Fog-Induced Changes in Optical and Physical Properties of Transported Aerosols over Sundarban, India

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ABSTRACT

A campaign was conducted at Kalas Island, Sundarban to address fog-induced changes in optical and physical properties of aerosols during the winter period (11–16 January 2014). Being an isolated remote island in the northern coastal region of Bay of Bengal, the measurement site provides a unique opportunity to investigate aerosol properties and foggy conditions during transported aerosol plumes from the Indo-Gangetic Basin (IGB). Two fog events were observed over Sundarban during the campaign increasing Aerosol Optical Depth (AOD) by almost a factor of three (1.6 ± 0.4) compared to “background” AOD of 0.52 ± 0.2 on a normal winter day. Back-trajectory analysis shows that aerosols mostly originate from the IGB contributing to higher fine-mode as well as coarse-mode aerosol concentrations during the foggy days. Black Carbon (BC), known as a tracer for anthropogenic sources, is found to be about 15.2 ± 1.3 µg/m³ at such a remote region and increased by 30% during foggy days indicating strong influence from transported anthropogenic aerosols from nearby urban regions. Similar enhancement is also observed in aerosol absorption coefficient, especially in the UV region. Low ventilation due to calm and cool atmosphere with a shallow boundary layer during foggy days could have ‘trapped’ BC over Sundarban and resulted in such an enhancement. On the other hand, the absorption angstrom exponent reduced indicating dominance of weakly spectral dependent aerosols during foggy period, mostly associated with fossil-fuel combustion. However, this could also be the result of BC coating with water-soluble species under high RH conditions. Enhancement of absorbing aerosols during foggy period reduces the incoming solar radiation, causing large perturbation in the radiation budget over the site.

Keywords: Aerosol; Black carbon; Fog; Indo-Gangetic basin; Sundarban.

INTRODUCTION

Fog is a common natural phenomenon in the Indo-Gangetic Basin (IGB) during winter (December–February) reducing visibility to less than 1 km, thus causing serious deleterious effects in transportation, delay of flights, car accidents and human loss (Goloub et al., 2001). Satellite observations (Di Girolamo et al., 2004; Ramanathan and Ramana, 2005; Badarinath et al., 2009; Kharol et al., 2011) show that fog is mainly detected along the IGB near to the Himalayan foothills extending up to Bangladesh and northern Bay of Bengal (BoB). From a meteorological point of view, scarcity of rainfall, along with low temperatures, high Relative Humidity (RH) and shallow boundary layer constitute favourable conditions for the formation and extension of fog during winter months (Gautam et al., 2007).

Previous studies showed remarkable increase in aerosol loading over northern India during winter due to increase in anthropogenic emissions mostly from fossil-fuel combustion, bio-fuel burning and agricultural crop residue burning (Dey and Di Girolamo, 2011; Kaskaoutis et al., 2011a, 2012; Ganguly et al., 2012). Significantly large anthropogenic aerosol loading is also noticed over the Himalayas during winter that is mostly transported from the IGB by up-slope mountain winds (Dumka et al., 2006; Babu et al., 2011; Dumka et al., 2014; Sarkar et al., 2015). The cold wind arriving from west Asia to northwest India and moving further to the east part of IGB can transfer and accumulate large amount of aerosols over Bangladesh and Ganges-Brahmaputra delta (Venkataraman et al., 2005, Nair et al., 2007; Kaskaoutis et al., 2014). During foggy periods, secondary aerosols and biomass burning were found to be the major contributors for the fog formation over the IGB (Ganguly et al., 2006; Mehta et al., 2009). Increased loading of fine anthropogenic aerosols under high RH conditions and reduced surface temperature caused by cold air coming from western India over the IGB favour dense...
fog and increase aerosol radiative forcing (ARF) during winter (Kaskaoutis et al., 2013). Increase in planetary cooling (larger negative ARF values at top of the atmosphere) was observed during foggy periods over IGB due to increased backscattered solar radiation at the top of the fog layer present within 0.5 km from the surface (Das et al., 2008). Air-craft measurements over central IGB showed a thick aerosol layer composed of significant fraction of Black Carbon (BC) peaking at 0.9 km during December (Tripathi et al., 2005), causing significant reduction in surface-reaching solar radiation during the foggy days (Ganguly et al., 2006).

In the present study, we investigate the aerosol properties during foggy events at Kalas Island, Sundarban (21.68°N, 88.57°E), which is the southern-most delta island in the estuary region of the Ganga River. It is far from the IGB industrial regions and mostly free of local sources of anthropogenic aerosols. Therefore, such a measurement site provides a unique opportunity to study the transported anthropogenic aerosols exclusively, wherein lies the novelty of the current study. AOD measurements from ground-based and space-borne instruments, surface aerosol number distribution, BC mass concentration and aerosol absorption coefficient are analysed during foggy and normal days in order to identify any modification in aerosol field that is associated or even favours the formation of fog over the site.

MEASUREMENT SITE

The research campaign was conducted during 11–16 January 2014 at Kalas Island (21.68°N, 88.57°E), an isolated delta island in the estuary of Ganga river within the ‘Sundarban’ mangrove forest region, in order to investigate the aerosol optical and physical properties during foggy periods. Continuous measurements of aerosol characteristics were carried out, while two fog events occurred during the morning hours of 12 and 15 January 2014. It should be noted that foggy conditions prevailed during the midnight or late night hours on all days, but are not detected via sun photometers and, therefore, they are not considered as foggy periods. Under favorable conditions, fog can persist until mid-morning and disappear during midday hours as occurred on 12 and 15 January. Fig. 1(a) shows the satellite image obtained from the Indian geostationary satellite Kalpana in the early morning hours (04:30 LST = UTC + 5:30) on 12 January 2014, while Fig. 1(b) shows the Sundarban region and the location of the measurement site at Kalas Island denoted by a star. The dense fog situated over Sundarban region and in many parts of the IGB is clearly detected by the satellite image.

The dark color in Fig. 1(b) represents the reserved mangrove forest region for wild animals, particularly the ‘Royal Bengal’ tigers. The population density is very low and mostly concentrated in the northern part of Sundarban, and the people are mostly involved in fishing related occupations. Kalas Island is about 100 km south of Kolkata, the capital metropolitan city of West Bengal, which has large number of vehicles, industries and thermal power plants. There are no residential houses in the island as well as in other nearby islands, making this region pollution-free and, therefore, suitable for the current research. The main transportation is a ferry that is used by the local police twice a day to survey the area. A few fishing boats, which are very small and manually operated, are found in the nearby regions and they do not produce any anthropogenic aerosols. All instruments were installed on the top of a tower in the island reserve forest office at 10 m above ground level and it was a free breeze passing site.

EXPERIMENTAL DETAILS AND INSTRUMENTATION

Ground-based spectral AOD, size segregated aerosol number distribution, aerosol absorption coefficient along with BC mass concentrations have been obtained from Microtops, aerosol size spectrometer and Aethalometer instruments during the frameworks of the campaign. AOD was measured during clear-sky daytime conditions, while the other aerosol properties were measured round the clock during the campaign period. Special care was taken for the inlets of the instruments, where ambient air was drawn through a common bottle that assisted in avoiding the direct entrance of ambient moisture into the instruments. Brief descriptions about individual instruments are given below.

Microtops

Spectral AODs were measured at six wavelengths using a hand-held sun-photometer (Model: MICROTOPS-II, Solar System Inc., USA; (Morys et al., 2001)). The instrument is very light weighted and installed on a tripod stand during the measurement period. Sunphotometer mainly measures surface-reaching solar radiation at five wavelengths, centered at 0.380, 0.500, 0.675, 0.936 and 1.020 μm. The instrument stores the intensity of incoming solar irradiance at the surface in different wavelengths (in mV), from which the absolute irradiance (in W/m²) is obtained by multiplying the measured signal with the calibration factor (W/m²/mV). Calibration relies on a high-performance voltage reference with very low temperature coefficient (less than 0.001% per degree Centigrade), which has very high long-term stability (about 0.005% per year). The full width at half maximum at each wavelength is about 2.4 ± 0.4 nm, while the accuracy of the sun-targeting angle is better than 1°. AOD observations at the measurement site were performed at half hour intervals between 09:00 and 16:00 hours local time under cloud free conditions. Three consecutive measurements were made each time and the least impressive scan was selected following the criteria described in Sharma et al. (2014). On foggy days, the AOD observations were taken when fog was moderately diluted, thus allowing sun-disk scanning by the sun photometer and continued until afternoon.

Aerosol Size Spectrometer

Size-segregated aerosol number distribution was measured during the campaign using aerosol size spectrometer (GRIMM aerosol tecknik, Germany; model 1.108) (Peters et al., 2006; Grimm and Eatough, 2009). The instrument provides the aerosol number size distribution in 15 different bins (0.3–0.4, 0.4–0.5, 0.5–0.65, 0.65–0.8, 0.8–1.0, 1.0–1.6,
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Fig. 1. (a) Location of Sundarban along with satellite image obtained from Indian geostationary satellite, Kalpana, at 0430 local hours on 12 January 2014 when fog was observed over Sundarban. (b) Location of measurement site (marked by star) at the isolated south-most delta island, Kalas Island in Sundarban in the northern coastal region of Bay of Bengal. Darker region indicates the reserved mangrove forest for the 'Royal Bengal Tiger'.

1.6–2.0, 2.0–3.0, 3.0–4.0, 4.0–5.0, 5.0–7.5, 7.5–10.0, 10.0–15.0, 15.0–20.0, > 20 μm diameter). The instrument is light weighted, field portable, occupies a small space and has a maximum operational period of up to 7 hours using an integral internal battery (or indefinite with an external 220 V supply) while operated at a constant ambient air flow rate (at 1.2 L/min). The ambient air is pumped through a detector cell, which contains a semiconductor laser light source, generating a scattered light signal proportional to the size of the aerosol particle causing the light scatter. A receptor diode collects 90 degree scattered light and the signal is processed in a multichannel size classifier. The optics is protected against contamination using a sheath air flow, and all particles are collected on a downstream filter attached at the backside outlet for gravimetric or chemical analysis (if required). Data were collected round the clock as 10-min averages, stored on a removable data card, and downloaded and processed using Grimm 1.177 software. Ambient temperature and humidity were also measured continuously using an accessory sensor probe and this data was also stored as 10-min averages. The measurement sensitivity is 1 particle per liter, ranging from 1 to two million particles per liter and reproducibility of the results is within ±2%. In an earlier study, combination of Quartz Crystal Microbalance (QCM) that is mainly used for measurements of size segregated aerosols mass concentration and Grimm instruments provided satisfactory results in different rural and urban stations over central India (Jayaraman et al. 2006).

**Aethalometer**

Spectral distribution of aerosol light absorbing coefficient at seven wavelengths centered at 0.37, 0.47, 0.52, 0.59, 0.66, 0.88 and 0.95 μm was obtained by a multichannel
Aethalometer (Model: AE-42, Magee Scientific, USA; (Hansen et al., 1982)). The instrument was operated continuously and measurements were recorded every 5 min during the campaign period (except on 15 January when storage problems arose). Aethalometer mainly measures the changes in attenuation of light passing through a filter paper when ambient air is passed at a certain flow rate for a given time interval and deposited ambient aerosols on that filter paper. The flow rate of ambient air through an inlet was kept at 3.0 litre per min. BC mass concentration was calculated from the measured attenuation coefficient at 0.88 μm multiplied by the calibration constant suggested by manufacturer (Hansen et al., 1982), while the measurements at other wavelengths were used for estimates of the spectral absorption coefficient and absorption Angstrom exponent using the Beer-Lambert's Law (Bodhaine, 1995; Weingartner et al., 2003). The average uncertainty in BC mass concentration measurements is around 10%, as quoted by manufacturer and verified via comparative studies of absorption coefficient measurements between Aethalometer and other instruments using different techniques for BC measurements (Hansen et al., 1982). Inherent errors of filter paper based on the optical attenuation measurements, like “shadowing effect”, are found to be less than 10% (Weingartner et al., 2003).

METEOROLOGICAL CONDITIONS

Surface reaching solar radiation, air temperature, RH, wind speed and wind direction at Sundarban obtained from the automated weather station on 12 January 2014 (foggy day) and 14 January 2014 (normal day) are shown in Fig. 2. 14 January 2014 is considered as the normal-background day when no fog was observed throughout the day and the AOD was the lowest (0.53). 12 January 2014 was a foggy day, with the foggy period during morning hours highlighted by the shaded region in Fig. 2. The surface-reaching solar radiation (0.4 to 1.1 μm in W/m²) was measured by Pyranometer (model: SP Lite 2, Kipp and Zenon) and the diurnal variation of it with 1 minute temporal resolution is shown at the top panel of Fig. 2. The solar radiation during the normal day follows the classic diurnal pattern maximizing at noon, whereas during the foggy day the solar radiation was significantly reduced by 40–50%, on average, during the foggy period. The influence of astronomical parameters (i.e., sun elevation, azimuth, declination) on radiation values is negligible for this two days interval and, therefore, any change is due to variation in aerosol loading, composition and properties (Badarinath et al., 2008), as well as to the presence of clouds. 14 January was an absolutely cloudless day, while on 12 January some light clouds were present at
noon to early afternoon hours (see gaps during the foggy day). Presence of cloud is also possible during the foggy period, but these clouds were not detected due to low-level fog. However, the gaps in solar radiation during the foggy period may be associated to fog presence only and for this reason we avoided any sun photometer measurement during that time slot.

Diurnal variations in air temperature and RH on foggy and normal days are shown in the second and third panels of the figure, respectively. The maximum and minimum temperatures are 17 and 24°C, respectively, on foggy day and 17 and 25°C, respectively, on the normal day. No significant differences are observed between the two days, except for a slightly higher temperature on the normal day in the afternoon hours. RH was maximum (~100%) during night and early morning taking its minimum values of about 55% during early afternoon hours on both days. During the fog period, RH was slightly higher by about 5% compared to the normal day. The last two panels show the hourly variation of wind speed and direction, respectively, indicating calm to very weak winds and a dominance of northwest-to-northeast directions on both days. Small differences are observed in the wind direction during the foggy period. However, the wind is mostly calm during the foggy day, while it reaches at 2–3 m/s during the normal day. These differences along with higher aerosol loading and possible different composition were able to generate the fog conditions on 12 January. The calm wind is an important parameter in favoring fog formation and at the time (11–12 hrs) wind started blowing, fog started to disperse.

RESULTS AND DISCUSSION

Variation in Aerosol Optical Depth

Fig. 3 shows the daily-averaged spectral AOD values over Kalas Island, Sundarban on foggy (12 January 2014) and normal (14 January 2014) days. As mentioned above, sun photometer measurements were avoided during the foggy period (before 11:00 on 12 January) due to unresolved problems in sun targeting due to dense fog. Average AOD (at 0.5 µm) over Sundarban was about 0.52 ± 0.2 on normal day and increased by a factor of three to 1.6 ± 0.4 on the foggy day. This could be due to enhancement of aerosols transported from nearby urban regions and accumulated over the site due to low ventilation caused by low boundary layer height and calm winds. Aerosols can also be coated with aqueous species of other water-soluble aerosols (organics, nitrates, sulphates, ammonium) under high RH conditions (Lubin et al., 2002; Das et al., 2008), thereby changing their optical, physical and chemical properties, increase in size and become more efficient scatterers. As a consequence, higher AOD was observed on the foggy day. The satellite imagery (Fig. 1) also supports the presence of fog and increased scattering over the site. On the other hand, on the normal day, although RH levels were similar to those on the foggy day, wind speed was significant and the transported aerosol plumes moved further into the BoB resulting in lower AOD and higher atmospheric transparency.

The higher AOD values over Kalas Island during the foggy day are in agreement with previous measurements over several sites in IGB that are summarized in Table 1 and show significantly higher AODs during foggy rather than normal winter days. This indicates a similarity in the aerosol-loading variations between foggy and non-foggy winter days over northern India, both in urban and rural and/or remote sites, causing serious changes to air quality and regional climate, and effecting ecosystems and human health (Singh and Kaskaoutis, 2014). This also supports that fog can cause accumulation of transported aerosols over remote regions due to low ventilation that is generally observed over urban regions in the IGB during foggy periods (Ganguly et al., 2006; Das et al., 2008; Safai et al., 2008, etc.).

![Fig. 3. Daily mean AOD spectral values obtained from Microtops during normal and foggy days. Vertical bars represent ± 1σ variation about the means and the best fitted curves obtained from power law are also shown. The angstrom exponents (α) during foggy and normal days are mentioned in the legend along with their standard deviation in the brackets.](image-url)
Angstrom exponent ($\alpha$) was calculated from the measured spectral AODs over Sundarban during the foggy and normal days. $\alpha$ is the slope of AOD versus wavelength in logarithmic scale and provides information about the size distribution of aerosols where higher (lower) $\alpha$ represents dominance of relatively smaller (bigger) particles (Das et al., 2008; Sinha et al., 2012). In the present study, $\alpha$ was calculated in the lower (0.38 to 0.50 µm), higher (0.675 to 1.02 µm) and entire (0.38 to 1.02 µm) wavelength range and is found to be 0.6 ± 0.1, 1.2 ± 0.2 and 1.0 ± 0.1, respectively, on normal day and 0.8 ± 0.1, 1.1 ± 0.3 and 0.9 ± 0.2, respectively, on the foggy day. From normal to foggy day, there is increase in lower wavelength $\alpha$, and this increase is higher than the decrease in higher wavelength $\alpha$ (and entire wavelength $\alpha$). This indicates that during the foggy day the size of the fine-mode aerosols decrease, suggesting additional transport of freshly emitted aerosols, mostly from urban and industrialized regions; concurrently, an increase in coarse-mode abundance is revealed due to slightly lower $\alpha_{0.38-1.02}$ that indicates a little lower fine-to-coarse mode ratio (Sinha et al., 2012). During the foggy period, there is ultra-fine aerosol formation by gas-to-particle conversion in nucleation mode (< 0.1 µm), as was observed over IGB urban areas (Ganguly et al., 2006; Das et al., 2008), which results in higher $\alpha$ in the shorter wavelengths. However, water uptake by hygroscopic aerosols may increase their size during the foggy period and therefore the coarse mode abundance, which can be removed more efficiently due to gravitational settling. In earlier studies, $\alpha$ was found to be around 1.1–1.4 during normal days over IGB, which decreased to about 0.8–1.1 during foggy days (Ganguly et al., 2006; Safai et al., 2008, etc.) in considerable agreement with the present results. Therefore, the comparison of AOD values and its spectral distribution between the current and previous studies conducted at different environments (urban and/or rural) over the IGB shows a great similarity in aerosol loading and optical properties suggesting the presence of a homogeneous fog-aerosol layer that extends over the entire region (Goloub et al., 2001).

The variations in hourly mean AOD at 0.5 µm and Angstrom exponent at 0.38–1.02 µm on foggy and normal days are shown in Fig. 4. AOD is about 2.1 on the foggy day when fog starts to disappear and reduces to 1.0 by afternoon. On the other hand, AOD decreases from 0.7 to 0.35 on the normal day. At the time of fog disappearing (~11:00), the AOD on foggy day is about three times higher than that on the normal day. Angstrom exponent also exhibits significant variation on the foggy day increasing from 0.8 to 1.2, while it remains nearly constant at 1.1 during the normal day. A lower Angstrom exponent of about 0.8 at the time of fog disappearing represents the dominance of coarser aerosols during the foggy period, mostly due to hygroscopic growth under high RH and calm wind. After fog, the wind starts blowing and $\alpha$ increases due to dominance of transported anthropogenic aerosols from nearby urban regions.

### Aerosol Source Apportionment

For identification of the aerosol source regions and hot-spot areas, five-days air mass back-trajectories ending over Sundarban are analyzed during the campaign period. Fig. 5 shows the air-mass back-trajectories ending at 500 m over the measurement site at 00:00 hrs on 12 January 2014, just before the fog occurred (pink solid line) and on 14 January (yellow dashed line), while the underlying map corresponds to spatial distribution of mean AOD during 8-12 January 2014 obtained from Aqua-MODIS sensor. High to very high (> 1.0) AOD is observed along the IGB and continues almost up to the Sundarban region. It is characteristic, that entire IGB is covered with AOD$_{550}$ above 0.7. Combined with back-trajectory analysis, the air-mass pathways indicate transported aerosol plumes from IGB up to the measurement site that cause dense fog over the coastal region of Bay of Bengal, as was also seen via satellite images during the W-ICARB campaign (December–January, 2009; Kharol et al., 2011). Both days reveal similar source regions for transported aerosols over the measuring site. This is also supported by similar spectral variation of AOD and $\alpha$ values (Fig. 3) indicating similar aerosol type, while the significantly higher AODs on the foggy day may be attributed to the calm wind speed and/or to larger aerosol-loading over IGB during that day.

### Variations in Aerosol Number Distribution

The daily variation of the aerosol size-segregated number distribution obtained from the Grimm instrument is shown in Fig. 6. The top panel shows the contour plot of time series of aerosol number size distribution and the bottom panel shows the time series of aerosol number concentrations for 0.2 micron (red) and 2.0 micron (blue) size measured at 0.3–0.4 and 3.0–4.0 diameter bins, respectively. These two sizes were chosen to represent fine and coarse-mode aerosols, respectively. On average, fine-mode aerosol number

| Measurement site | Condition       | AOD   | References          |
|------------------|-----------------|-------|---------------------|
| Delhi            | Fog             | 1.8   | Ganguly et al., 2006|
| Hissar           | Fog             | 0.99  | Das et al., 2006    |
| Agra             | Fog             | 1.22  | Safai et al., 2008  |
| Sundarban        | Fog             | 1.5   | Present study       |
| Delhi            | Normal Winter Day| 0.91  | Ganguly et al., 2006|
| Hissar           |                 | 0.54  | Das et al., 2006    |
| Agra             |                 | 0.63  | Safai et al., 2008  |
| Sundarban        |                 | 0.5   | Present study       |

Table 1. A comparison of AOD in foggy and normal winter days at different measurement sites located over Indo-Gangetic Basin in India is given below.
Fig. 4. Hourly variation of AOD and angstrom exponents (α) during foggy and normal days. Vertical bars represent ± 1σ variation about the hourly means.

Fig. 5. Five-days air parcel back-trajectory at Sundarban at 0000 hrs on 12 January 2014 (solid magenta) and 14 January 2014 (dashed yellow) at an initial height of 500 mb obtained from HySPLIT model. The contour presents the spatial distribution of mean AOD during 8–12 January 2014 retrieved from space-borne sensor MODIS on board Aqua satellite. Regions of AOD greater than 0.7 are indicated by white dotted contours to aid the eye.

The shaded regions in the bottom panel represent the foggy periods on the two foggy days, 12 and 15 January 2014. On the normal day (14 January), two peaks are observed in the morning and evening hours for both fine and coarse-mode concentrations. This is due to the daily evolution of the winter-time boundary layer height, and is the common diurnal variation of near-surface aerosols over IGB (e.g., Ganguly et al., 2006). During early morning and evening hours, a shallow boundary layer due to low temperature and weak thermal convection causes accumulation of aerosol and pollutants near the ground, while as the day progresses temperature increases, causing stronger thermal convection, increase in boundary layer height and better dilution. Furthermore, the fine-mode aerosols seem to increase more during the early morning and late-evening hours compared to coarse-mode particles. This may be attributed to bio-fuel and garbage burning as well as to open fires throughout
IGB during the cold periods of the day mostly for heating purposes releasing large amount of BC fine aerosols (Ganguly et al., 2006).

The temporal variation of aerosol number concentration shows that there is an overall increase in aerosol number concentration after 12 January, which maximizes on 13 January. This could be due to significant transport of aerosols from the metropolitan city, Kolkata, as it appears in back-trajectory analysis, which controls the daily variation and diurnal pattern in aerosol number concentrations. It is worth mentioning here that there was no fog over IGB on 13 January, while fog was observed only over central IGB region on 14 January, according to Kalpana satellite imagery. During the morning hours of 15 January dense fog was observed over the site, associated with increased aerosol number concentrations. On this day the fine-mode concentrations remain high even during the noontime (in contrast to that observed during the normal day, 14 January), indicating incapability of dilution or even transport of additional aerosol loading. The daily average fine-mode aerosol number concentration was $2.2 \times 10^5$ per litre on 15 January, which is much larger than that $(1.5 \times 10^5$ per litre) observed on the normal day (14 January 2014). The high fine aerosol concentrations on foggy mornings could be possible due to low ventilation and weak advection due to calm wind. At the same time, the coarse-mode aerosol concentration is significantly enhanced ($> 500$ particles per litre) during the foggy morning on 15 January. It is well known that the fine-mode aerosols are mostly radiatively active particles (sulphate and nitrate) and contribute significantly to the perturbation of radiation budget as they are mainly coming from anthropogenic activities like vehicular emissions and biomass burning (Badarinath et al., 2008). On the other hand, sea-salt aerosols are mostly in the coarse mode as they directly come from breaking of waves and bursting of bubbles in the marine region (Hess et al., 1998) and can also be abundant over Sundarban. Thereby, it is possible that during the foggy period, the fine hygroscopic aerosols may swell up by absorption of water vapor under high RH conditions and condensate to larger particles, thus increasing their number concentration. In synopsis, the analysis of the variation of the aerosol number size distribution shows that during the first foggy period on 12 January, the aerosol loading near the ground did not reach to high levels, as did during the early morning hours on 15 January, and the formation of fog is mostly a combination of aerosol loading, optical properties, RH and wind speed.

**Variations in Black Carbon**

Variations in hourly-mean BC mass concentrations during normal (14 January 2014) and foggy (12 January 2014) days are shown in Fig. 7. The vertical bars represent $\pm 1\sigma$ from the daily mean, while the shaded region represents the foggy period on the foggy day. The variation of BC shows two peaks, one in the morning and another in the evening, although evening peak is weaker and present for a shorter period than the morning one. In general, this variation is observed due to change in boundary layer height with peaks occurring when boundary layer height is lower. Similar diurnal variations of BC mass concentration have been observed at several urban sites in India characterized by large local vehicular and industrial emissions (Babu et al., 2002; Tripathi et al., 2005; Ganguly et al., 2006). However, Kalas Island is not an urban site and does not have any local production of BC but still exhibits the BC diurnal pattern observed over urban environments, although
smoothed, due to its proximity to densely populated and industrialized urban centers (Kolkata and Dhaka - the capital city of Bangladesh) and the strong influence of the transported aerosol plumes.

The mean BC concentration over Sundarban is about 20.4 ± 4.8 µg/m³ during the foggy period and 15.2 ± 1.3 µg/m³ during the same hours on the normal day, corresponding to an enhancement of about 30%. Due to absence of local emissions, the larger BC concentrations during the foggy morning are attributed to enhanced advection and possible ‘trapping’ of BC by the fog and mixing with other urban aerosols (sulphate, nitrate, organic) favored by the calm winds.

Variations in Aerosol Absorption Coefficient

The diurnal variations of the spectral absorption coefficient ($b_{abs}$) during normal (14 January 2014) and foggy (12 January 2014) days are shown in the top panels of Fig. 8. The $b_{abs}$ is proportional to $\lambda^{-\alpha_{abs}}$, where $\lambda$ is the wavelength and $\alpha_{abs}$ is the absorption angstrom exponent, which is also plotted for both days in the lower panels. The shaded region in the bottom right panel represents the foggy period. The absorption coefficients exhibit significant wavelength dependence with higher values at shorter wavelengths resulting in large absorption in the UV spectrum. In the present study, $b_{abs}$ seems to follow a similar diurnal variation with aerosol loading and BC, due to the reasons discussed above, while it is strongly dependent on the BC concentrations (Jacobson, 2000; Bond, 2001). The UV absorption increased twice during the foggy morning hours, while the $b_{abs}$ is higher by almost 30%, on daily mean basis, than that on the normal day. This is mostly because of the accumulation of BC during the foggy period (Fig. 7) favored by the calm winds, which is referred in the present study as ’BC trapped by fog’. As a direct consequence of the increased absorption, the surface-reaching solar radiation decreased significantly during the foggy period (Fig. 2), which favors the fog to sustain for a longer period.

$\alpha_{abs}$ is around 1.0 for pure BC from fossil-fuel combustion, while it ranges from ~1.2 to 3.0 for mixed BC and organic carbon from biomass burning and reduces to 0.8–0.9 for BC produced from vehicular emissions mixed with less absorbing aerosols like nitrate and sulfates (Bergstrom et al., 2003; Kirchstetter et al., 2004; Sandradewi et al., 2008). The mean $\alpha_{abs}$ during the foggy hours is 0.85 indicating generally low spectral dependence of absorption and dominance of BC aerosols from fossil fuel combustion mixed with urban scattering particles (organics, nitrates, sulphates, ammonium) transported from the urban-industrialized regions. The lower $\alpha_{abs}$ may also be the result of coating of BC and organics with marine aerosols over the coastal areas of BoB (Ramanthan et al., 2001). Similar values of $\alpha_{abs}(0.95–0.98)$ were also found over north and west BoB during the W-ICARB campaign (December–January, 2009) (Kaskaoutis et al., 2011b), showing a similarity in the composition of the IGB outflow between the current period and winter of 2009. However, the results show a rather constant, even with small fluctuations, diurnal pattern of the $\alpha_{abs}$ for both days with rather negligible fog effects, indicating a similarity in the composition of the aerosol outflow from the IGB to north BoB.

SUMMARY AND CONCLUSIONS

A research campaign was conducted during 11–16 January 2014 at Kalas Island, which is the southernmost island in Sundarban region at the Ganges delta. The island is completely isolated and presents a unique opportunity for investigation of the aerosol pollution outflow from the IGB to Bay of Bengal. The observational site also provides
a great opportunity to investigate the aerosol properties during fog which is a frequently occurring phenomenon during winter in the IGB. During the campaign, two dense fog events occurred during the morning hours on 12 and 15 January 2014, when the surface-reaching solar radiation reduced up to 40–50%. Aerosol optical and physical properties were investigated and the major findings are as follows.

1. AOD increased by a factor of three during the foggy periods at Sundarban, but without a considerable change in its spectral distribution, indicating similarity in aerosol types, composition and sources. The additional aerosol loading was mostly composed by freshly emitted fine aerosols, as well as coarse-mode particles after coagulation and or humidification (water uptake under high RH conditions).

2. Five days back-trajectories analysis and MODIS-AOD show that aerosols over Sundarban originate from the highly aerosol-laden areas of central and eastern Ganges Basin.

3. The BC mass concentration showed an enhancement of 30% with a mean value of 20.4 ± 4.8 µg/m³ during the foggy period on 12 January compared to the 15.2 ± 1.3 µg/m³ during the same hours on the normal day (14 January).

4. The aerosol absorption also increased by 30% during the foggy day indicating enhancement of absorbing aerosols during foggy conditions.

5. However, the absorption angstrom exponent did not exhibit any significant change between foggy and normal days, while its values lying around 1.0 or even lower indicate dominance of BC aerosols from fossil-fuel combustion, mixed with other non-absorbing aerosols (nitrates, sulphates, ammonium) from urban/industrial emissions and/or with marine particles (sea-salt sulphate).

The present study measures very high BC mass concentrations at Sundarban, which are related to transported plumes from Ganges Basin and nearby urban/industrial centers like Kolkata and Dhaka. The BC levels were found to be much higher during the foggy periods and, for the first time, we report about ‘trapping’ of BC by the foggy atmosphere under high RH and calm conditions that can have serious effects in solar dimming, radiative forcing and atmospheric heating due to significant absorption of solar radiation.

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