Enhanced layer of black carbon in a north Indian industrial city

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[1] During a comprehensive aerosol field campaign as part of Indian Space Research Organization Geosphere Biosphere Programme (ISRO-GBP), aircraft measurements of vertical profiles of aerosol black carbon (BC) were made during winter, for the first time, at Kanpur (80°20′E and 26°26′N), an urban industrial location in Northern India. Two vertical profiling from the same day (morning and afternoon) of BC showed that BC decreases with height up to ~600 m and then increases up to 900 m before becoming more or less constant with height. Potential temperature profile, derived from concurrent measurements of temperature, shows a stable layer at the same altitude where BC shows increased concentration. This vertical structure of boundary layer was further confirmed by separate temperature and relative humidity profiles obtained from balloonsondes during December. The increased BC at ~900 m suggests the presence of enhanced BC layer, which will have significant implications to BC radiative forcing and modifying cloud properties. **Citation:** Tripathi, S. N., S. Dey, V. Tare, S. K. Satheesh, S. Lal, and S. Venkataramani (2005), Enhanced layer of black carbon in a north Indian industrial city, *Geophys. Res. Lett.*, *32*, L12802, doi:10.1029/2005GL022564.

1. Introduction

[2] Black carbon (BC) aerosols are strong absorber of the solar radiation in the visible and near-infrared wavelengths contributing significantly to positive radiative forcing in the range of +0.16 W/m^2 to +0.80 W/m^2 [*Jacobson*, 2001]. The large uncertainties in BC radiative forcing arise due to insufficient information on its source and lack of proper estimates. But the positive forcing represents a considerable amount of heating of the lower atmosphere and has been conjectured as a potential factor causing global warming [*Jacobson*, 2001].

[3] Very high values of BC up to 12 μg m^{-3} were reported at altitudes 2.5 km from aircraft measurements during TRACE A experiment over Brazilian Forests [*Pereira et al.*, 1996]. *Novakov et al.* [1997] have found that BC mass fraction increases with altitude during aircraft measurements in the eastern coast of United States. During the Indian Ocean Experiment (INDOEX) and studies during ACE-Asia have indicated the presence of substantial amount of BC at altitudes up to ~5–6 km [*Mayol-Bracero et al.*, 2002]. Elevated BC layer over landmass with high reflectance or over scattering aerosol layer will enhance the atmospheric forcing and can even reverse the 'white house effect' [*Satheesh*, 2002].

[4] Direct radiative forcing due to BC crucially depends on the vertical profile of BC [*Haywood and Ramaswamy*, 1998]. Thus altitude variation of BC is very important in estimating its radiative forcing and influence on cloud properties. Limited information worldwide, and even fewer in India, is available on the altitude profile of BC despite its importance [*Moorthy et al.*, 2004]. Only one such attempt has been made in India to measure vertical profile of BC in Hyderabad (southern India, Figure 1a) [*Moorthy et al.*, 2004]. In this paper, we present the results of a pilot study, made for the first time in Northern India, for measuring the altitude variation of BC aerosols over an urban and near city location, Kanpur (an industrial city in Indo Gangetic basin) during the winter season.

2. Data and Methodology

2.1. Site Location

[5] Altitude and latitudinal profiles of BC aerosols were made (using aircraft measurements) in Kanpur (80°20′E and 26°26′N and 142 m altitude from mean sea level) (Figure 1a) as a part of the ISRO-GBP Land Campaign (LC)-II in January 2004. Kanpur is an industrial city with ~3.2 million population in the Indo-Gangetic basin where foggy conditions prevail during the winter season and is considered as highly polluted region. Altogether three sorties were made; two on January 4 in the morning and the afternoon (hereafter referred as experiment 1) and one in the afternoon on January 12 (hereafter referred as experiment 2). First two sorties were made with an aim to measure the vertical concentration of BC whereas the third one collected the information about latitudinal variation in BC in and around the city of Kanpur. On January 4 the morning flight took off at 10:39 local time (LT) and the aircraft flew up to an altitude ~2 km and continuous measurements were made during the flight until it landed at 11:58 LT (Figure 1b). In the afternoon, similar path has been followed during the flight from 16:06 to 17:35 LT. The wind speed during this experiment was moderate (3.96 km hr^{-1}) and the wind was mostly northeasterly. On January 12, the aircraft flew from IIT-Kanpur campus at 16:37 LT towards nearby industrial area, crossing the city

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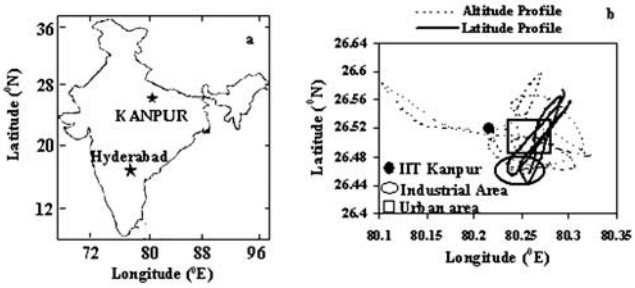

Figure 1. (a) Location of study area and (b) flight path for the altitude profile on January 4 and latitude profile on January 12 in and around Kanpur. For altitude profile, similar path has been taken both in the morning and in the afternoon. Location of IIT Kanpur and the extent of industrial and urban area are shown in Figure 1b; where as the rest of the area is rural.

and headed towards the rural area and returned to industrial area at the same altitude (Figure 1b). Three such rounds were made at 300, 600 and 900 m above ground level (AGL, ~142 m from mean sea level), to measure BC concentration at different altitude and latitude. The duration of the flight during experiment 2 was of 1 hr 10 min.

2.2. Experimental Details

[6] Piper Super Cub PA-18 manufactured by M/s Piper Aircraft Corporation, USA is an unpressurised high wing light airplane, which has been used for the experiments. It is a part of fleet at IIT-Kanpur. It is powered by one 150 HP Lycoming O-320 engine manufactured by Textron Lycoming, USA. Basic structure of this airplane is of tubular construction and covered by fabric. This aircraft can fly up to an altitude of 3000 m without oxygen but it was flown only up to 2000 m in the present experiments due to safety reasons. Being a high wing, it has excellent ground view, which helped locating the plumes, if any, during the flight. The undercarriage system is of tail wheel type with fixed main landing. An Aethalometer was placed inside the aircraft for measuring BC concentration. The instrument was connected with a Teflon pipe to the air suction. The inlet was placed at the wind strut, which was away from the exhaust and propeller slip stream. The instrument was powered with two batteries and an UPS with power back up for about one and half hour, which was sufficient for all the three flights. Measurements have been taken continuously from 10 minutes before the take off of the aircraft and continued up to 10 minutes after its landing. Temperature data were measured simultaneously with BC measurements and the coordinate of each BC measurement has been measured with a hand-held Global Positioning System receiver during both the experiments.

[7] The Aethalometer (AE-21-ER) and accessories such as size selective inlet BGI Sharp cut cyclone (model SCC-1.828) and filter tape are from Magee Scientific, Berkeley, USA [*Hansen*, 1996]. The instrument was operated at a flow rate of 6.5 liters/min and at an average time base of 1–3 min depending upon the experiment. The instrument is fully automatic and completely self-contained and uses a continuous filtration and optical transmission technique to measure BC concentration in near real time. The instrument has been factory calibrated and errors in the measurements are ~±10%.

2.3. Data Analysis

[8] The Aethalometer was set to operate at standard temperature (T_1 = 293 K) and pressure (P_1 = 1017 mb). This has to be adjusted (equation (1)) when the aircraft flies at high altitude, say at temperature T_2 and pressure P_2 in the atmosphere, to take into account the fact that the pump will aspirate more volume of air in order to maintain the same mass flow rate of the instrument [*Moorthy et al.*, 2004].

$$V_2 = V_1 \frac{[P_1 T_2]}{[P_2 T_1]} \tag{1}$$

Accordingly each measurement of BC concentration (M_1) was converted to actual BC concentration (M_2) using equation (2).

$$M_2 = M_1 \left[\frac{P_1 T_2}{P_2 T_1}\right]^{-1} \tag{2}$$

3. Results and Discussion

3.1. Altitude Profiles of BC

[9] In order to construct the vertical profiles, BC concentration data was grouped in five altitude zones; 250–300 m, 500–650 m, 800–900 m, 1100–1200 m, and 1500–1800 m. Figure 2a shows two profiles of BC concentration in the morning and afternoon of January 4. Each point in the figure is average of four data points. Furthermore, any negative (unphysical) value of BC, reported by Aethalometer due to insufficient time for flow adjustment, was discarded. This reduced the error in the BC measurements. BC shows a sharp decrease with height in both profiles up to about 600 m where it starts increasing to give another peak at about 900 m. At 900 m, BC concentration was observed to be 1.48 and 1.99 μg m^{-3} in the morning and afternoon respectively. Above 900 m BC becomes almost constant with altitude. The decrease in BC with height up to 600 m in the morning (gradient ~1.04 μg m^{-3}/100 m) is more than the afternoon (gradient ~0.24 μg m^{-3}/100 m). The observed surface BC concentration (7.29 μg m^{-3}) in the morning in Kanpur is higher than the BC concentration

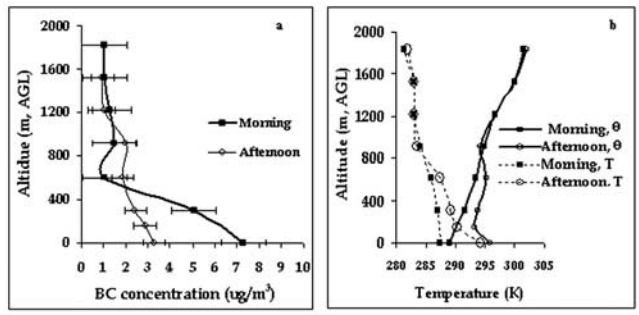

Figure 2. (a) Vertical profiles of BC concentration and (b) vertical profiles of temperature (T) and potential temperature (θ) in experiment 1. The error bars represent ±1 standard deviation of the corresponding measurements.

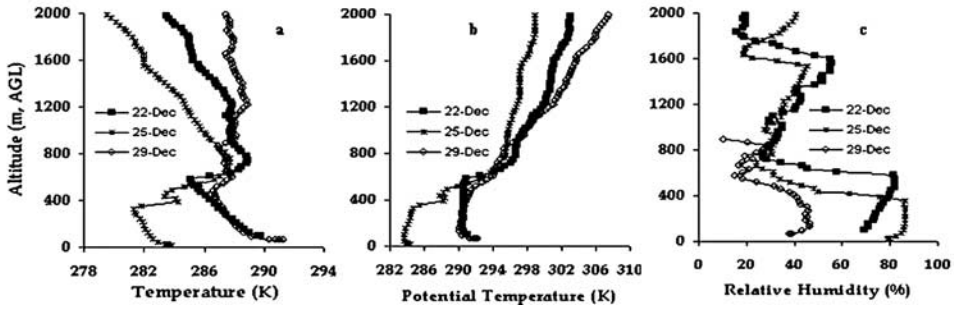

Figure 3. Vertical profiles of (a) temperature (T), (b) potential temperature (θ), and (c) relative humidity obtained from balloon soundings.

measured in Hyderabad by a factor of 2, although Hyderabad is a bigger city than Kanpur.

[10] Figure 2b shows the profiles of temperature (T) and potential temperature (θ) for experiment 1,where θ is calculated by:

$$\theta = T_2[P_1/P_2]^{\kappa} \quad (3)$$

where $\kappa = R/c_p$; R is the specific gas constant for dry air and c_p is the specific heat capacity of dry air at constant pressure ($\kappa \approx 0.286$). Increasing θ with height clearly indicates the presence of a stable layer near the surface during morning hours, which resembles the classical boundary layer structure during the morning hours in winter [*Stull*, 2000]. Due to this stable boundary layer, BC is not mixed well and strong gradient in BC exists. As the day progresses, more entrainment occurs; which changes the potential temperature profile and therefore the BC decreases much slowly with height.

[11] However, enhanced BC concentration was seen in both profiles at 900 m, which suggests the presence of a BC layer aloft. Three balloon soundings were made in the morning hours, as part of ISRO-GBP LC II, during December and T, θ, relative humidity (RH) profiles obtained are shown in Figures 3a, 3b, and 3c, respectively. It should be noted that due to some technical problem in relative humidity sensor on December 29, the data above 900 m were erroneous and hence not considered. Profiles of θ show the presence of stable layer except very near to surface where θ decreases with height with the enhanced mixing. Variation of RH with altitude shows similar trend, between 200–800 m on all the three days, as in the case of BC. The observed morning BC profile was found to be consistent with the temperature and RH profiles obtained from balloonsonde December 22 and 29. T and RH profiles on December 25 were different due to occurrence of dense fog.

3.2. Latitudinal Variation in BC

[12] The latitudinal variations of BC concentration at three altitude zones, ~300 m, 600 m and 900 m have been examined (Figure 4). The flight paths for all three altitude zones, were started from the industrial zones (around 26.45 N) towards the rural area (>26.55 N) crossing the urban area in between. At the lowest level, i.e. 300 m, BC concentration shows a very week decreasing trend as we move from the industrial area towards the rural area. Average BC concentration at this altitude is ~2.48 μg m^{-3}, which is very similar to the observed BC at same level (2.43 μg m^{-3}) in the afternoon flight on January 4. Similar trend has also been observed at 600 m altitude, but surprisingly, at 900 m altitude, a week increasing trend has been observed. BC concentration at this altitude (~2.73 μg m^{-3}) has been found to be higher than that at 600 m altitude level (~2.6 μg m^{-3}) over the urban area (between 26.5 to 26.55 N latitude) confirming the presence of enhanced BC layer. In the rural areas, BC concentration at these two altitudes is similar. The latitudinal profile of BC concentration shows that though the source of BC is concentrated mainly within the industrial and urban areas, its concentration remains almost same at remote rural areas even at higher altitude due to extensive biofuel and biomass burning in winter. The latitudinal as well as the altitudinal trend of BC concentration during experiment 2 indicates the transport of BC from the source regions to a higher altitude by convective mixing, thus affecting the remote rural areas along with the polluted urban and industrial areas.

3.3. Implications to Radiative Forcing

3.3.1. Direct Effect

[13] High concentration of elevated BC is of particular significance over continental locations, compared to ocean, because of the enhancement in forcing resulting from the increased surface reflectance of land (especially over regions like Kanpur). The enhanced layer of BC found in Kanpur was not observed in the earlier profiles obtained in Hyderabad due to difference in sources and boundary layer structure [*Moorthy et al.*, 2004]. The difference in forcing between the steadily decreasing and increasing BC aloft is as much as a factor 1.3 in case of short wave in clear skies.

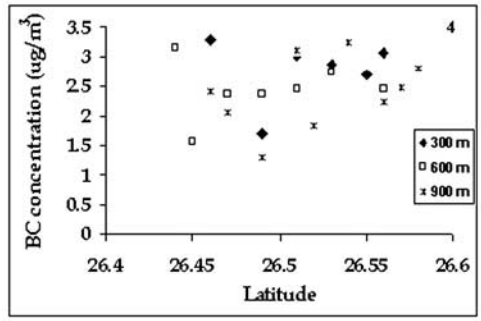

Figure 4. Latitudinal variation of BC during experiment 2 at 300, 600 and 900 m altitudes.

For long wave, *Lubin et al.* [2002] have shown that differences can be as much as a factor of two. Presence of an elevated BC layer above the cloud results in an increased absorption due to enhanced interaction of sunlight with BC reflected back by the cloud [*Satheesh*, 2002]. However, the magnitude of this effect is less, if the elevated layer is present below the cloud; as clouds intercept a major fraction of the available sunlight for such interaction. But in both cases, the sign of the radiative forcing is positive as compared to negative sign of radiative forcing in cloud-free conditions.

3.3.2. Indirect Effect

[14] Aerosols can act as cloud condensation nuclei for the formation of clouds. An increase in the aerosol concentration can result in an increased concentration of cloud droplets and reduces the mean droplet size, which in turn can increase the albedo (reflectance) of clouds. This causes a decrease in the visible solar radiation reaching the Earth's surface indicating significance of cloud albedo in determining the global energy balance. As the water vapor availability per aerosol reduces when aerosol number is more, this increases the cloud lifetime and thus inhibits precipitation (rain). *Ackerman et al.* [2000] based on model simulations and observations during INDOEX reported an alternate mechanism by which BC aerosols reduce the cloud cover. The enhanced layer of black carbon aerosols reported in this paper has implications to the issue of the reduction of cloud cover by BC induced atmospheric heating suggested by *Ackerman et al.* [2000]. They demonstrated a mechanism through which aerosols reduce cloud cover and hence offset the aerosol induced radiative cooling at the top of the atmosphere on a regional scale. The study of this aspect needs more extensive measurements of clouds and aerosols on a regional scale.

4. Conclusions

[15] 1. Altitude profiles of BC measured at an industrial, urban location in Northern India for the first time shows an enhanced BC layer (concentration $\sim$1.48 to 1.99 $\mu g\ m^{-3}$) at around 900 m altitude. BC concentration decreases steadily up to 600 m from the surface and then shows an increase up to 900 m, before becoming almost constant with altitude.

[16] 2. The gradient of BC concentration from the surface up to 600 m is more than four times higher in the morning ($\sim$1.04 $\mu g\ m^{-3}$ per 100 m) compared to that during the afternoon ($\sim$0.24 $\mu g\ m^{-3}$ per 100 m) due to stable morning boundary layer condition.

[17] 3. The latitudinal profiles show that BC concentration is high not only in the urban and industrial areas, but can be significant in the rural areas, which has significant impact on the regional climate forcing.

[18] **Acknowledgments.** This work has been carried out under ISRO-GBP Land Campaign II. We acknowledge the efforts made by staffs of Flight Lab, Department of Aerospace Engineering, IITK, Dr. A. K. Ghosh, Mr. S. Das, Mr. V. Mathur and Mr. A. Singhal and also Mr. H. Vishwakarma for making the experiment possible in quick time.

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