerosol concentration increases from South to North with maximum over the IGP region (see Fig. 1). During pre-monsoon season, the aerosol loading peaks over the regions of IGP, North India as well as elevated slopes of the Himalayas (Pant et al., 2006; Ram et al., 2010; Sanap et al., 2014). The IGP, one of the highly polluted and populated regions of the Indian subcontinent records dominance of absorbing type of aerosols (e.g., dust, BC, and OC) and recognized as one of the regional BC hotspot (Ramanathan and Ramana, 2005; Niranjan et al., 2007; Prasad and Singh, 2007; Gautam et al., 2011; Giles et al., 2011; Praveen et al., 2012; Srivastava et al., 2012). The prevailing westerly air-mass causes large influx of mineral dust, originating over the arid and desert regions of Southwest Asia to Thar Desert. This transported dust further mixed with local anthropogenic emissions over IGP (Dey et al., 2008). Recent study by Srivastava and Ramachandran (2013) demonstrated that degree of mixing i.e., percentage of mass fraction of aerosols involved in core shell mixing is found to have seasonal variation. However, absence of the study on quantification between the solar absorption in internal and external mixtures over IGP limits our knowledge on the topic. Because of the Himalayan barrier, dust accretion is high over IGP and foothills of Himalaya. Convective activities during pre-monsoon and monsoon season and large scale topography variation allow dust particle to reach vertically up to middle to upper troposphere (Lau and Kim., 2006; Liu et al., 2008; Gautam et al., 2009a,b,c; Vinoj et al., 2014) leading to enhanced absorption of solar radiation and regional tropospheric warming (Satheesh et al., 2008). The modeling study by Wang (2004) demonstrated that the effect of BC on weather and climate is more significant in regional scale than in the global scale. He also suggested the importance of coupled climate models to deal with the problems related to climate impact of the aerosols.

Absorbing aerosols surrounded in or near a cloud layer heat the layer and endorse cloud evaporation. This is called as "semi-direct effect", first illustrated by Hansen et al. (1997). Cloud burn-off gives more opportunity to absorbing aerosols to heat the atmosphere (Jacobson, 2002; Koch and Del Genio, 2010). Large eddy simulation study by Ackerman (2000) showed that boundary layer absorbing aerosols decrease the relative humidity, increase the rate of cumulus cloud detrainment, and stabilize the boundary layer, which further lead to reduction in cumulus cloud fraction. Recent studies have suggested that the study on semi-direct/indirect effects over Indian subcontinent is important to understand the aerosol–monsoon interactions in a changing climate more clearly (Bollasina et al., 2008; Nigam and Bollasina, 2010; Panicker et al., 2014; Sanap and Pandithurai, 2014). The role of absorbing aerosols on monsoon has drawn significant attention worldwide through rapidly increasing publications in the literature (Ramanathan et al., 2001; Menon et al., 2002; Chung and Ramanathan, 2004; Lau et al., 2006; Lau and Kim, 2006, 2010; Meehl et al., 2008; Gautam et al., 2009a; Wang et al., 2009; Manoj et al., 2010; Ganguly et al., 2012a,b; Lee et al., 2013). As aerosol distributions and processes over Indian subcontinent are not appropriately represented in many of the global climate models (GCMs) (Sanap et al., 2014), it is important that monsoon response to the absorbing aerosols needs to be examined with more refined GCMs and correct representation of aerosols. This review focuses on assessment and analysis of the absorbing aerosol and Indian monsoon relationship using observational as well as modeling studies. The research efforts and results of role of the absorbing aerosols in modulation of the Indian monsoon rainfall and circulation will be discussed in the following sections presenting respectively the elaborative information about hypotheses on absorbing aerosols–monsoon relationship, observational and modeling studies, local and remote impacts.

2. Hypotheses on absorbing aerosols and Indian summer monsoon

Absorbing aerosol induced heating during pre-monsoon season over the southern slope of the Tibetan Plateau, IGP and northern India draws warm and moist low level inflow from Northern Indian Ocean as the monsoon season approaches. The deep convection forces the enhanced upward motion which further heats up the troposphere through release in latent heat of condensation, leads to enhanced local meridional circulation with rising motion over northern India and foothills of Himalayas and sinking motion over Northern Indian Ocean. Once the monsoon sets in over Indian region, aerosol loading reduces due to rainout and washout, but anomalous deep convection, which set up in May continues to amplify and strengthen the meridional overturning circulation through release of latent heat of condensation. This mechanism was