**Global aerosol model-derived black carbon concentration and single scattering
albedo over Indian region and its comparison with ground observations**

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1 **Abstract**

2 Black carbon (BC) aerosols through their light-absorbing properties create strong
3 perturbation in the atmosphere by heating the atmosphere. BC mass concentration and
4 single scattering albedo (SSA) are important parameters to investigate atmospheric heating.
5 In the present study, measurements of BC and SSA over Indian region from the literature
6 are summarized and compared with simulations by a global aerosol model SPRINTARS. It
7 has been observed that BC emission inventory widely used in the world is underestimating
8 and the model-simulated SSA tends to be higher than observed-SSA. In addition to the
9 inventory, we have run the global model using the different BC emission inventory
10 interpolated by Streets et al. (2003) over Asia. The model runs with this inventory was found
11 to provide comparable results with ground observations for BC and SSA. Aerosol radiative
12 forcing due to direct effect (ADRF) over Indian region estimated to be -2.76 W/m^2 at the
13 surface and -1.91 W/m^2 at the atmosphere using the modified emission inventory in the
14 global aerosol model. The atmospheric heating is estimated to be $+0.85 \text{ W/m}^2$, which is
15 three times higher than the original emission inventory estimated value of $+0.25 \text{ W/m}^2$.
16 Results of the study suggest that the differences in various BC emission inventories widely
17 used in the world's research community should be studied for proper estimation of the
18 aerosol radiative forcing over the Indian region.

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21 Key Words: global aerosol model, black carbon, single scattering albedo, radiative forcing

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1. Introduction

Aerosol optical thickness (AOT), single scattering albedo (SSA) and black carbon (BC) are key parameters for estimating aerosol radiative forcings. BC aerosols strongly absorb shortwave radiation and are the second largest heating agents next to carbon dioxide (Forster et al., 2007). The Asian region is one of the most polluted areas in the world, having three major atmospheric brown cloud (ABC) regions including East Asia, the Indo-Gangetic Plain in South Asia, and Southeast Asia, where many BC aerosols could exist (e.g., Ramanathan et al., 2008). There are a number of reports on aerosol measurements over Indian region, but there are limited review papers especially for BC and SSA (Lawrence and Lelieveld, 2010).

The annual-averaged BC mass concentration over Indian region shows a wide range from $\sim 2 \mu\text{g}/\text{m}^3$ in Ahmedabad (Rastogi and Sarin, 2009) to $\sim 18 \mu\text{g}/\text{m}^3$ in Delhi (Rai et al., 2002) and its values tend to be comparable to those over China (Zhang et al., 2008; Han et al., 2009). The BC values over south-Asian region are much larger than those over other industrialized regions such as Europe and North America (Novakov et al., 2005; Koch et al., 2009). During dry seasons, the BC mass concentration is very large with values in the range of $30 \mu\text{g}/\text{m}^3$ in New Delhi, India (Miyazaki et al., 2009). The BC mass concentration reaches up to $\sim 3 \mu\text{g}/\text{m}^3$ over oceans around India during premonsoon season (Mayol-Bracero et al., 2002). Single scattering albedo (SSA) is less than 0.7 during pollution episodes such as dust storms and forest fires are observed over New Delhi, India (Singh et al., 2010). Large seasonal variations in SSA and lower SSA values with a range of less than 0.9 are reported over Indian region suggesting positive aerosol radiative forcing (Ramanathan et al., 2008).

Koch et al. (2009) compared global simulated BC distributions using 17 different global aerosol models and analyzed differences in the BC distribution between model simulations and measurements. The study did not show results over Indian region due to limited ground measurements. In the present study, a global aerosol transport model, SPRINTARS, developed by Takemura et al. (2000, 2002, 2005, 2009), coupled with MIROC-AGCM developed by Center for Climate System Research of the University of Tokyo, National Institute for Environmental Studies, and the Frontier Research Center for Global Change (K-1 Model Developers, 2004) is used to simulate spatial variations of BC, AOT and SSA over Indian region. In the global aerosol transport model simulations, BC inventory data from the AeroCom project (Diehl, personal, 2009) and inventory by Streets et al. (2003) are used for comparison with ground measurements over Indian region

1 summarized from published literature. Furthermore, we have summarized measurements of
2 both BC mass concentration and SSA at different sites over Indian region (Tables 1 and 2)
3 and compared them with global aerosol model simulations. The study is unique as it
4 provides a comprehensive collection of measured BC, SSA and its validation with widely
5 used aerosol emission inventories over Indian region.

7 **2. Measurement and Model description**

8 BC aerosol mass concentration measurements normally carried out using a
9 two-channel or seven-channel aethalometer from Magee Scientific, USA. The other
10 methods for BC measurements such as thermal evolution carbon analyzer, Aerosol Mass
11 Spectrometer-Scanning Mobility Particle Sizer (AMS-SMPS), Single Particle Soot
12 Photometer (SP2), Multi-Angle Absorption Photometer (MAAP), and Photoacoustic
13 Spectrometer (PAS) are described elsewhere (Watson and Chow, 2002; Slowik et al., 2007).
14 The BC measured at 880 nm wavelength provides a true measure of BC in the atmosphere
15 as at this wavelength BC is the principal absorber of light while the other aerosol
16 components have negligible absorption at this wavelength. The aethalometer uses
17 continuous filtration and optical transmission technique to measure the BC mass
18 concentration in near- real- time. The instrument draws ambient air through an inlet at a
19 preset flow rate and the particles in the air impinge on its quartz fiber filter tape. BC mass
20 concentrations are estimated by the change in transmittance of this quartz fiber tape over
21 which the deposition of the particles takes place. The beam attenuation (ATN) provides a
22 measure of the absorber mass. The mass concentration of BC is obtained from an
23 incremental ATN between two measurements using the effective specific mass absorption
24 cross-section value of $16.6 \text{ m}^2/\text{g}$, for 880 nm channel for the BC deposited on the filter area
25 of the sample spot, and the flow rate (Hansen et al., 1984; Bodhaine, 1995; Wiengartner et
26 al., 2003; Arnott et al., 2005; Schmid et al., 2006). The uncertainty in BC measurement will
27 be in the range $0.040\text{--}0.060 \text{ }\mu\text{g}/\text{m}^3$. The limitations and uncertainties of aethalometer in BC
28 measurements and corrections needed are well documented in the recent literature.

29 The global three-dimensional aerosol transport-radiation model, Spectral
30 Radiation-Transport Model for Aerosol Species (SPRINTARS) latest version 3.84, is used in
31 the present study and details for the SPRINTARS model have been described elsewhere
32 (Takemura et al., 2000, 2002, 2005, 2009). In this study, we use T42 horizontal resolution
33 (approximately 2.8° by 2.8° in latitude and longitude) and 20 layers of the vertical resolution

1 with a time step of 20 min. The model calculates the mass mixing ratios of the main
2 tropospheric aerosols, i.e., carbonaceous aerosol (BC and organic carbon; OC), sulfate, soil
3 dust, sea salt, and the precursor gases of sulfate, i.e., sulfur dioxide (SO₂) and
4 dimethylsulfide (DMS). The aerosol transport processes include emission, advection,
5 diffusion, sulfur chemistry, wet deposition and gravitational settling. All experiments use the
6 monthly-averaged global distributions for sea surface temperature and sea ice re-analyzed
7 by the Hadley Centre, UK Met Office. The model simulations are conducted with nudged
8 meteorological fields from the NCAR/NCEP reanalysis data (wind, water vapor, and
9 temperature) every six-hour for proper simulation of aerosol distribution,

10 The radiation scheme, MSTRN-8, in the MIROC-AGCM can handle scattering,
11 absorption, and emission by aerosol and cloud particles, as well as absorption by gaseous
12 constituents (Nakajima et al., 2000). The particles are treated as external mixtures except
13 for carbonaceous aerosols. The secondary OC and 50% BC mass from fossil fuel source
14 are treated as externally mixed particles, but other carbonaceous particles are treated as
15 internal mixtures of BC and primary OC with assumed BC/OC fractions of 0.3 and 0.15.
16 Mixing ratios are calculated for various size bins from 0.1 to 10 μm for soil dust and sea salt
17 aerosols (Takemura et al., 2009). The dry mode radii for carbonaceous and sulfate aerosols
18 are set to 0.1 and 0.0695 μm, respectively (Takemura et al., 2002). The aerosol densities
19 hygroscopicities, and refractive indices are set to the same values as suggested by
20 Takemura et al. (2002). The scattering properties estimated from Mie theory with these
21 prescribed optical parameters are described elsewhere (e.g., Schutgens et al., 2010). The
22 combinations of both pre-calculated extinctions and absorptions for all aerosol species and
23 simulated aerosol mixing ratios provide the simulated AOT and SSA. Aerosol direct radiative
24 forcing (ADRF) due to the direct effect of all aerosols is calculated as the difference in the
25 net radiative fluxes with and without the aerosols under the same meteorological conditions.

26 Emission inventories of aerosols (primary OC and BC) and its precursors (i.e.
27 SO₂) used in the first model simulations are widely used in the AeroCom (AC) project. The
28 anthropogenic primary OC and BC emissions are based on Bond et al. (2004) and the
29 anthropogenic SO₂ emissions are based on EDGAR 32FT2000
30 database(http://www.pbl.nl/en/themasites/edgar/emission_data/edgar_32ft2000/index.html).
31 Hereafter, this BC emission inventory is called AC emission and the AC emissions during
32 1980-2008 are included in the inventory. Biomass burning emissions in each month and
33 year is based on the fire maps derived from MODIS. In the second model simulation, we

1 interpolate the anthropogenic BC emission flux by Streets et al. (2003) over Asia to the
2 emission inventory by Takemura et al. (2005). The emission inventories by Streets et al.
3 (2003) and Takemura et al. (2005) are only for the year 2000. In order to make the
4 anthropogenic BC emission inventory for other years i.e., 2001-2008, we generate the new
5 emission inventory using scaling factors derived from ratios of AC emission in each year
6 during 2001-2008 to the AC emission in the year 2000. Hereafter, this BC emission
7 inventory is called ST emission. The two BC emission inventories are shown in Figure 1 and
8 the value of the BC emission over India in year 2008 is estimated to be about 0.18 Tg in the
9 AC emission and about 0.69 Tg in the ST emission, respectively. The oxidant
10 concentrations such as ozone and hydroxyl radical, which are not predicted in the
11 SPRINTARS model but are needed to calculate sulfate chemistry, are given by a global
12 chemical transport model, CHASER, which also has been implemented in the
13 MIROC-AGCM (Sudo et al., 2002). Emission processes for dust, seasalt, and DMS are
14 online-calculated in the SPRINTARS model (Takemura et al., 2000, 2009). In this study, the
15 strength of the dust emission around the Middle-east Asia is tuned to obtain closer AOT to
16 satellite-retrieved AOT with a factor of three, as suggested by Takemura et al. (2000).

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18 **3. Results and discussion**

19 In the present study, simulations with global aerosol model are carried out using
20 BC emission inventories by AeroCom (AC) and Streets (ST). The simulated BC
21 concentrations using the AC emission inventory are much underestimated and simulated
22 values with the ST emission inventory are closer to the observed values as shown in Figure
23 2. It can be observed in Figure 2(a) that more than 60% of simulations for the AC emission
24 scenario are smaller than the ground observations with an underestimate of more than 70%,
25 whereas more than 75% of the simulations are within a factor of three compared to
26 observations. This is reflected from the differences in the BC emission fluxes between the
27 AC and ST inventories. However, the simulated BC concentrations using the ST emission
28 are still underestimated in the areas where values of observed BC concentrations are more
29 than $15 \mu\text{g}/\text{m}^3$ in dry season. These underestimates are caused probably due to large
30 uncertainty in the BC emission inventory including undetected local emissions and also
31 possibly due to coarse size of the model grids in the global model (~ 300 km). The SSA
32 comparison as shown in Figure 2(b) also suggests that model simulations with the AC
33 emission inventory generally overestimate the values compared to ground-based

1 observations, whereas the simulations with the ST emission inventory are more comparable
2 to observations. However, the simulated SSA with the ST emission inventory is much
3 underestimated compared to the observations in post-monsoon season. This could be
4 primarily due to emissions from biomass burning that are not properly accounted for in the
5 emission inventory (Badarinath et al., 2007, 2009). The model simulated SSA values are in
6 the range 0.84-0.97 for the AC emission and 0.80-0.90 for the ST emission. Proper
7 simulation of SSA values is important for the estimation of aerosol radiative forcing
8 (Ramanathan et al., 2001a). Judging from underestimation of BC values during the season,
9 we suppose that scattering components are underestimated during post monsoon season.
10 In spite of this uncertainty, combination of BC and SSA comparison results bring
11 straightforward consistency that underestimated BC causes overestimated SSA around
12 Indian region.

13 Model simulated AOT comparison with satellite-retrieved AOT over Indian region
14 is shown in Figure 3. The model simulated AOT using the ST emission inventory is providing
15 comparable estimates to MODIS-retrieved AOT with values in the range of 0.2-1. However,
16 simulated AOT is slightly overestimated compared to MODIS-retrieved AOT over western
17 India with a difference of more than 0.2. The errors in the model estimates could be due to
18 overestimation of dust aerosols from Persian Gulf region. The satellite estimates of AOT
19 over land suffer from inaccuracies associated with surface reflectance properties (Remer et
20 al., 2008). The difference in AOT between two simulations using the AC and the ST
21 emission inventories suggest that the AOT values with the ST emission are larger than
22 those in the AC emission with a difference in range of 0.1-0.2 over Indian region.

23 Aerosol direct radiative forcing (ADRF over Indian region is calculated for both
24 model simulations as shown in Figure 4 and the values are tabulated in Table 3. At the top of
25 atmosphere (TOA), the magnitude of the ADRF reflects not only on the total aerosol amount
26 but also on the contributions of absorbing components such as BC to the total components.
27 At the surface (SFC), on the other hand, the magnitude of the ADRF does not reflect on
28 contents of absorbing components. The ADRF at the TOA is smaller than that at the SFC
29 due to higher concentration of BC aerosols. The spatial variations in magnitude of ADRF at
30 the TOA with higher BC loading are smaller than those with lower BC loading. This suggests
31 that conditions under the higher BC loading bring more heating of the atmosphere
32 compared to conditions under the lower BC loading. The magnitude of the ADRF at the TOA
33 in the model simulation with the AC emission inventory is larger than that with the ST

1 emission inventory. The ADRF at the TOA over Indian region is calculated to be varying from
2 -3.0 to -1.5 W/m² in the AC emission and from -2.5 to -1.0 W/m² in the ST emission,
3 respectively. At the SFC, the ADRF is calculated to be from -3.0 to -2.5 W/m² in the AC
4 emission and from -3.5 to -2.5 W/m² in the ST emission, respectively. The ADRF values
5 under the all and clear skies for the region (75°E-90°E, 13°N-28°N) are given in Table 3. The
6 magnitude of atmospheric heating in the simulation with the ST emission inventory is +0.85
7 W/m² and the difference between two simulations is estimated to be +0.60 W/m². The
8 impact of different BC emission inventories on the ADRF over Indian region is large. Since
9 the ST emission scenario is providing the model results comparable to the observations, it
10 can be concluded that approximately three times heating of the atmosphere could be
11 possible as compared to earlier predictions using the AC emission inventory. Furthermore,
12 this impact under the whole sky is larger than that under the clear sky. The effect of
13 increased atmospheric heating caused by increase in BC loading is also seen in decreased
14 SSA over the region (Haywood and Shine, 1997).

16 **4. Conclusions**

17 In the present study, aerosol observations over Indian region published in literature were
18 summarized for validating global aerosol model simulations with BC emission inventories by
19 AeroCom project and Streets et al. (2003).

- 21 (1) BC mass concentrations and SSA over Indian region showed large variations with urban
22 areas having higher BC values and lower SSA values.
- 23 (2) Model simulations suggested that BC emission inventory from the AeroCom project
24 underestimated the aerosol properties and the simulations with the Streets's data
25 provided better results.
- 26 (3) The differences in BC, SSA, and AOT with the two simulations were significantly large
27 and could lead to large errors in estimation of aerosol radiative forcing.
- 28 (4) The differences in aerosol direct radiative forcing between two simulations were
29 estimated to be 0.5 W/m² at the SFC and 0.1 W/m² at the TOA under the whole sky
30 conditions. Model simulations with ST emission inventory suggested increased
31 atmospheric heating of +0.6 W/m² over Indian region.

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1 Tables

2 **Table 1.** Measured BC mass concentrations over Indian region tabulated from literature.

Location	Reg. ^a	Mass	Reference
Ahmedabad (Annual, 2002)	L	2.1	Rastogi and Sarin (2009)
Chandigarh (Annual, 2001)	L	3.7	Chowdhury et al. (2007)
Delhi (Annual, 2001-2002)	L	17.9	Rai et al. (2002)
Delhi (Annual, 2006-2007)	L	4-15	Singh et al. (2010)
Karachi (Annual, 2006-2007)	L	2-3	Dutkiewicz et al. (2009)
New Delhi (Annual, 2007)	L	14±12	Tiwari et al. (2009)
Pune (Annual, 2005)	L	4.1	Safai et al. (2007)
Trivandrum (Annual, 2000-2001)	L	0.3-5	Babu et al. (2002)
Agra (Dec, 2004)	L	20.6	Safai et al. (2007)
Ahmedabad (Dry, 2002-2005)	L	5.5±2.8	Ganguly et al. (2006)
Ahmedabad (Dry, 2008)	L	11.6±2.9	Ramachandran and Kedia (2010)
Ahmedabad (Jan, 2004)	L	5	Ramachandran and Rajesh (2007)
Ahmedabad~Hyderabad (Feb, 2004)	L	2	Ganguly et al. (2005b)
Allahabad (Dec, 2004)	L	6.2±2.0	Ram and Sarin (2010)
Delhi (Dec, 2004)	L	29±14	Ganguly et al. (2006)
Delhi (Dec, 2006)	L	16.7	Singh et al. (2010)
Delhi (Feb, 2006)	L	19	Beegum et al. (2009)
Delhi (Jan, 2006)	L	27	Beegum et al. (2009)
Delhi (Mar, 2006)	L	8.1	Beegum et al. (2009)
Delhi (Dec, 2001)	L	17.4	Chowdhury et al. (2007)
Hisar (Dec, 2004)	L	1.5-7.2	Ramachandran et al. (2006)
Hisar (Dec, 2004)	L	3.8±1.4	Rengarajan et al. (2007)
Hyderabad (Feb, 2006)	L	25	Beegum et al. (2009)
Hyderabad (Jan, 2006)	L	21	Beegum et al. (2009)
Hyderabad (Mar, 2006)	L	13	Beegum et al. (2009)
Jaduguda (Dec, 2004)	L	11.6±2.0	Ram and Sarin (2010)
Kanpur (Dec, 2004)	L	6-20	Tripathi et al. (2005)
Kanpur (Dry, 2007-2008)	L	4.9±1.5	Ram et al. (2010)
Kanpur (Dry, 2007)	L	4.8±3.0	Ram and Sarin (2010)

Kanpur (Mar, 2007)	L	5.8±4.1	Ram et al. (2010)
Karachi (Dry, 2007)	L	9.1	Dutkiewicz et al. (2009)
Kharaghpur (Dec, 2004)	L	8.0-28.0	Nair et al. (2007)
Kharaghpur (Feb, 2006)	L	7.5	Beegum et al. (2009)
Kharaghpur (Jan, 2006)	L	9.3	Beegum et al. (2009)
Kharaghpur (Mar, 2006)	L	6.9	Beegum et al. (2009)
Kolkata (Dry, 2001)	L	26.5	Chowdhury et al. (2007)
Lahore (Dry, 2005-2006)	L	21.7	Husain et al. (2007)
Minicoy (Feb, 2006)	L	0.47	Beegum et al. (2009)
Minicoy (Jan, 2006)	L	0	Beegum et al. (2009)
Minicoy (Mar, 2006)	L	0.22	Beegum et al. (2009)
Mumbai (Dry, 1999)	L	12.4±5.1	Venkataraman et al. (2002)
Mumbai (Dry, 2001)	L	8.2	Chowdhury et al. (2007)
Nainital (Dec, 2004)	L	1.36	Pant et al. (2006)
Nainital (Feb, 2006)	L	1.5	Beegum et al. (2009)
Nainital (Jan, 2006)	L	0.67	Beegum et al. (2009)
Nainital (Mar, 2006)	L	1.4	Beegum et al. (2009)
New Delhi (Dry, 2006-2007)	L	40.4 ^b	Miyazaki et al. (2009)
Pune (Feb, 2006)	L	6.4	Beegum et al. (2009)
Pune (Jan, 2006)	L	7.3	Beegum et al. (2009)
Pune (Mar, 2006)	L	5.4	Beegum et al. (2009)
Trivandrum (Dry+Premonsoon, 2006)	L	5.7	Beegum et al. (2009)
Trivandrum (Dry+Premonsoon, 2006)	L	5.2	Beegum et al. (2009)
Trivandrum (Dry+Premonsoon, 2006)	L	3	Beegum et al. (2009)
Visakhapatnam (Dry, 2006)	L	8.01	Sreekanth et al. (2007)
Hyderabad (Dry+Premonsoon, 2003)	L	0.5-68	Latha and Badarinath (2003)
Hyderabad (Dry+Premonsoon, 2006)	L	2-18	Badarinath and Kharol, (2008)
Ahmedabad (Jul, 2004)	L	0.8	Ramachandran and Rajesh (2007)
Ahmedabad (Monsoon, 2002-2005)	L	1.5±0.8	Ganguly et al. (2006)
Ahmedabad (Monsoon, 2008)	L	2.1±0.8	Ramachandran and Kedia (2010)
Delhi (Aug, 2006)	L	3.26	Singh et al. (2010)
Delhi (Dec, 2001)	L	4	Chowdhury et al. (2007)

Gadanki (Monsoon, 2008)	L	1	Gadhavi and Jayaraman (2010)
Hyderabad (Monsoon, 2004)	L	6	Latha et al. (2005)
Karachi (Monsoon, 2006)	L	2	Dutkiewicz et al. (2009)
Kolkata (Monsoon, 2001)	L	6.6	Chowdhury et al. (2007)
Visakhapatnam (Monsoon, 2006)	L	1.67	Sreekanth et al. (2007)
Ahmedabad (Postmonsoon, 2002-2005)	L	7.3±3.7	Ganguly et al. (2006)
Ahmedabad (Postmonsoon, 2008)	L	10.9±1.5	Ramachandran and Kedia (2010)
Bangalore (Nov, 2001)	L	4.2	Babu et al. (2002)
Delhi (Postmonsoon, 2001)	L	11.5	Chowdhury et al. (2007)
Kanpur (Postmonsoon, 2007)	L	4.1±1.3	Ram et al. (2010)
Karachi (Postmonsoon, 2006)	L	10	Dutkiewicz et al. (2009)
Kolkata (Postmonsoon, 2001)	L	9.1	Chowdhury et al. (2007)
Mumbai (Postmonsoon, 2001)	L	5.6	Chowdhury et al. (2007)
Visakhapatnam (Postmonsoon, 2006)	L	0.43	Sreekanth et al. (2007)
Sinhagad (Nov2004-Apr2005)	L	1.5	Safai et al. (2007)
Ahmedabad (Premonsoon, 2002-2005)	L	2.2±1.0	Ganguly et al. (2006)
Ahmedabad (Premonsoon, 2008)	L	3.9±2.5	Ramachandran and Kedia (2010)
Delhi (Apr, 2006)	L	12	Beegum et al. (2009)
Delhi (May, 2006)	L	11	Beegum et al. (2009)
Delhi (Premonsoon, 2001)	L	9.1	Chowdhury et al. (2007)
Gadanki (Premonsoon, 2008)	L	4	Gadhavi and Jayaraman (2010)
Hyderabad (Apr, 2006)	L	15	Beegum et al. (2009)
Hyderabad (May, 2006)	L	12	Beegum et al. (2009)
Kanpur (Premonsoon, 2007)	L	2.1±0.9	Ram et al. (2010)
Karachi (Apr, 2006)	L	4	Dutkiewicz et al. (2009)
Kharaghpur (Apr, 2006)	L	8.4	Beegum et al. (2009)
Kharaghpur (May, 2006)	L	2.7	Beegum et al. (2009)
Kolkata (Premonsoon, 2001)	L	6.1	Chowdhury et al. (2007)
Minicoy (Apr, 2006)	L	0.16	Beegum et al. (2009)
Minicoy (May, 2006)	L	0.065	Beegum et al. (2009)
Mumbai (Premonsoon, 2001)	L	3.7	Chowdhury et al. (2007)
Nainital (Apr, 2006)	L	1.6	Beegum et al. (2009)

Nainital (May, 2006)	L	1.3	Beegum et al. (2009)
Pune (Apr, 2006)	L	2.2	Beegum et al. (2009)
Pune (May, 2006)	L	1.5	Beegum et al. (2009)
Trivandrum (Dry+Premonsoon, 2006)	L	2.3	Beegum et al. (2009)
Trivandrum (Dry+Premonsoon, 2006)	L	1.8	Beegum et al. (2009)
Visakhapatnam (Premonsoon, 2006)	L	3.33	Sreekanth et al. (2007)
Mt Abu (Annual, 2005-2006)	M	0.5±0.5	Ram et al. (2008)
Manora Peak (Dec, 2004)	M	0.89±0.33	Rengarajan et al. (2007)
Manora Peak (Dry, 2005)	M	1.8±0.8	Ram et al. (2008)
Manora Peak (Dry, 2006)	M	1.5±0.6	Ram et al. (2008)
Manora Peak (Dry, 2007-2008)	M	2.0±0.9	Ram and Sarin (2010)
Manora Peak (Dry, 2007)	M	1.0±0.7	Ram and Sarin (2010)
Mt Abu (Dry, 2005)	M	0.8±0.6	Ram et al. (2008)
Manora Peak (Monsoon, 2005)	M	0.4±0.1	Ram et al. (2008)
Manora Peak (Monsoon, 2006)	M	0.3±0.2	Ram et al. (2008)
Mt Abu (Monsoon, 2005)	M	0.2±0.1	Ram et al. (2008)
Manora Peak (Postmonsoon, 2005)	M	1.3±0.6	Ram et al. (2008)
Manora Peak (Postmonsoon, 2006)	M	0.9±0.4	Ram et al. (2008)
Mt Abu (Postmonsoon, 2005)	M	0.7±0.3	Ram et al. (2008)
Langtang (Postmonsoon, 1999-2000)	M	0.52±0.48	Carrico et al., 2003
Nagarkot (Postmonsoon, 1999-2000)	M	1.0±0.7	Carrico et al., 2003
Manora Peak (Premonsoon, 2005)	M	0.9±0.5	Ram et al. (2008)
Manora Peak (Premonsoon, 2006)	M	1.5±0.6	Ram et al. (2008)
Mt Abu (Premonsoon+Monsoon, 2005)	M	0.1±0.1	Ram et al. (2008)
Hanimaadhoo (Dry, 2004-2005)	O	0.48±0.26	Corrigan et al. (2006)
Hanimaadhoo (Nov, 2004)	O	0.052±0.055	Corrigan et al. (2006)
Hanimaadhoo (Oct, 2004)	O	0.031±0.038	Corrigan et al. (2006)
Indian Ocean			
(0-1.2km, Premonsoon, 2001)	O	2.3±1.0	Mayol-Bracero et al. (2002)
Indian Ocean			
(1.3-3.2km, Premonsoon, 2001)	O	3.2±2.0	Mayol-Bracero et al. (2002)
Indian Ocean (Premonsoon, 2006)	O	2.4±0.6	Moorthy et al. (2009)

^a Location in the sites is categorized by Land (L), Mountain (M), and Ocean (O).

^b The BC mass concentration is in unit of $\mu\text{gC}/\text{m}^3$.

Table 2. Measured single scattering albedo (SSA) values over Indian region tabulated from literature.

Location	Reg. ^a	SSA	Reference
Delhi (Annual, 2006-2007)	L	0.79±0.05	Singh et al. (2010)
Gadanki (Annual, 2008)	L	0.92-0.99	Gadhavi and Jayaraman (2010)
Kanpur (Annual, 2001-2004)	L	0.88-0.94	Jethva et al. (2005)
Ahmedabad (Dry, 2002-2005)	L	0.73±0.1	Ganguly et al. (2006)
Ahmedabad~Hyderabad (Feb, 2004)	L	0.75-0.90	Ganguly et al. (2005a)
Chennai (Dry, 2004)	L	0.77	Ramachandran (2005)
Delhi (Jan, 2004)	L	0.74±0.03	Singh et al. (2010)
Hisar (Dec, 2004)	L	0.88	Ramachandran et al. (2006)
Kanpur (Dec, 2004)	L	0.76	Tripathi et al. (2005)
Kanpur (Dry, 2001-2005)	L	0.91	Dey and Tripathi (2008)
Kathmandu (Dry, 2003)	L	0.7-0.9	Ramana et al. (2004)
New Delhi (Mar, 2006)	L	0.84	Pandithurai et al. (2008)
New Delhi (Dec, 2004)	L	0.68	Ganguly et al. (2006)
Delhi (Dry+Premonsoon, 2006)	L	0.74-0.84	Pandithurai et al. (2008)
Pune (Dry+Premonsoon, 2001-2002)	L	0.81	Pandithurai et al. (2004)
Ahmedabad (Monsoon, 2002-2005)	L	0.81±0.03	Ganguly et al. (2006)
Delhi (Aug, 2006)	L	0.89±0.04	Singh et al. (2010)
Kanpur (Monsoon, 2001-2005)	L	0.89	Dey and Tripathi (2008)
Ahmedabad (Postmonsoon, 2002-2005)	L	0.73±0.08	Ganguly et al. (2006)
Kanpur (Postmonsoon, 2001-2005)	L	0.9	Dey and Tripathi (2008)
Ahmedabad (Premonsoon, 2002-2005)	L	0.84±0.04	Ganguly et al. (2006)
Delhi (Premonsoon, 2003)	L	0.67	Singh et al. (2005)
Hyderabad (0-2km, Premonsoon, 2006)	L	<0.80	Satheesh et al. (2008)
Hyderabad (<1km, Premonsoon, 2006)	L	0.85-0.95	Satheesh et al. (2008)
Kanpur (Premonsoon, 2001-2005)	L	0.9	Dey and Tripathi (2008)
New Delhi (Apr, 2006)	L	0.78	Pandithurai et al. (2008)

New Delhi (Jun, 2006)	L	0.74	Pandithurai et al. (2008)
New Delhi (May, 2006)	L	0.75	Pandithurai et al. (2008)
AS ^b (May, 2001)	O	0.9	Satheesh (2002)
AS ^b (0.5-1.5km, Jan, 2009)	O	0.85	Babu et al. (2010)
AS ^b (2-3km, Jan, 2009)	O	0.7	Babu et al. (2010)
AS ^b (Dry, 1999)	O	0.89	Ramanathan et al. (2001b)
AS ^b (Jan, 2009)	O	0.80±0.09	Babu et al. (2010)
AS ^b (Surface, Jan, 2009)	O	0.94±0.05	Babu et al. (2010)
AS ^b , BoB ^c , and NIO ^d (Dry, 1999)	O	0.88±0.04	Clarke et al. (2002)
BoB ^c (Apr, 1999)	O	0.84±0.03	Nair et al. (2008)
BoB ^c (Dry, 2001)	O	0.86	Ramachandran (2005)
BoB ^c (Dry, 2006)	O	0.93±0.03	Nair et al. (2008)
BoB ^c (Feb, 2003)	O	0.88	Vinoj et al. (2004)
BoB ^c (Mar, 2001)	O	0.85	Satheesh (2002)
Indian Ocean (Dry, 1999)	O	0.85±0.06	Sheridan et al. (2002)
Indian Ocean (Mar, 2001)	O	0.97	Satheesh (2002)
Indian Ocean (Surface, Dry, 1999)	O	0.85-0.9	Ramanathan et al. (2001b)
KCO ^e (Dry, 1998)	O	0.90±0.06	Müller et al. (2003)
KCO ^e (Dry, 1999)	O	0.8-0.9	Satheesh et al. (2002)
KCO ^e (Dry, 1999)	O	0.877	Collions et al. (2002)
KCO ^e (Dry, 1999)	O	0.9	Satheesh et al. (1999)
Southern Arabian Sea (Dry, 1999)	O	0.9	Ramanathan et al. (2001b)
Hanimaadhoo (Oct, 2004)	O	0.96-0.98	Corrigan et al. (2006)
Hanimaadhoo (Nov, 2004)	O	0.94-0.97	Corrigan et al. (2006)
Hanimaadhoo (Postmonsoon, 2004)	O	0.93±0.02	Corrigan et al. (2006)
BoB ^c (Premonsoon, 2006)	O	<0.8	Satheesh et al. (2008)
BoB ^c (Premonsoon, 2006)	O	0.92-0.95	Moorthy et al. (2009)
Southeastern AS ^b (Premonsoon, 2006)	O	>0.96	Moorthy et al. (2009)

1 ^a Location in the sites is categorized by Land (L), Mountain (M), and Ocean (O)

2 ^b Arabian Ocean

3 ^c Bay of Bengal

4 ^d North Indian Ocean

^e Kaashidoo Climate Observatory

Table 3. Annual-averaged aerosol direct radiative forcings (W/m^2) over India (75°E - 90°E , 13°N - 28°N) during years (2000-2008) at the surface (SFC), top of the atmosphere (TOA) and atmosphere (ATM), using two simulations with different BC emission inventories (AC and ST) under the whole and clear sky conditions.

	Whole-sky		Clear-sky	
	AC	ST	AC	ST
SFC	-2.70	-2.76	-4.10	-4.93
TOA	-2.45	-1.91	-3.84	-4.04
ATM	+0.25	+0.85	+0.27	+0.90

Figures captions

Figure 1. Two emission inventories of BC used in this study for the year 2008. (a) is AeroCom emission inventory and (b) is the original emission inventory based on Streets et al. (2003) over Asia and Takemura et al. (2005) over other areas.

Figure 2. Comparison of (a) BC mass concentrations and (b) SSA over land as described in Table 1 and Table 2.

Figure 3. Comparison of annual mean aerosol optical thickness (AOT) from model and MODIS data over Indian Region for the year 2008.

Figure 4. Spatial variations in annual mean aerosol direct radiative forcing (ADRF) under the whole-skies over Indian region during the years (2000-2008) at top of atmosphere (TOA) and surface (SFC).

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(a) BC comparisons

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(b) SSA comparisons

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6 ●: annual, O: dry, +:pre-monsoon, X: monsoon, -:post-monsoon

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