Aerosol black carbon radiative forcing at an industrial city in northern India

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[1] During a comprehensive aerosol field campaign as part of ISRO-GBP, extensive measurements of aerosol black carbon were made during December 2004, for the first time, at Kanpur, an urban continental location in northern India. BC diurnal variation is associated with changes in boundary layer mixing and anthropogenic activities. BC concentration in Kanpur is comparable to those measured in other mega cities of India but much higher than in similar locations of Europe, USA and Asia. High BC concentration is found both in absolute terms (6–20 $\mu g\ m^{-3}$) and mass fraction ($\sim$10%) yielding very low single scattering albedo (0.76). The estimated surface forcing is as high as $-62 \pm 23\ W\ m^{-2}$ and top of the atmosphere (TOA) forcing is $+9 \pm 3\ W\ m^{-2}$, which means the atmospheric absorption is $+71\ W\ m^{-2}$. The short wave atmospheric absorption translates to a lower atmospheric heating of $\sim$1.8°K/day. Large surface cooling and lower atmospheric heating may have impacts to regional climate. **Citation:** Tripathi, S. N., S. Dey, V. Tare, and S. K. Satheesh (2005), Aerosol black carbon radiative forcing at an industrial city in northern India, *Geophys. Res. Lett.*, *32*, L08802, doi:10.1029/2005GL022515.

1. Introduction

[2] Black carbon (BC), the optically absorbing component of carbonaceous aerosol, has become a great interest in recent times, because it is a strong absorber of the solar radiation in the visible and near-infrared wavelengths, and subsequently because of its potential to alter the radiation budget [*Haywood and Ramaswamy*, 1998; *Jacobson*, 2001]. Estimates of the global mean clear sky radiative forcing at the top of the atmosphere due to BC is between +0.4 to $+0.8\ Wm^{-2}$. This 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] To understand radiative effect of BC aerosols, several international experiments such as Indian Ocean Experiment (INDOEX), Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX), Aerosol Characterization Experiments (ACE-1 and ACE-2) and Smoke, Clouds, Aerosol, Radiation-Brazil (SCAR-B) have been carried out. In India, BC concentration is being monitored at very few locations, Trivandrum [*Babu and Moorthy*, 2002], Bangalore [*Babu et al.*, 2002] and Hyderabad [*Latha and Badarinath*, 2003] in Southern part of India (shown in Figure 1). Although the Gangetic basin in the northern India is one of the most polluted regions in the world, no measurements of BC aerosols are reported in this region so far. Recently, *Di Girolamo et al.* [2004] have shown very high aerosol optical depth during winter season retrieved from Multi-angle Imaging Spectroradiometer (MISR) in the Northern India; although it is lower compared to the ground-based point measurements as it is spatial average over a large area. In this paper, we present, for the first time, the results of surface measurements of BC aerosols during a land campaign in December 2004 by ISRO Geosphere Biosphere Program at Kanpur, an industrial city in the Ganga Basin. Diurnal variation of BC is discussed along with the associated variations in local meteorological parameters. Finally, the impact of BC aerosols on net radiative forcing has been assessed and its implications have been discussed.

2. Methodology and Data

2.1. Site Location and Synoptic Meteorology

[4] For monitoring of BC aerosols, an Aethalometer (model AE-21-ER, Magee Scientific, USA) has been deployed in the campus of Indian Institute of Technology (IIT), Kanpur (80°20′E and 26°26′N) as a part of the ISRO-GBP Land Campaign-II in December 2004. The IIT Kanpur campus is about 17 km away from the center of Kanpur City (Figure 1), where the major sources of black carbon are automobiles, power plants and other industries and biomass burning (particularly in the winter season).

[5] The wind during the month of campaign was weak (1.5 to 4 km hr^{-1}), variable but mostly northerly (Figure 1). The relative humidity (RH) was very high, especially during the nighttime (>85%), whereas during the daytime, it comes down to $\sim$55% (Figure 2). There was no rainfall throughout the month and the temperature varied in the range of 9 to 22°C.

2.2. Experimental Details

[6] Simultaneous measurements of BC concentration (M_b), total aerosol mass concentration (M_T) and meteorological parameters were carried out at $\sim$10 m above local ground level (142 m from mean sea level) using an Aethalometer (AE-21-ER), 10 channel Quartz Crystal Microbalance (QCM) impactor (PC-2 of California Measurements Inc., USA) and automatic weather station (EnviroTech Instruments Pvt. Ltd.) respectively. The Aethalometer was operated at a flow rate of 3 liters/min and at an average time

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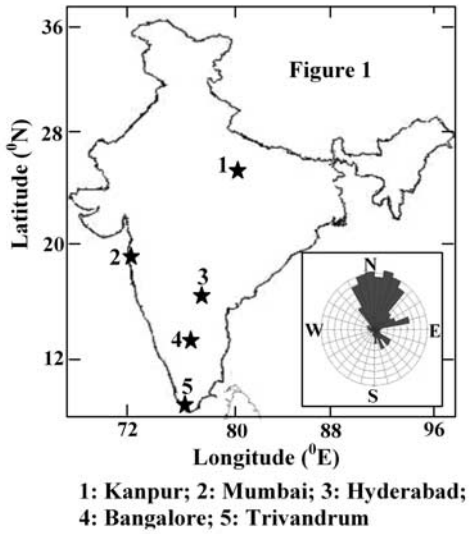

Figure 1. Location of the study area along with other urban stations in India, where BC concentration has been measured. The frequency distribution of wind direction during December 2004 at Kanpur shown in the inset of Figure 1 reveals dominantly northerly wind.

of 5 min. It uses a continuous filtration and optical transmission technique to measure the concentration of BC in near real time and aspirates ambient using its inlet tube and its pump. BC mass concentration is estimated by measuring the change in the transmittance of a quartz filter tape, on to which the particles impinge [*Hansen et al.*, 1984]. The uncertainty in BC concentration is ~10% [*Babu and Moorthy*, 2002] and the specific absorption coefficient used is 16 m^2 g^{-1}.

[7] Measurements by QCM were made at hourly intervals for the whole month of December with the sampling duration of 6 min at RH < 75% in the size range 0.05 to >25 μm over 10 size bins. Stage 1 collects all particles with diameter >25 μm, whose monthly concentration is very low (3.08 μg m^{-3}) compared to other size bins; hence no geometric mean diameter is assigned to that size bin. As M_T is directly proportional to the change in the frequency difference of the sensing and the reference crystal, the short-term stability of the crystal oscillator during the sampling time of 6 min is of more importance than long-term drift. The uncertainty in QCM measurements is ~15–20% for M_T < 10 μg m^{-3} and the error is much less for higher M_T [*Pillai and Moorthy*, 2001]. Aerosol Optical Depth (AOD) has been measured by CIMEL radiometer at 380, 440, 500, 670, 870 and 1020 nm wavelengths with an error of ±0.01 for λ > 440 nm and ±0.02 for λ < 440 nm [*Singh et al.*, 2004]. The wind speed and temperature sensors operate with an accuracy of 0.36 km hr^{-1} and 0.1°C, while the accuracy of RH sensor is 2% for RH < 90% and 3% for RH in the range of 90–100%.

3. Results and Discussion

3.1. BC Variability

[8] Daily average values show significantly high values of BC in the range of 6–20 μg m^{-3}. No measurements were made on three days during 22–24 December due to unavailability of tape. Monthly mean diurnal variation of BC is shown in Figure 3 with two maxima peaks during morning 07:00–09:00 local time (LT) and evening 19:00–21:00 LT. BC shows higher variability during the nighttime and the early morning hours when values as high as up to 50 μg m^{-3} has been observed. BC concentration starts rising gradually after the sunrise and attains a peak at 09:00 LT. The diurnal trends of the temperature and relative humidity are opposite and out of phase, which is quite obvious, but the variability is much higher during the daytime. Similar type of diurnal variations of boundary layer parameters in winter season has been observed by *Ramana et al.* [2004] in an adjacent city Lucknow. The high concentration of BC in morning hours, higher than the corresponding late evening values, is mainly because of two reasons. First, increased anthropogenic activities such as biomass burning for heating purpose and commencement of the industrial activities during the morning hours emit more BC and secondly, due to fumigation effect, when the pollutants are being brought near the surface from the residual nocturnal boundary layer [*Stull*, 1998]. The magnitude of the fumigation effect is however less than that observed at coastal stations, where the effect is enhanced by the land/sea breeze activity. During daytime increased mixing within the turbulent boundary layer as temperature increases leads to fast dispersion of BC aided by relatively higher wind speed (2–4 km hr^{-1}), thus reducing its near surface concentration. In the evening, boundary layer mixing again decreases due to inversion and as a result

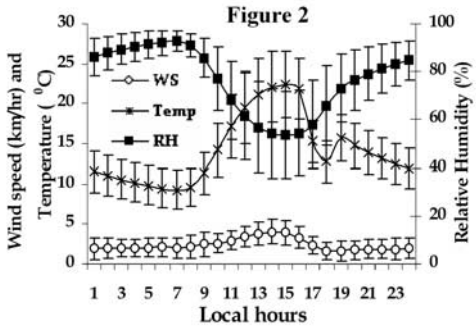

Figure 2. Monthly mean diurnal variations of wind speed (WS), temperature (Temp) and relative humidity (RH) for December 2004 with the standard deviation of each point shown as vertical bars.

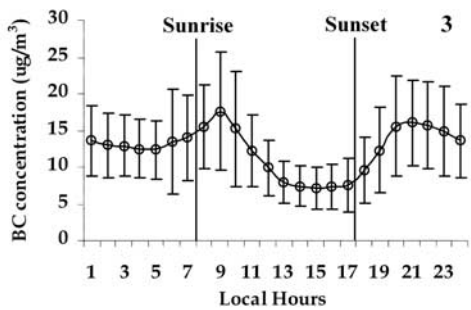

Figure 3. Monthly mean diurnal variation of BC. The error bars represent the standard deviation from the mean for respective days.

Table 1. BC in Urban Locations

Location (References)	Period	$M_b(\mu g\ m^{-3})$
Urban, Europe[a]	DJF	3.5–4.2
Near city, Europe[a]	Annual	1–2.5
Road canyon, Europe[a]	Annual	6–9.0
Bologna, Europe (Urban Background)[a]	Oct	1.5–2.0
Uniontown, USA (semi-urban)[b]	Summer	0.27–3
Maryland, USA (Suburban)[c]	Annual	0.25–3
Chongju, Korea[d]		4–6
Trivandrum, India[e]	Dec	4–8
Hyderabad, India[f]	Jan–Jul	0.5–68
Mumbai, India[g]	Jan–Mar	7.5–17.5
Bangalore, India[h]	Nov	0.4–10.2
Kanpur (present study)	Dec	6–20

[a]*Putaud et al.* [2003].
[b]*Allen et al.* [1999].
[c]*Chen et al.* [2001].
[d]*Lee and Kang* [2001].
[e]*Babu and Moorthy* [2002].
[f]*Latha and Badarinath* [2003].
[g]*Venkataraman et al.* [2002].
[h]*Babu et al.* [2002].

BC gets trapped near the surface and attains maximum value around 19:00–21:00 LT. As the night progresses, the anthropogenic activities and the industrial emission get reduced, as a result BC concentration decreases.

[9] Earlier observations of BC in urban and near city locations are given in Table 1 for comparison purpose. BC in Kanpur shows much higher values (factor of two to five) than other urban or near city locations of Europe, USA and Asia (Korea) but lower than that reported in Hyderabad. BC in Kanpur is also higher than that in Trivandrum (coastal) and Bangalore (urban) in Southern India. Although BC in present study was measured in IIT Kanpur campus, which is characterized as near city location; still BC values are comparable or higher than those found in urban or street locations of Europe. The reason for this could be the transport of BC from the city and a busy national highway, which is 1.5 km from the measurement site. Low single scattering albedo (SSA) values (0.73–0.85) along with high imaginary refractive index (>0.01) values during the winter season also indicate high concentration of absorbing aerosols in this region [*Singh et al.*, 2004].

3.2. Mass Fraction of BC

[10] The mass fraction of BC (F_{BC}) is important in estimating its impact on aerosol radiative forcing. During INDOEX, *Satheesh et al.* [1999] have estimated that a 6% BC fraction to total aerosol mass contributed ~11% to the aerosol optical depth; 35% to aerosol radiative forcing and 50% to aerosol atmospheric forcing [*Podgorny et al.*, 2000]. F_{BC} was computed from the simultaneous measurements of M_T and M_b. Due to operational constraint during nighttime, when RH becomes greater than 75%, QCM was not operated during the nighttime throughout the month. Therefore we have used daytime average values of M_b and M_T and computed the F_{BC} from the ratio M_b/M_T. Figure 4 shows the daytime mean of F_{BC} during December with the values in the range of 7–15%. The uncertainties in the measurements of M_b and M_T give an overall uncertainty of ~14% to F_{BC} [*Babu and Moorthy*, 2002]. The values of F_{BC} in Kanpur is higher than the values reported in Trivandrum but comparable to F_{BC} in Mumbai during INDOEX [*Venkataraman et al.*, 2002], Bangalore [*Babu et al.*, 2002] and in INDOEX program [*Satheesh et al.*, 1999]. Such high F_{BC} could affect the climate more significantly over the land as the surface reflectance of land is much higher compared to that of ocean.

3.3. Implications to Radiative Forcing

[11] As measurements of aerosol chemical composition were not available, we have used a hybrid approach to estimate the aerosol radiative forcing. We have used the measured BC concentration as input to Optical Properties of Aerosols and Clouds (OPAC) model of *Hess et al.* [1998] by adopting urban aerosol model. We have introduced observed values of BC and total aerosol mass in OPAC model and the concentrations of other components are adjusted (constrained by observed BC mass fraction). This iterative procedure was continued such that estimated spectral optical depths and Ångström wavelength exponent are consistent with the observations. This procedure is described in earlier papers [*Babu et al.*, 2002]. The SSA of the composite aerosol (500 nm) worked out to be ~0.76. The SSA estimated in our study is ~0.76 and that reported from AERONET measurements at Kanpur is 0.78 ± 0.08. This indicates close agreement.

[12] The single scattering albedo, aerosol spectral optical depth and Ångström wavelength exponent are incorporated in a Discrete Ordinate Radiative Transfer model [Santa Barbara DISORT Aerosol Radiative Transfer (SBDART) model] to estimate the short-wave clear sky aerosol radiative forcing at the surface and top of the atmosphere (TOA). This model is designed and developed by University of California, Santa Barbara [*Ricchiazzi et al.*, 1998], which is based on a collection of well-tested and reliable physical models, which were developed by the atmospheric science community over the past few decades. We used eight streams in the radiative transfer calculation and computations were made for solar zenith angles at every 5°. While estimating radiative forcing over land, surface reflection is an issue. The MODIS Albedo Product (MODIS/Terra Albedo; 16-Day; Level-3 Global 1 km SIN Grid) provides both the white-sky albedo and the black-sky albedo (at local solar noon) for MODIS bands 470, 555, 659, 858, 1240, 1640 and 2100 nm. Using MODIS black sky and white sky albedo actual surface albedo has been computed and albedo estimated over a 1° × 1° grid at Kanpur was used here. The surface albedo used in the present study is 0.17 ± 0.06. The average aerosol optical depth (at 500 nm) during the

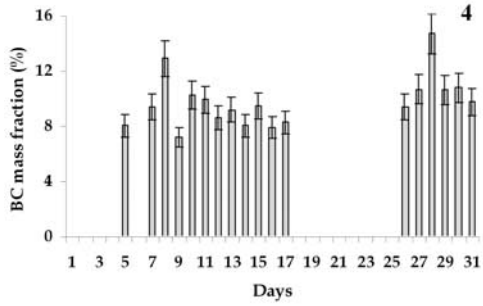

Figure 4. Daytime average BC mass fraction with the error bars representing the uncertainties in the measurements.

campaign period was 0.77 ± 0.29 (with an Ångström wavelength exponent of 0.81 ± 0.33). The value reported here is a mean of estimate made for individual measurements of spectral AOD following *Ångström* [1964]. The wavelength range used for estimating Ångström exponent is 440 to 870 nm. The estimated surface forcing (clear-sky and diurnally averaged) is as high as -62 ± 23 W m^{-2} and top of the atmosphere (TOA) forcing (clear-sky and diurnally averaged) is $+9 \pm 3$ W m^{-2}. The difference between the two, which is +71 W m^{-2} is absorbed in the atmosphere. This short wave atmospheric absorption translates to a lower atmospheric heating of ~1.8°K/day. On a day to day basis, surface forcing was in the range of -31 to -98 W m^{-2}. Similarly, TOA forcing has been found in the range +5 to +13 W m^{-2}. The corresponding change in heating rate was in the range of 0.9 to 2.8°K/day.

4. Conclusions

[13] 1. Daily average BC was found to be between 6–20 μgm^{-3} with values as high as ~50 μg m^{-3} during morning hours. BC concentration observed in Kanpur is comparable to those measured in other mega cities of India but much higher than in similar locations of Europe, USA and Asia.

[14] 2. BC mass fraction estimated from composite mass and BC mass was found to vary between 7–15%.

[15] 3. The presence of black carbon aerosols over northern India decreases the short wave radiation reaching the surface by as much as 62 W m^{-2} and the top of the atmosphere reflected radiation by 9 W m^{-2}.

[16] 4. The short wave atmospheric absorption translates to a lower atmospheric heating of 1.8°K/day.

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