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Tethered balloon-born and ground-based measurements of black carbon and particulate profiles within the lower troposphere during the foggy period in Delhi, India

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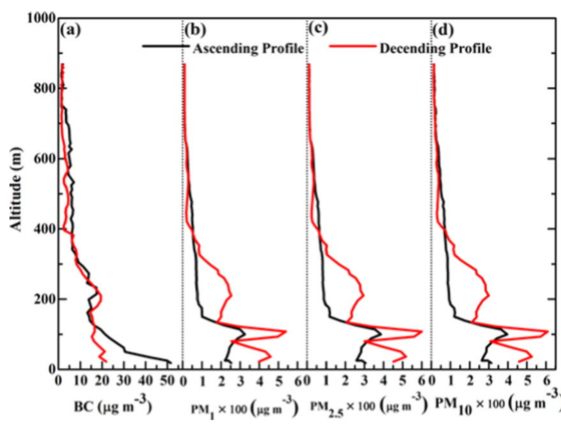
HIGHLIGHTS

- First time - a tethered balloon-based soot measurement in a megacity "Delhi".
- Sign. higher BC conc.(~1.9 μg/m^3) near the boundary layer (BL) during the foggy period
- ~20% contribution of BC to near ultrafine particles ($PM_{1.0}$) at surface and BL
- Cons. of $BC_{370\ nm}$ and PM_{10} increased ~85% & 46% during dense foggy period.
- Higher heating (2.71 K day^{-1}) due to BC, influences regional climate.

GRAPHICAL ABSTRACT



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ABSTRACT

The ground and vertical profiles of particulate matter (PM) were mapped as part of a pilot study using a Tethered balloon within the lower troposphere (1000 m) during the foggy episodes in the winter season of 2015–16 in New Delhi, India. Measurements of black carbon (BC) aerosol and PM <2.5 and 10 μm ($PM_{2.5}$ & PM_{10} respectively) concentrations and their associated particulate optical properties along with meteorological parameters were made. The mean concentrations of $PM_{2.5}$, PM_{10}, $BC_{370\ nm,}$ and $BC_{880\ nm}$ were observed to be 146.8 ± 42.1, 245.4 ± 65.4, 30.3 ± 12.2, and 24.1 ± 10.3 μg m^{-3}, respectively. The mean value of $PM_{2.5}$ was ~12 times higher than the annual US-EPA air quality standard. The fraction of BC in $PM_{2.5}$ that contributed to absorption in the shorter visible wavelengths ($BC_{370\ nm}$) was ~21%. Compared to clear days, the ground level mass concentrations of $PM_{2.5}$ and $BC_{370\ nm}$ particles were substantially increased (59% and 24%, respectively) during the foggy episode. The aerosol light extinction coefficient (σ_{ext}) value was much higher (mean: 610 Mm^{-1}) during the lower visibility (foggy) condition. Higher concentrations of $PM_{2.5}$ (89 μg m^{-3}) and longer visible wavelength absorbing

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Biomass/biofuel
Climate change

$BC_{880\ nm}$ (25.7 μg m^{-3}) particles were observed up to 200 m. The $BC_{880\ nm}$ and $PM_{2.5}$ aerosol concentrations near boundary layer (1 km) were significantly higher (~1.9 and 12 μg m^{-3}), respectively. The BC (i.e BC_{tot}) aerosol direct radiative forcing (DRF) values were estimated at the top of the atmosphere (TOA), surface (SFC), and atmosphere (ATM) and its resultant forcing were - 75.5 Wm^{-2} at SFC indicating the cooling effect at the surface. A positive value (20.9 Wm^{-2}) of BC aerosol DRF at TOA indicated the warming effect at the top of the atmosphere over the study region. The net DRF value due to BC aerosol was positive (96.4 Wm^{-2}) indicating a net warming effect in the atmosphere. The contribution of fossil and biomass fuels to the observed BC aerosol DRF values was ~78% and ~22%, respectively. The higher mean atmospheric heating rate (2.71 K day^{-1}) by BC aerosol in the winter season would probably strengthen the temperature inversion leading to poor dispersion and affecting the formation of clouds. Serious detrimental impacts on regional climate due to the high concentrations of BC and PM (especially $PM_{2.5}$) aerosol are likely based on this study and suggest the need for immediate, stringent measures to improve the regional air quality in the northern India.

1. Introduction

Black carbon (BC) particles are primary particles emitted into the atmosphere as a product of incomplete combustion of hydrocarbon-containing materials including biofuel/biomass and fossil fuels. Their emission has rapidly increased several folds and represents an important component of atmospheric particulate matter (PM) (IPCC, 2013; Bond et al., 2013). Being, light-absorbing particle, it plays a similar role to greenhouse gasses as a cause of climate warming. They also impair visibility and affect the atmosphere indirectly by changing the properties of liquid cloud droplets and ice nuclei (Ramanathan and Carmichael, 2008; Bond et al., 2013). They have chain aggregate morphologies, are insoluble in water and common organic solvents, and have strong light absorption in the visible range with an average 7.5 m^2 g^{-1} (550 nm) and vaporization temperature of ~4000 K (Bond and Bergstrom, 2006). BC deposited on snow and ice can reduce the surface albedo and accelerate melting (Flanner et al., 2007; IPCC, 2013). BC also adversely affects human health through inhalation of the BC particles that can include adsorbed harmful materials like polycyclic aromatic hydrocarbons (Dachs and Eisenreich, 2000). Because of its adverse effects on both human health and climate, reducing BC is viewed as a policy strategy target with potential co-benefits (Anenberg et al., 2012).

South Asia (SA) has been rapidly increasing in population density, urbanization, industrialization, and resulting energy demands over the last four decades, and consequently, there have been many fold increases in the emissions of atmospheric particles as well as gaseous pollutants (Oshima et al., 2009; Lawrence and Lelieveld, 2010 and references therein). The atmospheric aerosol over this region is a major factor contributing to regional atmospheric warming, interruption in precipitation patterns, an increase of storms, and melting of the Himalayan glaciers and snow (Ramanathan et al., 2007; references therein). Because of the variety of particulate matter sources and sinks, the influence of meteorological mixing processes and the interaction with clouds, there are large uncertainties in understanding its influence on the regional/global climate change. Shiraiwa et al. (2008) conducted a study on the mixing state and size distribution of aerosol by a ground-based single particle soot photometer at a remote island in Japan and found that the absorption coefficient was around three times higher when the air masses passes from Asian continental at receptor site than in the clean air.

Over the Indian subcontinent, the distribution of aerosol influences the heating stability and thermal structure of the atmosphere (Menon et al., 2002; Lau and Kim, 2006; Ramachandran and Kedia, 2010; Chakraborty et al., 2012; Lee et al., 2016). Despite the fact that the surface aerosol concentrations and columnar properties by means of lidar, aircraft, or balloons have been examined over SA, near-surface vertical aerosol profiles have not been well monitored and documented except in a few studies (Satheesh et al., 2006; Tripathi et al., 2007; Rajeev et al., 2010; Komppula et al., 2012; Misra et al., 2012; Sinha et al., 2013; and references therein).

The most observations of BC and PM (in broad size ranges) have been made at surface level. However, atmospheric pollution management and modeling groups require an understanding as well as its characteristics within the boundary layer (lower troposphere). The importance of vertical distributions of BC to the evolution of planetary boundary layer and cloud properties have been demonstrated by prior studies for altitudes of up to 10 km using aircraft (Corrigan et al., 2008; Ramanathan and Carmichael, 2008; McMeeking et al., 2010; Ferrero et al., 2011a,b; Hara et al., 2013; Oshima, et al., 2013; Samset et al., 2013; Li et al., 2015; Zhao et al., 2015; Zhong et al., 2015; Ran et al., 2016). However, the vertical profiles of BC aerosol have been measured in a few field campaigns in India (Tripathi et al., 2007; Babu et al., 2011; Safai et al., 2012; Sinha et al., 2013; Rahul et al., 2014) producing limitations on reliably estimation of regional climatic effects of BC under severe atmospheric pollution conditions driven by rapid economic growth by industrialization, urbanization, etc. In Delhi, no vertical distributions of air pollutants have been made until those being reporting in this work.

BC is the primary particulate species investigated in this study and the main objectives are to explore the characteristics of BC, PM, and meteorological conditions profiles (a pilot study using a tethered balloon of the vertical observation), within the boundary layer over the highly polluted megacity Delhi in the northern India during the foggy period. In addition to this, observations of BC and PM were conducted over the whole winter season at the ground level to obtain a better understanding of the climatic impacts of atmospheric particles. The results from the present study will also help in the improvement of forecasts by regional air quality models in the foggy conditions.

2. Experimental setup

2.1. Experimental area and instrumentation

A pilot field campaign was operated in Delhi (28°37′N, 77°12′E, ~218 m amsl) for the measurement of the surface meteorological parameters (MP), surface particulate matter (PM) and black carbon (BC), vertical profiles of BC, PM, wind speed (WS), wind direction (WD), temperature (Temp), and relative humidity (RH) during the winter period of 2015–16 at 15 m above to the ground level. The sampling site for vertical profiles of BC, PM, and MP measurement was on the premises of the Indian Institute of Tropical Meteorology (IITM), New Delhi Branch located near the National Physical Laboratory (Fig. 1). The site (urban background with heavier traffic density in the morning and evening) is surrounded by a greenbelt on three sides and a major link road leading to the Gurgaon, Haryana on the other side (Tiwari et al., 2015a,b). Delhi has a semi-arid climate and is located in between the rain-washed Indo-Gangetic plains (IGP) which is one of the highly populated and polluted regions in the world, and the semi-arid tracts of Rajasthan to the east and southwest. The city, is ~1100 km away from the Arabian Sea, has ~17.8 million inhabitants, and is the fourth most polluted city