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Two-way Relationship between Aerosols and Fog: A Case Study at IGI Airport, New Delhi

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ABSTRACT

The frequency and intensity of fog episodes during the winter season has been increasing during the past decade over the megacity of Delhi due to the high pollution load. The role of atmospheric aerosols is very important in the life cycle of fog in the urban areas. This paper presents the results on the variation in aerosol optical properties (scattering and absorption coefficients) and the black carbon (BC) mass concentration during the foggy period in winter (December 2015 to February 2016) at the Indira Gandhi International (IGI) Airport, New Delhi. The interaction between scattering and absorbing aerosols, and fog before, during and after the foggy period has been studied as a typical case. The BC mass concentration, along with the aerosol scattering and absorption coefficients, increased before and during the initial phase of the dense foggy period. However, there was a steep decrease in them after the sustained period of dense fog, which suggests possible scavenging by fog droplets. Also, it was observed that the decrease in ambient temperature and depression temperature (DT) and the increase in relative humidity (RH) played a major role in sustaining the dense fog despite the reduction in aerosol load. The single-scattering albedo (SSA) decreased during the dense fog due to a higher reduction of the scattering aerosols than the absorbing ones. Both the scattering and the absorption coefficients showed a significant correlation with cloud condensation nuclei (CCN).

Keywords: New Delhi Airport; Winter fog; Scattering and absorption coefficients; Black carbon; Visibility.

INTRODUCTION

Fog is comprised of visible cloud water droplets or ice crystals suspended in the air at or near the surface of the earth (Gultepe, 2007). Fog is influenced by nearby water bodies, topography of the region, prevailing winds and availability of aerosols suspended in the air which are originated from different natural sources and man-made activities. Heavy and persistent fog is a common feature in the winter season over the northern Indian region and it is one of the major weather disasters that impacts all forms of transport including aviation, rail and road journey. Consequently, it affects the human activities, economy and overall life of the people in the region. Maximum occurrence of fog over northwest India is about 48 days every year with atmospheric visibility < 1000 m, mostly during the months of December to February. Over the Indo-Gangetic Plain (IGP) region, the frequency of fog occurrence has significantly increased during winter months in the last four decades (Srivastava *et al.*, 2016). In spite of its regular occurrence and importance in various human related phenomena, we still lack the understanding of the physical and chemical characteristics of fog and reasons for its rapid thickening over the IGP region. In addition, the information on role of meteorological factors responsible for formation, sustenance and dissipation of fog is required for sufficiently reliable forecast of fog and thereby proper and timely mitigation of the fog events. Therefore, an intensive ground-based measurement campaign termed as Winter Fog Experiment (WIFEX) was conducted at the IGI Airport, New Delhi, under the initiation by Ministry of Earth Sciences, Government of India. Extensive set of comprehensive ground based instrumentation for observations on surface meteorological parameters, radiation balance, turbulence, thermodynamical structure of the surface layer, fog droplet and aerosol microphysics, aerosol optical properties, and aerosol and fog water chemistry were deployed at the IGI Airport (Ghude *et al.*, 2017).

Several studies have underlined the importance of aerosols in fog life cycle over the IGP region (Ganguly *et*

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al., 2006; Tripathi *et al.*, 2006; Gautam *et al.*, 2007; Das *et al.*, 2008; Safai *et al.*, 2008; Mehta *et al.*, 2009; Mohan and Payra, 2014). However, there is a need for understanding the interaction of aerosols with fog microphysical processes. Growth of fog droplets depends on the physicochemical properties of the aerosols. Hygroscopic aerosols which act as CCN, can influence fog supersaturation and its formation. Several studies have been reported concerning the aerosol-fog interaction (Cheng and Tsai, 2000; Elias *et al.*, 2009; Singh and Dey, 2012; Chen *et al.*, 2016; Liu *et al.*, 2016; Molnar *et al.*, 2016; Zhao *et al.*, 2016; Chelani, 2017). In the present paper, results related with variation of aerosol scattering and absorption coefficients, mass concentration of BC aerosols during the dense foggy conditions as well as before its commencement and during the dissipation stage are discussed. The changes in meteorological parameters such as temperature, relative humidity and atmospheric pressure are also studied. The results obtained from this study will be useful in the ongoing research in aerosol-fog interaction and subsequent mitigation strategies aimed towards controlling the adverse impacts of poor atmospheric visibility conditions faced by the entire northern Indian region during the winter months.

SAMPLING LOCATION AND METHODOLOGY

The observations were carried out at about 15 m above the ground at IGI Airport, New Delhi (28.56°N, 77.09°E), during December 2015 to February 2016. At the airport, there is a vast open area experiencing frequent fog formation particularly during the winter season and observations of visibility are routinely carried out over there. Instruments were installed on the northern side of the airport which is about 400 m away from the runway that was less operational during the WIFEX observational period. Aerosol scattering coefficient (σ_{sca}) was measured using a multi wavelength integrating nephelometer (Aurora 3000, Ecotech, Australia) at one-minute intervals. An aethalometer (AE-33/7, Magee Scientific, USA) was used to measure BC mass at one-minute intervals. In addition to the BC mass, this equipment also shows the percentage fraction of BC from biomass burning using the method applied by Sandradewi *et al.* (2008a, b). The next generation aethalometer also gives the corrected BC mass concentration after applying dual spot technique to compensate for the filter loading effect thereby reducing the uncertainty in the measurements (Drinovec *et al.*, 2015). The BC mass was further used to compute the absorption coefficient (σ_{abs}). Absorption and scattering coefficients at a common wavelength 520 nm were considered in this study for comparison and computation of extinction coefficients and single scattering albedo (SSA).

Observations on visibility were obtained from India Meteorological Department (IMD) through their runway visual range (RVR) systems installed along the runway at IGI Airport. Also, simultaneous observations on meteorological parameters (temperature, relative humidity and atmospheric pressure) were carried out during the study period. In addition, observations on cloud condensation nuclei were carried out using CCN Counter (Droplet Measurement Technologies, USA). Details on these observations are mentioned elsewhere (Ghude *et al.*, 2017).

RESULTS AND DISCUSSION

Variation of BC Mass and Aerosol Optical Properties during Fog

Atmospheric BC aerosols mainly originate from incomplete combustion processes involving fossil fuel and biomass burning activities. Fig. 1(a) depicts the daily mean mass concentration of BC in comparison with the atmospheric visibility at IGI Airport during the study period. The BC concentration varied from 8.0 to 58.3 µg m^{-3} during the entire period with mean concentration of 18.2 ± 8.3 µg m^{-3}. It was observed on many occasions that BC concentration showed enhancement prior to the very dense fog (visibility < 50 m). Dey *et al.* (2006) have reported BC mass concentration of 15 µg m^{-3} during clear days which increased to 65 µg m^{-3} during foggy/hazy days at Delhi during the winter season of 2004. Smoke and absorbing aerosols were reported to be the major constituents of winter fog over Pakistan (Khokhar *et al.*, 2016). Similarly, Safai *et al.* (2008), Niranjan *et al.* (2007) and Ramachandran *et al.* (2006) have reported increase in BC mass during winter fog at Agra, Kharagpur and Hisar, respectively. BC correlated negatively with visibility ($r = –0.51$, $p < 0.0006$). As observed from Fig. 1(b), both σ_{sca} and σ_{abs} showed increase during foggy days indicating impact of scattering as well as absorbing aerosols on fog formation. During the entire observational period, the mean σ_{sca} was 403 ± 263 Mm^{-1} which varied from 99 to 1316 Mm^{-1}, whereas the mean σ_{abs} was 251 ± 102 Mm^{-1} which varied from 111 to 485 Mm^{-1}. There was a negative correlation between σ_{sca} and visibility ($r = –0.35$, $p < 0.03$) and similarly between σ_{abs} and visibility ($r = –0.48$, $p < 0.006$). This indicates towards important role of atmospheric aerosols in the visibility degradation particularly during the winter months over this region. The biomass burning percentage (BB %) to total BC mass can be obtained from built-in software of the aethalometer AE33 using the Sandradewi model (Sandradewi *et al.*, 2008a; Magee Scientific, 2014). BB % to BC mass was studied for this period. The mean BB % to total BC mass was 12.8 ± 5.4% with values varying between 1 to 24%. This indicates towards dominance of fossil fuel burning at the observational site mainly due to the aviation related activities at the airport.

Reduction in atmospheric visibility is related with the attenuation of light from gases and aerosols. In the present study, we are considering light attenuation due to aerosols only. Light attenuation by aerosols is through scattering and absorption and is represented by extinction coefficient (σ_{ext}) which is obtained by addition of σ_{sca} and σ_{abs}. Using the σ_{sca} and σ_{abs} data, σ_{ext} has been computed and further an attempt is made to calculate the atmospheric visibility by applying Koschmieder formula on relationship between visibility and σ_{ext} (Hovrath, 1971) as follows (Eq. (1)):

$$\text{Visibility} = 3.219/\sigma_{ext} \tag{1}$$

The number 3.912 denotes the minimum observable

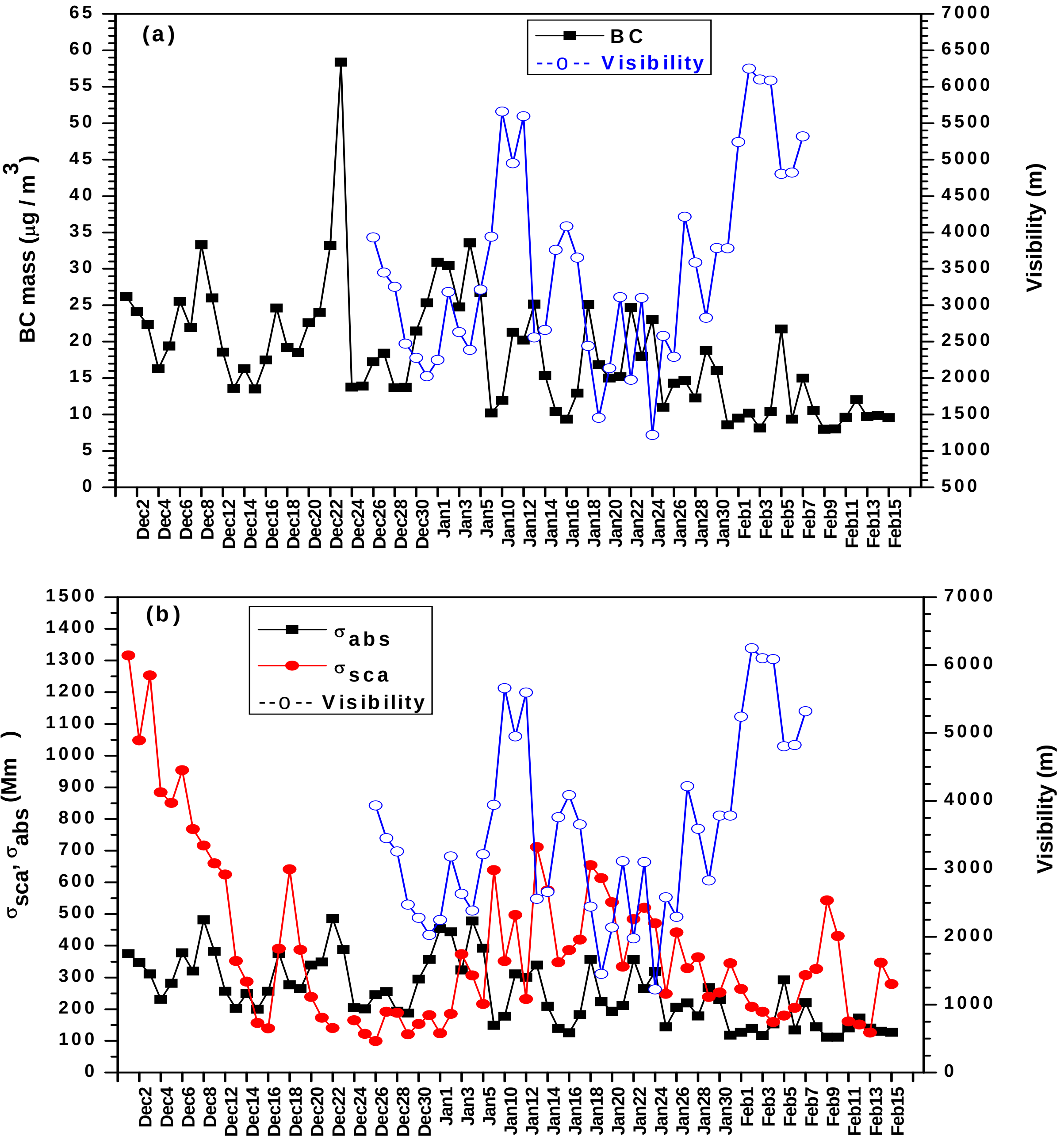

Fig. 1. Variation of daily mean (a) mass concentration of BC, (b) σ_{sca} and σ_{abs} in comparison with the atmospheric visibility during WIFEX 2015–16.

contrast between an appropriately large, black object against the horizon sky called the contrast threshold.

It was observed that the visibility as computed from this method compared reasonably well with that measured by RVR at the airport (Fig. 2). The computed and measured visibility correlated well with each other ($r = 0.60$, $p < 0.0003$). This indicates towards the vital role of aerosols in the visibility degradation and thereby in the mechanism of fog formation.

A Typical Case Study on Variation of Aerosols during Dense Foggy Period

In the present study, a typical data set on dense foggy period (visibility < 1000 m) during 2100 IST on 23 Jan 2016 to 0500 IST on 24 Jan 2016 is considered in comparison with the same time duration on 16–17 Jan 2016 and 1–2 Feb 2016 as proxy for less foggy days before and after the dense fog, respectively (Fig. 3). Mean BC mass concentration was 43 µg m^{-3} that ranged from 36 to 51 µg m^{-3} during this dense foggy period. It was 13 µg m^{-3} during the less foggy period both prior to dense fog and after dense fog. Thus there was > 3 times more BC mass during dense foggy period than that during less foggy period. Both σ_{sca} and σ_{abs} at 520 nm also showed significant increase during dense foggy period as compared to the less foggy period. During the dense foggy period, the mean σ_{sca} was 757 Mm^{-1}, whereas the

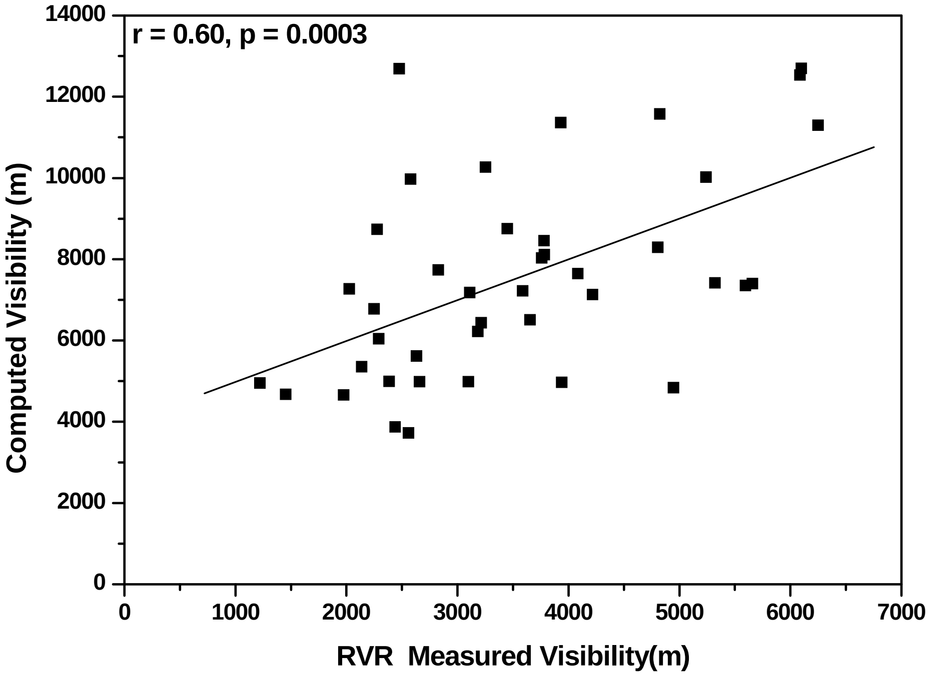

Fig. 2. Computed visibility (from Koschmieder formula) and RVR measured visibility at IGI Airport, New Delhi during WIFEX 2015–16.

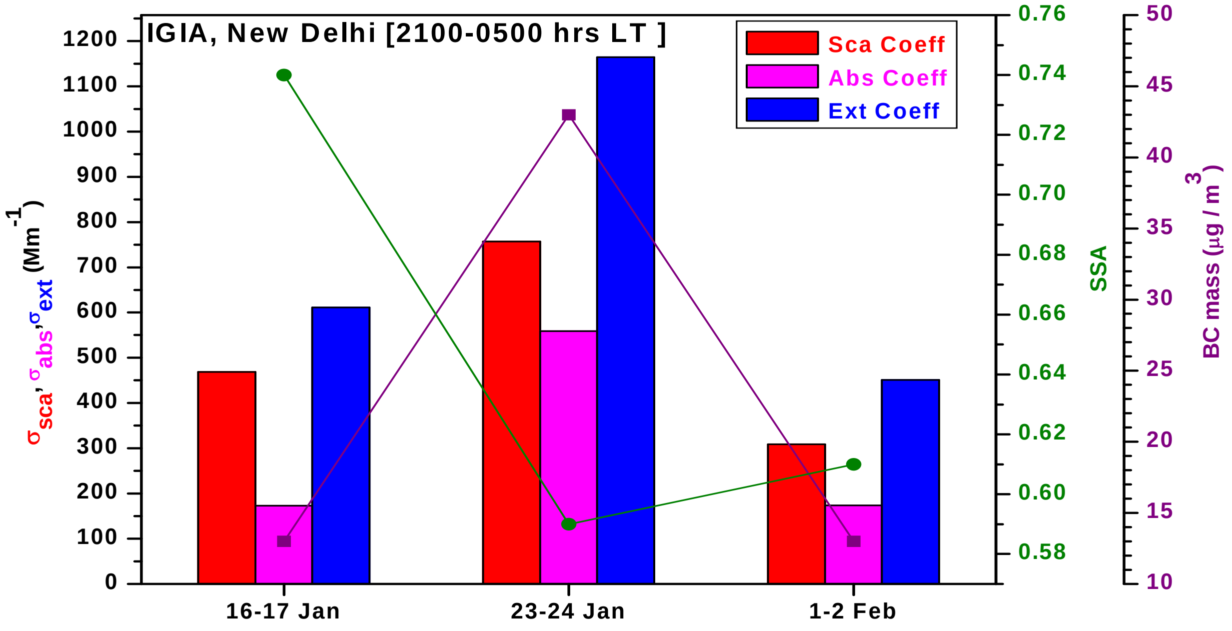

Fig. 3. Mean σ_{sca}, σ_{abs}, σ_{ext}, BC mass and SSA during dense foggy and less foggy period during WIFEX 2015–16.

mean σ_{abs} was 559 Mm^{-1}. Whereas during less foggy period period prior to dense fog, mean σ_{sca} and σ_{abs} were respectively 469 and 173 Mm^{-1} and the same during less foggy period after the dense fog were respectively 309 and 174 Mm^{-1}.

Using the σ_{sca} and σ_{abs}, single scattering albedo (SSA) at 520 nm was computed for the dense foggy as well as less foggy period as Eq. (2):

$$SSA = \sigma_{sca} / (\sigma_{sca} + \sigma_{abs}) \quad (2)$$

SSA is one of the important climate variables in the aerosol radiation studies. More SSA indicates dominance of scattering aerosols that leads to cooling effect, whereas low SSA shows more absorbing type aerosols leading to warming effect (Goody, 1996; Takemura *et al.*, 2002). In the present study, SSA values decreased during the dense foggy period. Mean SSA was 0.59 during dense foggy period whereas it was 0.74 and 0.61 during less foggy period before and after dense fog, respectively. Increase in absorbing aerosols, i.e., BC, was accompanied by decrease in SSA during dense foggy period. Ramachandran *et al.* (2006) have reported low SSA values during foggy conditions (0.76) as compared to that in clear conditions (0.88) at Hisar, which was attributed to more absorbing (BC) aerosols.

However, during the dense fog, even though BC, σ_{sca} and σ_{abs} showed increase in the initial hours, there was decrease in the latter phase with about 50% reduction within next few hours. As seen from Fig. 4(a), mass concentration of BC which had reached up to 51 µg m^{-3} during the onset and initial phase of dense fog (at around 0245 IST on 24 Jan 2016), declined gradually to reach up to about 27 µg m^{-3} at around 0500 IST on 24 Jan 2016. Almost similar trend was observed during this period for σ_{sca} and σ_{abs} (Figs. 4(c) and 4(d)) with values decreasing from 900 Mm^{-1} to 350 Mm^{-1} for σ_{sca} and those for σ_{abs} reduced from 670 Mm^{-1} to 360 Mm^{-1}. This clearly infers towards scavenging of both scattering and absorbing aerosols as well as hydrophilic and hydrophobic aerosols and their conversion into fog droplets (Dall'Osto *et al.*, 2009). Also, the SSA decreased during dense foggy period from 0.66 to 0.45 (Fig. 4(b)). This is indicative of less scavenging of absorbing aerosols as compared to that of scattering type. As already mentioned in section 3.1, there is > 80% contribution to BC from fossil fuel sources which could mainly be hydrophobic in nature and thereby responsible for less scavenging by fog droplets.

The further interesting part is that even though aerosols showed steep decline after the initial phase of dense fog formation, the dense fog itself persisted for several hours even reaching the minimum visibility of ≤ 50 m during 0400 IST to about 0700 IST and up to 200 m till 1030 IST on 24 Jan 2016. Therefore, it is quite clear that the other controlling factors, mainly prevailing meteorological conditions, took over the responsibility of sustenance of dense fog. This is confirmed from the data on ambient temperature, relative humidity and atmospheric pressure at the sampling site. Fig. 5 shows the variation of various meteorological parameters during this period in comparison with atmospheric visibility. It can be observed that ambient temperature decreased from 12.5°C at the onset of dense fog on 24 Jan 2016 to about 8.5°C at commencement of very dense fog with visibility < 50 m (around 0245 IST) to

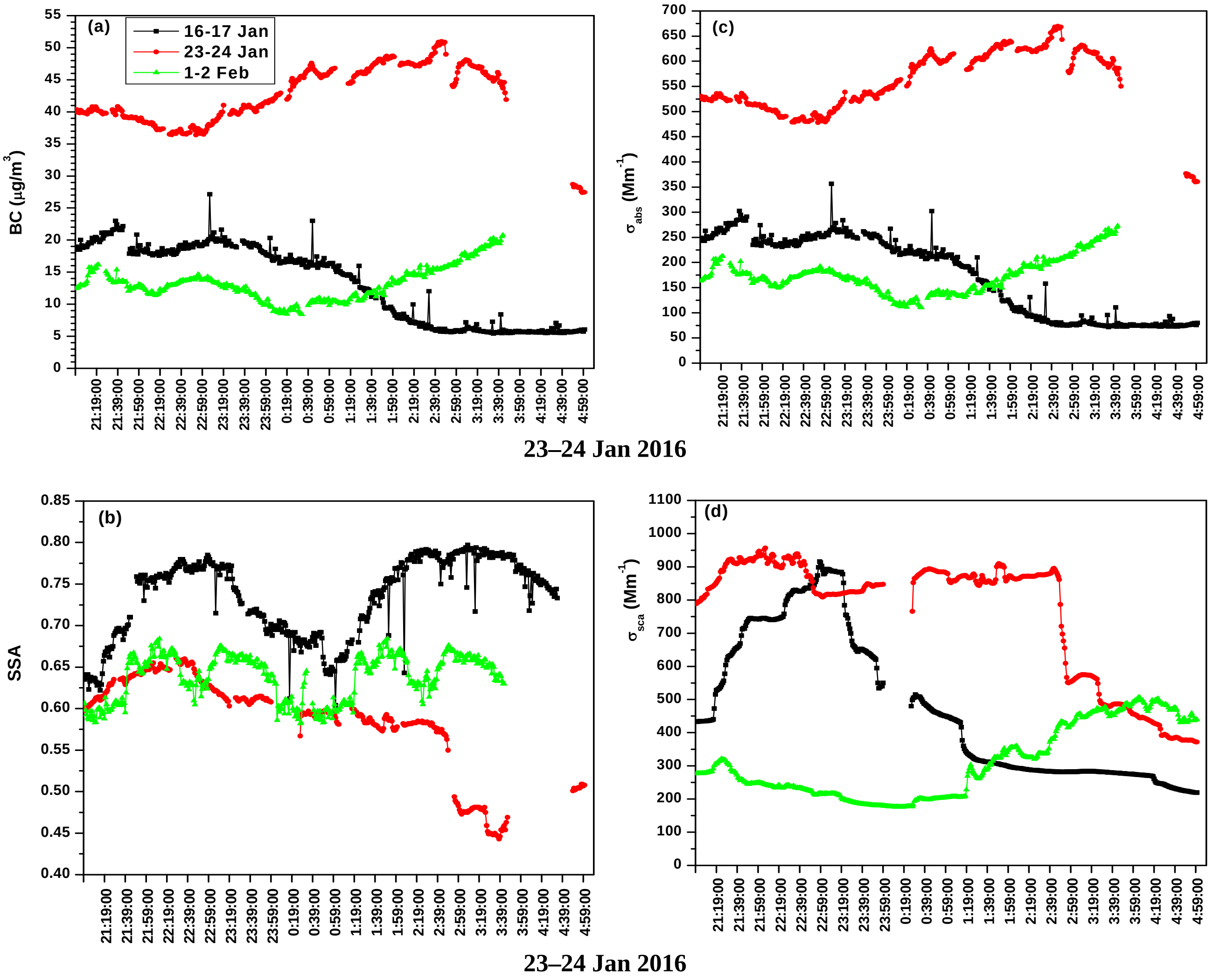

Fig. 4. Variation of (a) BC mass, (b) SSA, (c) σ_{abs} and (d) $\sigma_{sca,}$ during dense foggy and less foggy period during WIFEX 2015–16.

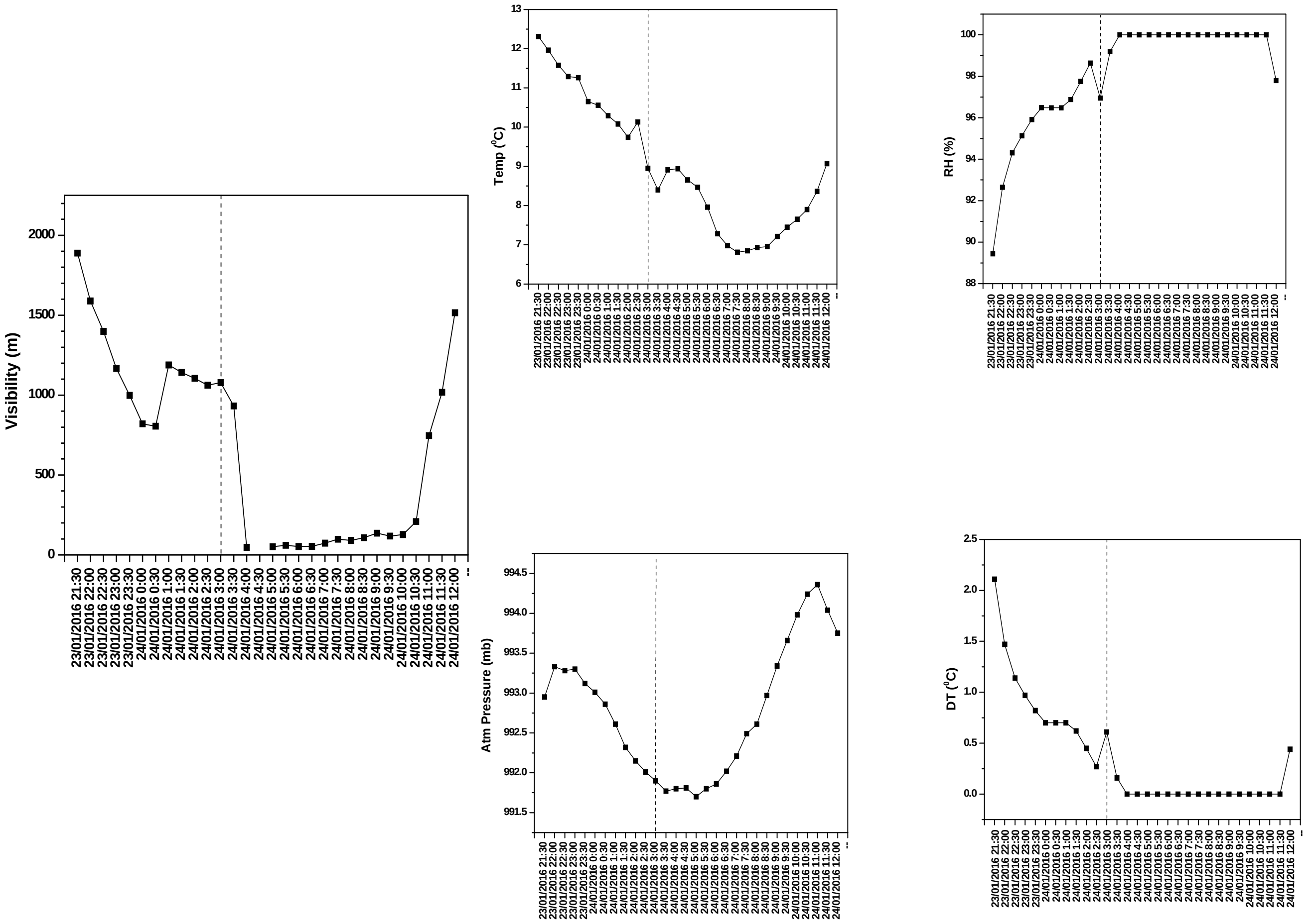

Fig. 5. Variation of meteorological parameters and DT in comparison with atmospheric visibility during dense fog on 23–24 Jan 2016 (Dotted vertical line indicates commencement of dense fog).

as low as 6.8°C during very dense fog at around 0700 IST on 24 Jan 2016. During this period, RH also showed gradual increase from about 89% to reach 100% and atmospheric pressure decreased from 993.5 mb to 991.5 mb. Dew point temperature (Td) was also computedfor this period as Eq. (3):

$$\mathrm{Td} = \mathrm{T} - ((100 - \mathrm{RH})/5) \tag{3}$$

where T and RH represent measured ambient temperature and relative humidity, respectively.

Td showed decrease from 10.5°C to 6.8°C during this period. During the dense foggy period, atmospheric visibility showed a significant positive correlation with temperature and Td ($r = 0.83$, $p < 0.0001$) whereas negative correlation was observed between RH and visibility ($r = -0.85$, $p < 0.0001$). Further, the depression temperature (DT) was computed as difference between T and Td (Tiwari *et al.*, 2011). DT showed decrease from 2.1 to 0 from the initial fog formation (visibility < 1000 m) to its development in very dense fog (visibility < 50 m) and remained 0 throughout the very dense foggy period till about 1030 IST in the morning of 24 Jan 2016. All the aerosol parameters (BC, σ_{sca} and σ_{abs}) showed gradual increase from 1030 IST on 24 Jan 2016 when dissipation of dense fog started. Thus, it is seen that even though aerosols acted as nuclei for fog formation in the initial phase/onset, they later on got reduced due to scavenging by fog droplets. This mutual dependency indicates towards the two-way relationship between aerosols and fog with aerosols playing critical role during the formation of fog and later on fog controlling the aerosol abundance through the scavenging mechanism. The dense fog still persisted even though the aerosols decreased mainly due to the favourable meteorological conditions till its dissipation. The important role of atmospheric temperature and RH along with the air quality including both particulate and gaseous components on observed fog trends is discussed by Klemm and Lin (2016).

It was also observed that the cloud condensation nuclei (CCN) and both σ_{sca} and σ_{abs} showed similar variation during the dense foggy period on 23–24 Jan 2016 (Figs. 6(a) and 6(b)) and CCN correlated significantly well with them ($r = 0.91$, $p < 0.0001$ and $r = 0.81$, $p < 0.0001$ respectively with σ_{sca} and σ_{abs}). This indicates towards the important role of both scattering and absorbing aerosols in the formation of CCN at ground level, i.e., fog droplets. Scattering aerosols are generally hygroscopic and act as good CCN. Whereas, absorbing aerosols (BC) are not considered as good CCN. Especially, the freshly emitted BC particles are reported to be hydrophobic in nature (Zhang *et al.*, 2008). However, when they are aged or when they come into contact with

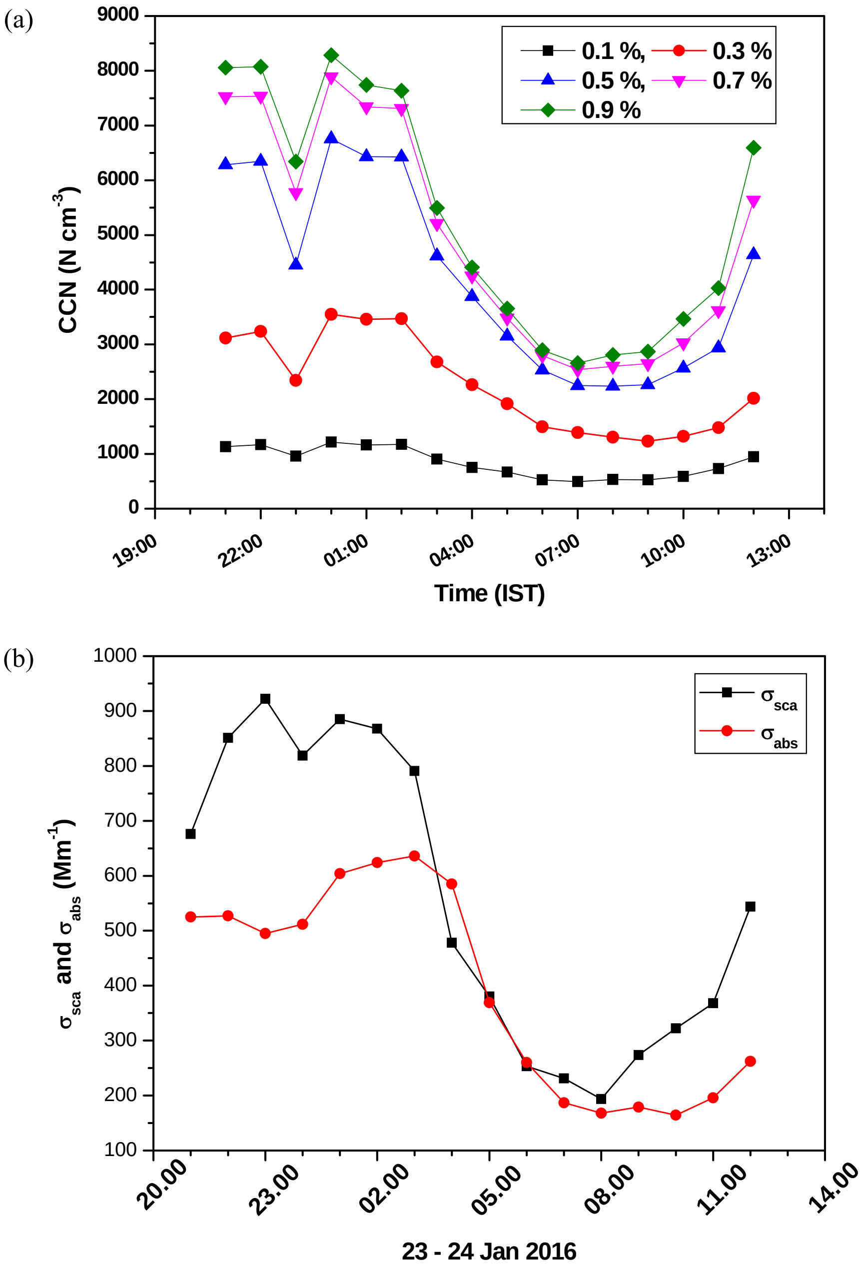

Fig. 6. Variation of (a) CCN at different suspersaturations and (b) σ_{sca} and σ_{abs} during the dense foggy period on 23–24 Jan 2016.

other hygroscopic aerosols, their morphological and chemical properties get changed and they can act as CCN (Dusek *et al.*, 2006; Furutani *et al.*, 2008). Maskey *et al.* (2017) have reported activation of CCN by BC particles coated with sulphuric acid.

CONCLUSIONS

Observations on BC, and the aerosol scattering and absorption coefficients were made from December 2015 to February 2016 during the Winter Fog Experiment at the IGI Airport, New Delhi. The mass concentrations of BC, and σ_{sca} and σ_{abs} showed significant enhancement on foggy days. However, the micro-analysis of these parameters indicated that the formation of fog could have been catalysed by an enhanced load of scattering and absorbing aerosols, which were subsequently reduced due to scavenging by fog droplets, although the fog density persisted because of prevailing meteorological conditions, including a low temperature, high RH and low atmospheric pressure as well as the lowest depression temperature. Thus, the aerosols and fog displayed a mutually dependent relationship with each other. A decrease in SSA during dense fog suggested reduced scavenging of BC aerosols, signifying fossil fuel burning as their major source. Also, both σ_{sca} and σ_{abs} correlated significantly with CCN, indicating the vital role of both scattering and absorbing aerosols in the formation of fog droplets.

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