Research Article

Radiative Forcing of Black Carbon over Delhi


Indian Institute of Tropical Meteorology, Pune 411 008, India

Correspondence should be addressed to Gufran Beig; beig@tropmet.res.in

Received 15 February 2013; Revised 23 August 2013; Accepted 12 September 2013

1. Introduction

Atmospheric aerosols play a major role in the earth climate because of their potential to perturb the radiation balance of the earth at regional and global scales. They influence the weather and climate directly by scattering and absorbing solar radiation [1] and indirectly by acting as cloud condensation nuclei, thereby affecting the droplet concentrations, optical properties, precipitation rate, and lifetime of clouds [2]. Among the absorbing aerosols, black carbon (BC) is gaining considerable significance because it is a strong absorber of the solar radiation in the visible and near-infrared wavelengths and subsequently because of its ability to alter the radiation budget [3, 4]. BC is the second strongest contributor to global warming next to carbon dioxide [5]. BC is produced as primary particles from incomplete combustion processes such as fossil fuel and biomass burning, and hence most of the BC in the atmosphere originates from human-made activities. BC emissions have varied in response to changes in fossil fuel usage and technology development, and the estimated fossil fuel BC emissions are the highest in developing countries, especially China and India [6].

Highly industrialized cities in the world face major threats from air pollution. New Delhi, the capital city of India, is also no exception to this, and since it is located in the Indo-Gangetic Plains (IGP), a significant part of the pollutants over there are of absorbing type. Rapid urbanization and industrialization has brought up growingly large number of vehicles, factories, as well as power plants in Delhi and surrounding areas during the last two decades [7]. As a result, Delhi has evidenced serious air pollution problem [8–11]. Significant portion of the population in Delhi is regularly exposed to unhealthy levels [8, 11, 12] of pollution which is a cause of concern. The significant impact of particulate matters on the pollution over Delhi has been reported in [12, 13]. It may be noted that total number of vehicles in the city had reached about 5.73 million by the year 2010 [14]. Increased level of pollution in the Delhi region was a cause of immense concern to the Commonwealth Games 2010 Organizing Committee as well as to the government of India and the Delhi government and there was a real need of improvement in the air quality of the Delhi region for successful organization of the games during October-November 2010.

Delhi hosted the XIX Commonwealth Games (CWG-2010), for the first time in India, and it lasted from 03 October to 14 October, 2010. As an initiative, the government of Delhi executed an ambitious air quality monitoring program to
reduce the emissions of air pollutants and also to monitor
the different pollutant levels before and during the games
period. The aim of these restrictions was to improve the air
quality through control measures, which has shown some
success in the past during large international sporting events
in polluted cities like Beijing [15, 16]. Under this initiative the
“System for Air quality Forecasting And Research” (SAFAR)
was an intensive experiment initiated by the Ministry of Earth
Sciences (MoES), government of India, for investigating the
air quality in Delhi during the CWG period and evaluating
the effectiveness of the air pollution control measures. The
SAFAR program for CWG-2010 provided a unique opportu-
nity not only to examine ambient air quality during games but
also to assess the air quality of Delhi as a whole.

In the present study, we investigate the radiative effect
of BC aerosols during the year 2010–2011, in which the
CWG event had taken place. The geographical features of
the study location are presented in Section 2, and data
and methodology are given in Section 3. The results and
discussions are provided in Section 4, and the summary and
inferences are rendered in Section 5.

2. Study Location: Site Description
and Meteorology

New Delhi, the capital region of India, situated in the
northern part of the country, is located between the latitudes
of 28° 24' and 28° 53' North and 76° 50' and 77° 20' East.
It stretches over an area of 1483 square kilometers. The
population of Delhi according to the 2011 census stands at
about 16 million, making it the 18th most populated state
in India [17]. The Thar and Margo Deserts in the western
India are very close to the location of Delhi. So this city is
faced with a typical problem of desert aerosols every year
during the premonsoon period, that is, April–June. These
aerosols are brought by windblown dusts from the Thar
Desert in Rajasthan. The total suspended particulate matter
(TSP) concentration during this period goes enormously
high. Consequently, the visibility is reduced and the local
radiative forcing is significantly affected. The summers in
Delhi are very hot and winters are very cold. The temperature
ranges from 45°C in the summer to 3°C in the winter.
The rainy season is from July to September with average
annual rainfall of ~670 mm. Well before the commencement
of the commonwealth games, Delhi was in the grip of
heavy monsoonal rain. Cloudy sky condition persisted for
a prolonged duration until a week before the games when
monsoon withdrawal began in Delhi. The Delhi region was
completely devoid of monsoonal/rainfall activity during the
games period.

3. Measurements and Methodology

3.1. Black Carbon Mass Concentration Measurements. A net-
work of air quality monitoring system (AQMS) had been set
up in Delhi. More details on the Delhi SAFAR network and air
quality and weather monitoring setups used can be found at
http://safar.tropmet.res.in/. Black carbon mass concentration
measurements were made using seven wavelengths (370,
470, 520, 590, 660, 880, and 950 nm) AE31 Aethalometer
(Magee Scientific, USA). The aethalometer measures BC
mass concentrations from the attenuation of a beam of light
transmitted through the sample collected on a filter, which is
proportional to the amount of BC mass loading in the filter
deposit [18]. This attenuation absorption coefficient is then
converted into BC mass concentration. The conversion of
attenuation absorption coefficient into BC mass concentra-
tion is done using appropriate absorption efficiency, which
varies as a function of wavelength. Absorption coefficients of
aerosols as a function of wavelength are calculated [19, 20] as
follows:

\[ \beta_{\text{abs}}(\lambda) = -\frac{1}{CR} \frac{A \ln(i_2/i_1)}{Q \Delta t}, \]  

where \( i_1 \) and \( i_2 \) are the intensities of the sample and the
reference beams, respectively, after a sampling time interval
(\( \Delta t \)), \( Q \) is the volume of air sampled during the time interval
\( \Delta t \), and \( A \) is the area of the exposed spot on the filter where
aerosols are collected. Coefficient \( C \) is the correction factor
applied to account for any change in the absorption occurring
due to aerosols on the filter over that of the airborne particles.
Coefficient \( R \) is an empirical correction factor and describes
the change in the aethalometer response with increased
particle loading on the filter. The value obtained for \( \beta_{\text{abs}}(\lambda) \)
is divided by a mass absorption coefficient, \( \sigma_{\text{abs}}(\lambda) \) (in units of
m² g⁻¹), to obtain the mass concentration \( M_{\text{BC}}(\lambda) \) in µg m⁻³
[21]

\[ M_{\text{BC}}(\lambda) = \frac{\beta_{\text{abs}}(\lambda)}{\sigma_{\text{abs}}(\lambda)} = \frac{\beta_{\text{abs}}(\lambda) C}{\sigma_{\text{att}}(\lambda)}, \]

where \( \sigma_{\text{abs}}(\lambda) \) and \( \sigma_{\text{att}}(\lambda) = \sigma_{\text{abs}}(\lambda) C \) are the mass specific
absorption and attenuation cross sections, respectively. The
method is described in detail by [22]. The hourly averaged
data of BC compiled for a period from 20 August 2010 to 31
July 2011 were analyzed in this paper.

3.2. Estimation of BC Radiative Forcing

3.2.1. Necessary Inputs: Aerosol Optical Properties. The clear
sky total (direct + diffuse) aerosol radiative forcing at the
surface and top of the atmosphere was calculated in the
shortwave (0.2–4.0 µm) region using the SBDART model,
developed by Ricchiuzzi et al. [23]. SBDART computes plane
parallel radiative transfer in clear sky conditions within the
earth atmosphere and at the surface. The model is well
suited to study the radiation budget of the earth atmo-
sphere system. The primary input parameters required for
calculating aerosol radiative forcing are aerosol optical depth
(AOD), single scattering albedo (SSA), and the asymmetry
parameter (ASP). BC mass fractions were used as input in
the Optical Properties of Aerosols and Clouds (OPAC)
model developed by Hess et al. [22] to derive spectral aerosol
optical parameters such as aerosol optical depth (AOD),
single scattering albedo (SSA), and asymmetry parameter
(ASP) at different relative humidity conditions over Delhi.
Subsequently BC mass fractions alone were used in OPAC to
derive spectral aerosol properties solely for BC component as explained in [24]. We used the standard urban model, as the observational site experiences similar to environmental conditions during observational periods. The values of SSA and ASP for the 550 nm wavelength are 0.208 and 0.353.

3.2.2. Additional Inputs: Atmosphere, Ozone, Water Vapor, and Surface Reflectance. In addition to aerosol properties, atmospheric profiles of temperature, pressure, columnar ozone, and water vapor are necessary for the aerosol radiative forcing. As no vertical profiling data of aerosol and meteorological parameters were available over the site, we used the standard midlatitude atmospheric model of temperature and humidity [25] in SBDART model in both the cases (for “with BC” analysis and for “without BC” case) for this study. Aerosol vertical distribution is constrained from the McClatchey et al. [25] models of vertical aerosol profiles for visibility 5 and 23 km, for the average visibility conditions prevailed over the site as described by [23]. The vertical profiles for visibility 5 and 23 km follow exponential profiles with density scale heights of 0.99 and 1.45 km, respectively. A weighted average of these vertical distributions is used when an intermediate value of visibility is selected. The standard sand albedo model defined in SBDART [23] has been used to constrain surface reflectance. The monthly mean total column ozone (TCO) and precipitable water content (PWC) over Delhi as obtained from Ozone Monitoring Instrument (OMI) have been used for the estimation of BC radiative forcing using a one-dimensional radiative transfer Santa Barbara Discrete ordinate Atmospheric Radiative Transfer (SBDART) model. Columnar ozone shows a winter low and a summer high, consistent with the seasonal variation over tropics (Figure 1). Columnar water vapour in Delhi is showing a maximum during the summer months of August-September (2010) and June-July (2011) (Figure 1). In order to analyze the stability of atmosphere with regard to the BC loading, we have used the atmospheric sounding data from the URL: http://weather.uwyo.edu/upperair/sounding.html.

3.3. Radiative Forcing Calculation. BC Radiative Forcing has been calculated for four individual days in a month for “with BC” condition and “without BC” condition and monthly average BC forcing has been taken for each month. We used the methodology explained in [24] to estimate the BC radiative forcing. Direct BC radiative forcing (RF) is defined as the difference in net fluxes at the surface, bottom of atmosphere (BOA), or at the top of atmosphere (TOA), with and without BC. The RF is given by the expression:

\[
(RF)_{BOA,TOA} = [F_{BC} - F_{NoBC}]_{BOA,TOA},
\]

where

\[
F_{BC,NoBC} = (F_{down} - F_{up})_{BC,NoBC}.
\]

The difference between the radiative forcing at the top of the atmosphere and the surface is designated as the atmospheric forcing and is written as

\[
(RF)_{ATM} = (RF)_{TOA} - (RF)_{BOA},
\]

where the subscript ATM represents the energy trapped within the atmosphere due to the presence of black carbon. If the \((RF)_{ATM}\) is positive, the BC produces a net gain of radiative flux leading to heating, while a negative \((RF)_{ATM}\) indicates a net loss and thereby cooling.

The absorption and emission processes in the long wave at different altitudes in the atmosphere, when integrated over all the wavelengths, can result in either a net gain (warming) or loss (cooling) of radiative energy [26], while solar radiation always warms the atmosphere (5). The amount of energy trapped in the atmosphere, \((RF)_{ATM}\), due to BC
in the shortwave region, gets converted into heat. The solar heating rate can be calculated as

$$ \frac{\partial T}{\partial t} = -\frac{1}{\rho C_p} \frac{(RF)_{ATM}}{\Delta z}, $$

where $\partial T/\partial t$ is the heating rate (K/day), $\rho$ is the density, and $C_p$ is the specific heat capacity of air at constant pressure [27].

4. Results and Discussions

4.1. Seasonal and Diurnal Variation of BC. BC aerosol mass concentrations measured for 24 hrs per day during each month are averaged and the monthly mean BC mass concentrations are obtained. Figure 2 shows the monthly mean variation of the BC aerosols. Vertical bars denote the standard deviation from the mean, which indicate the variability in the BC mass concentration measured during that month. BC mass concentrations in Delhi exhibit a strong seasonal cycle marked by a winter high and a summer low. The monthly mean BC concentrations vary between $15.935 \pm 2.063 \mu g m^{-3}$ (December 2010) and $-2.445 \pm 0.58 \mu g m^{-3}$ (July 2011). During winter the boundary layer is shallow and holds the pollutants in a smaller volume near the earth surface when compared to summer.

BC exhibited a distinct diurnal variation with the highest concentration occurring 0600h to 0900h and again at around 2000h till midnight and low concentration from 1000h to 1700h (Figure 3). The diurnal pattern is mainly due to the changes in the mixing heights. In the morning, after the sunrise, the nocturnal boundary layer brakes, lifting up the particles, especially those in fine size. This gave a sharp peak in the morning. After that, the concentrations went on decreasing gradually due to increased convective activity and the minimum value reached at about 16h; afterwards concentrations started building up slowly again due to the decadence of the local boundary layer and the second peak
was observed in the evening. Similar variations depending upon the changes in local boundary layer have been reported by [28–30].

Apart from these local boundary layer variations, the effect of traffic intensity is also a crucial factor as vehicular emissions are one of the major sources for BC aerosols [24].

4.2. BC Radiative Forcing. It has been observed that the monthly mean BC forcing is the highest in the month of November (66 ± 6.86 Wm⁻²) and December (65.43 ± 6.9 Wm⁻²). The forcing solely due to BC during winter was found to be −45.31 Wm⁻² at the surface and +20.45 Wm⁻² at TOA, indicating strong radiative absorption by BC. Figure 4 shows the average variation in BC radiative forcing obtained over Delhi at the surface, top of the atmosphere (TOA), and in the atmosphere every month. The lowest forcing is found to be in the month of July (23 ± 3.89 Wm⁻²). This could be due to that, in normal conditions, the amount of atmospheric aerosols is the minimum during the monsoon months (JJAS), because of the scavenging due to wet removal processes. Figure 5 shows the monthly mean shortwave heating rates obtained over Delhi during the period August 2010–July 2011.

Even though there is a strict imposed restriction setup by the Delhi government during the CWG period, there is considerable amount of BC loading into the atmosphere; therefore a relatively high radiative forcing (44.36 ± 2.4) was observed during the month of October 2010. During the games, the high value of BC concentration and high radiative forcing suggest that control action taken to reduce pollution during games did not have the desired policy-induced effect to reduce pollution levels below the air quality guidelines.

4.3. BC Radiative Forcing in relation to Atmospheric Stability. The accumulation of aerosols in the atmosphere depends on the stability of the atmosphere. A stable atmosphere traps pollutant and hence there will be large pollutants and large forcing. We examine the static stability of the lower atmosphere by determining the change in potential temperature ($\theta$), with respect to the height ($\z$), for three periods (pre-, during, and post-CWG). Stability conditions of the atmosphere in terms of potential temperature are given as

$$\left| \frac{d\theta}{dz} \right| > 0 \quad \text{Stable} \quad \left| \frac{d\theta}{dz} \right| < 0 \quad \text{Unstable} \quad \left| \frac{d\theta}{dz} \right| = 0 \quad \text{Neutral}.$$  \hspace{1cm} (7)

During the month of October, it has been observed that the condition of the lower atmosphere is relatively stable (Figure 6), which is favourable for less dispersion and enhanced trapping of particles in the boundary layer. In spite of having heavy traffic restrictions, the high BC values in October during CWG compared to pre-post-CWG periods are associated with the highly stable atmosphere, which traps the pollutants, indicated by positive potential temperature values.

5. Summary and Conclusions

BC radiative forcing is high during the month of November 2010 and it is very low during the month of July 2011. It
was expected that the imposed restriction on the traffic, construction activities, and the functioning of thermal power plants would result in reduction of BC and other pollutants, ensuring an improvement in air quality during the international games event. However, the observations and radiative forcing calculations indicate that this expected result was not achieved, with higher pollution and radiative forcing during the games period. This result reveals that pollution reductions measures for CWG-2010 were not sufficient to eliminate BC and other pollutants to ensure good air quality. A speculation based on the present study is made that further increase in the industrial and the vehicular activities in Delhi and surrounding areas may cause emission of BC aerosols and production of secondary pollutants to an extent which may deteriorate the air quality extremely in Delhi and in turn may enhance the radiative forcing effect, which will remain as an uncontrollable serious threat to the plantation and human health in future. Therefore, more relevant and cautious steps need to be taken to reduce the pollutants' emissions to significantly improve the air quality in Delhi and the surrounding regions.

Acknowledgments
The authors would like to thank the System of Air quality Forecasting and Research (SAFAR) project and Ministry of Earth Sciences (MOES) for financial support. Divya E. Surendran gratefully acknowledges Dr. S. Dipu for providing the suitable technical support.

References
Workshop, Clean Air Initiative for Asian Cities, Yogyakarta, Indonesia, 2006.


Submit your manuscripts at http://www.hindawi.com