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Short term introduction of pollutants into the atmosphere at a location in the Brahmaputra Basin: A case study

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ABSTRACT

Intensive fire ignition and cracker work activities takes place during the festival of light called Diwali in India, celebrated for a period of few days in the month of October or November every year. The firecracker releases several pollutants [such as particulate matter (PM), black carbon (BC), organics, trace gases] near the surface. The effect of firecrackers on the atmospheric constituents is evaluated over Dibrugarh by monitoring the concentrations of PM, PM_{10} (particle radius ≤10 µm), $PM_{2.5}$ (particle radius ≤2.5 µm) and BC during the Diwali and post–Diwali days (5 days after the Diwali Festival) in the years 2009 and 2010. Monthly average concentrations of each species except for the Diwali and post Diwali days is considered as the background concentrations. The concentration levels of the pollutants as recorded on the Diwali days are found to be a number of times higher (5.33 and 2.50 times for PM_{10}, 5.74 and 2.65 times for $PM_{2.5}$, 1.21 and 1.66 times for BC for the year 2009 and 2010, respectively) than the background levels at the peak hours of the fire work activity. To delineate the contribution of fireworks to the high concentrations of the species we performed air mass back trajectory analysis using the NOAA–HYSPLIT model in order to examine the existence of the transported aerosols. The ten day accumulated MODIS fire maps are also analyzed to mark out the contribution of aerosols from biomass burning. These analyses reveal that the higher concentrations of near surface aerosols including BC during the festival is due to the local effect of firework activities, neither because of long–range transport nor due to biomass burning activities. However, the higher concentration of pollutants for short periods has not degraded air quality substantially to cause health risks to people exposed to the festival in this environment.

Keywords: *Diwali Festival, fireworks, particulate matter, black carbon, air quality*

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1. Introduction

Diwali known as the festival of light is a major festival in India celebrated for a period of few days either in the month of October or November every year. During the festival traditionally people of all ages enjoy firecrackers. Enormous amounts of crackers and sparklers are burned by people from evening to late night hours mostly on the Diwali day and also on the day before Diwali (pre–Diwali) and after Diwali (post–Diwali). The burning of firecrackers release a significant amount of pollutants including particulate matter (PM), black carbon (BC), and toxic gases which are very harmful to health of all living beings. Firecrackers include a large number of chemicals such as potassium nitrates, potassium chlorate, potassium perchlorate, charcoal, sulfur, manganese, sodium oxalate, aluminum and iron dust powder, strontium nitrate, and barium nitrate, etc. (Ravindra et al., 2003; Wang et al., 2007). Besides the air pollution, the high level noise generated by various firecrackers is beyond the permissible noise levels that make noise pollution which also affects the living beings adversely. Wang et al. (2007) reported enhanced concentrations of air pollutants such as SO_2, NO_X, $PM_{2.5}$, PM_{10} in Beijing (China) and estimated five times higher levels for primary and secondary components of aerosols during fireworks of lantern days than on normal days. A number of studies have been performed that linked the effect of fireworks during Diwali Festival at different places in India (Babu and Moorthy, 2001; Kulshrestha et al., 2004; Barman et al., 2008; Singh et al., 2010; Mandal et al., 2012; Pathak et al., 2013a). Intense firework activities during Diwali Festival resulting in air quality degradation and its impact on health has been noted by Limaye and Salvi (2010). The complex character of pollutant particles emitted during fireworks may cause difficulty in assessing the health effects as reported by Ravindra et al. (2001). Vecchi et al. (2008) reported a rise in PM_{10} of 33.6 µg/m^3, due to fireworks displays, with a 4 h time resolution. Perry (1999) found an enhancement of 18.5 µg/m^3 in $PM_{2.5}$ averaged over 24 h. Ravindra et al. (2003) reported that there is a short term variation in air quality and 2–3 times increase in concentrations of total suspended PM and PM_{10} in Hisar city due to fireworks during Diwali Festival. Similarly, Thakur et al. (2010) recorded 11.6 times increase for suspended PM, 22.3 times for PM_{10}, and 34.3 times for $PM_{2.5}$, 1.73 times for SO_2 and 1.27 times for NO_2 compared to a typical winter day value at Salkia, near Kolkata on Diwali. Higher night–time PM_{10} concentration of 711 µg/m^3 during Diwali 2010 at the residential commercial site Kankurgachi, in Northern Kolkata has been reported by Chatterjee et al. (2013). The observed concentration was ~5 times higher than the average nighttime concentration on normal days. Yerramsetti et al. (2013) also reported that on Diwali day the maximum BC concentration was ~12 µg/m^3 at ~24:00 IST with about 133% increase for the year 2009 and 50% increase for the year 2010 compared to control day BC value over Hyderabad, India. Babu and Moorthy (2001) reported 3–4 times increase in BC concentration associated with extensive fireworks during the Diwali Festival for the year 2000 over Thiruvananthapuram, India. The effect of fireworks on significant rise in the concentrations of O_3, NO_X, SO_2, CO and BC during the peak hours of firework activity of the Diwali Festival over Dibrugarh for the year 2012 has earlier been reported by Pathak et al. (2013a).

In the current study, PM and BC aerosol mass concentrations are monitored to observe the short–term effect of firework on their concentrations during the Diwali Festival of two consecutive years 2009 (17 October) and 2010 (5 November) at Dibrugarh, in the North–East India situated in the eastern Himalayan foothills.

2. Approach

2.1. Study area and prevailing meteorology

The study area Dibrugarh (27.3°N, 94.6°E, 111 m asl) is a major gateway to the northeastern corner of India and is the main commercial centre of industry, communication and healthcare of the state Assam. The monitoring station is in the Dibrugarh University campus at a distance of about five kilometers to the south of the Dibrugarh town (Figure 1). The district is famous for its oil and tea industries and oil and natural gas fields are scattered all around. The climate of this region is sub–tropical, humid in nature. The climatological mean minimum temperature in the present study location ranges from ~8 °C in winter to ~20 °C in monsoon, while that for the maximum temperature is ~21 °C to 36 °C in monsoon. Maximum rainfall occurs during the monsoon season, when the location receives ~63% of annual total rainfall and RH is always >70% (Pathak et al., 2012). The distribution of near surface pollutants depends on the evolution of the boundary layer heights (BLH). BLH estimated from the MEERA data shows that after sunrise BLH rises gradually to different heights in different seasons. The maximum daytime height of ~2.4 km is reached in the pre–monsoon season while it is ~1.2 km in winter. In the post monsoon season boundary layer rises up to 1.7 km in the afternoon hours and decreases to ~1.1 km at night (Bhuyan et al., 2014).

The meteorological parameters are measured by an Automatic Weather Station (AWS) installed within the University campus where the observation site is located. It is noted that wind speed/ direction during 18:00–24:00 h is absent for most of days due to instrumental error. The variation of temperature and RH for Diwali day, post–Diwali day and monthly average value for the month of October 2009 (top panel) and November 2010 (middle panel) is shown in Figure 2a. During the Diwali day there is no any significant variation of temperature and relative humidity over the study location for the both years. An average temperature of 28 °C (monthly average is ~24 °C) and 24.5 °C (monthly average is ~21 °C) and average RH of 73% and 74% are observed on the Diwali days in the year 2009 and 2010 respectively. In the bottom panel of Figure 2a the vertical profile of temperature during the Diwali days of 2009 and 2010 is presented. The vertical temperature profile is obtained from European Centre for Medium Weather Forecast (ECMWF, 2014). The diurnal evolution of wind speed and direction for all the days of October 2009 and November 2010 are shown in Figure 2b. The red star represents the wind speed/direction for the Diwali days. The wind speed is mostly within 1–4 m/s. The dominating wind direction is from the northeast (0–90°). But during the daytime the wind comes from other directions too. The synoptic wind pattern over the Indian region is simulated using WRF–ARW for the Diwali days of October 2009 (top panels) and November 2010 (bottom panels) is shown in Figure 2c. The top panels [i.e., figures (i) and (ii) are the wind pattern at 5:30 h and 17:30 h for the Diwali day of 2009 and bottom panels i.e., figures (iii) and (iv)] are the same for the Diwali day 2010. The wind speed during the both local times and years of observation are very week, only 0.5 m/s with change in direction from morning to evening hours. No precipitation was recorded during the Diwali days.

2.2. Sampling technique and data analysis

For the collection of near surface particulate matter (PM) a Quartz Crystal Microbalance (QCM) Impactor (Model PC–2, California Measurements Inc., USA) have been used (Pathak et al., 2010; Pathak et al., 2013b). The QCM provides aerosols mass concentration collected at 10 different stages as a function of particle diameter with size ranges from 0.05 µm to >12.5 µm assuming a density of 2 g/cm^3 at a sampling flow rate of 240 mL per minute. In the QCM instrument the aerosols particles are made to impact on sensing quartz crystals which are stacked one below the other and by monitoring the change in frequency difference between the reference crystal and the sensing crystal, the mass concentration of aerosols deposited in each stage is obtained. The data from the QCM sensing stack are processed in the micro-processor based control unit and further provides printout of the mass concentration in each stage. QCM measurements are made at hourly intervals with sampling time duration of 5 minutes and it is restricted to relative humidity less than 75% as quartz crystals are sensitive to high relative humidity. Thus the measurement time was restricted to 7:30–22:30 h. The measurement inaccuracy for QCM remains within 15% (Moorthy et al., 2007). The composite aerosol or particulate matter (PM) mass concentration is given as:

$$\mathrm{PM} = \sum_{i=1}^{10} m_{ci} \quad (1)$$

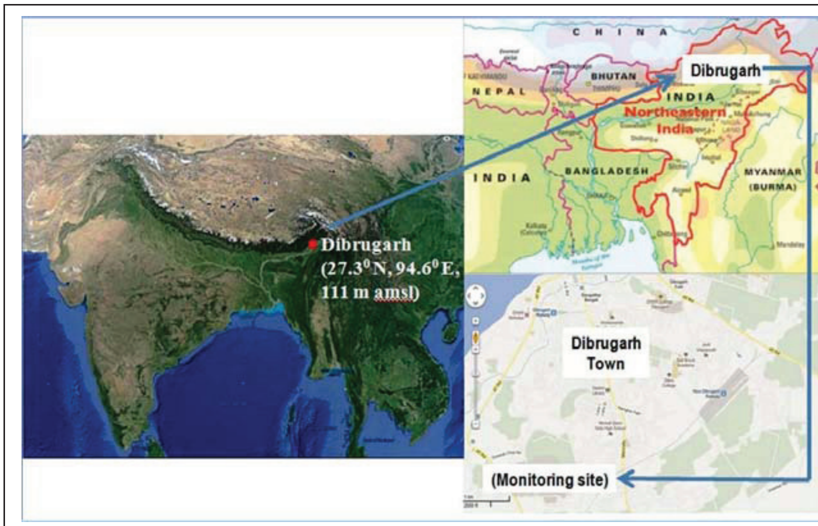

Figure 1. *Location of the monitoring site Dibrugarh (27.3°N, 94.6°E, 111 m amsl).*

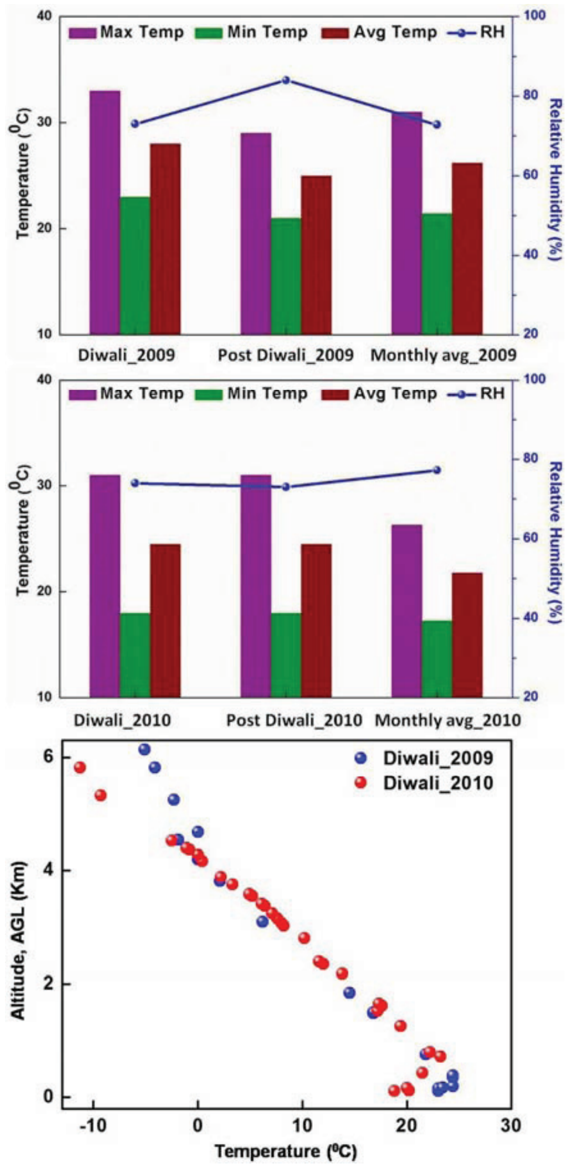

***Figure 2a**. Variation of temperature and relative humidity for Diwali day, post–Diwali day and monthly average value for the month of October, 2009 (top panel) and November, 2010 (middle panel) over Dibrugarh. The bottom panel shows the vertical profile of temperature during the Diwali days of 2009 and 2010.*

where, m_{ci} is the size segregated mass concentration for the i^{th} size bin from i=1 to 10.

For environmental assessment, the size segregated mass concentrations are divided into various fractions based on aerodynamic diameter. In these respect two fractions namely PM_{10} and $PM_{2.5}$ are of interest in view of clean air regulations. From the size segregated mass concentration provided by QCM, PM_{10} is contributed by the QCM stages from 3 to 10 with aerodynamic diameter less than 10 µm and $PM_{2.5}$ from stages 5 to 10 with aerodynamic diameter less than 2.5 µm following Pillai and Moorthy (2001). Accordingly PM_{10} and $PM_{2.5}$ are expressed in terms of QCM stages as:

$$\mathrm{PM}_{10} = \sum_{i=3}^{10} m_{ci} \tag{2}$$

$$\mathrm{PM}_{2.5} = \sum_{i=5}^{10} m_{ci} \tag{3}$$

The size distribution of aerosols is critical to all climate impact studies. For this, number–size distribution is deduced from mass–size distribution of QCM by using the expression:

$$\frac{dn(r)}{dr} = \frac{3}{4\pi\rho r^3}\frac{dm}{dr} \tag{4}$$

where, $dn(r)/dr$ is the number of aerosol particles in the radius range r and $r+dr$, dm/dr is the mass size distribution and ρ is the density of aerosols. $dn(r)/dr$ is an important parameter in the estimation of spectral extinction of solar radiation by aerosols and its impact on Earth's radiation budget.

For measuring real–time black carbon (BC) mass concentrations the Aethalometer is one of the most widespread instruments all around the world. A seven channel Aethalometer (Model AE 31–ER, Magee Scientific, USA) has been used for around the clock measurement of BC mass concentrations over Dibrugarh (Pathak et al., 2010; Pathak et al., 2013b). The principle of operation of Aethalometer is optical attenuation, where measurement of the reduction of a beam of light transmitted through the sample collected on the quartz fiber filter tape is made. The particles in the incoming air flow with a rate of 4 liters per minute through the inlet port are continuously deposited on the quartz fiber filter tape and the reduction of light beam at seven different wavelengths, i.e., 370, 470, 520, 590, 660, 880 and 950 nm are measured by the Aethalometer. Among the seven channel, the 880 nm channel is considered as the standard channel for BC measurement, as fossil fuel sources have more sensitivity to 830 nm spectral channel compared to other aerosol species (Sreekanth et al., 2007). Also at this wavelength BC is the principal absorber of light and other aerosol components have negligible absorption. When the sample spot which is collected on a quartz fiber filter tape reaches a certain density, then the tape will move and during the sample collection a continuous optical analysis is made by the Aethalometer. Typical errors in the derivation of BC concentration are less than 5% (Ganguly et al., 2005; Das and Jayaraman, 2011).

The expression for measurement of BC mass concentration by Aethalometer is given by:

$$M_{BC}(\lambda) = \frac{\beta_{abs}(\lambda)}{\sigma_{abs}(\lambda)} = \frac{\beta_{ATN}(\lambda)}{\sigma_{ATN}(\lambda)R} \tag{5}$$

where

$$\beta_{abs}(\lambda) = -\frac{1}{C\,R}\,\frac{A\,ln(\frac{I_0}{I})}{Q\,\Delta t} \tag{6}$$

Here, C=2.14, R=1, are Weingartner correction factors (Pathak et al., 2010), Q=4 liter per minute is the flow rate, A=1.67 cm^{-2} is the area of collecting spot of the fiber tape and σ_{abs} and σ_{ATN} (=$\sigma_{abs}.C$) are the specific absorption and attenuation cross–sections respectively.

In the present study near–surface PM and BC aerosol mass concentrations during the Diwali days are presented and compared with the post–Diwali day and the background levels, which is the monthly average value of the species excluding the Diwali and post–Diwali days. The post–Diwali day is chosen a day after 5 days of Diwali Festival so that effect of fire crackers is completely removed from the atmosphere. The data after 19.30 h is discarded due to overloading of the crystals under the high humidity condition (RH>80%).

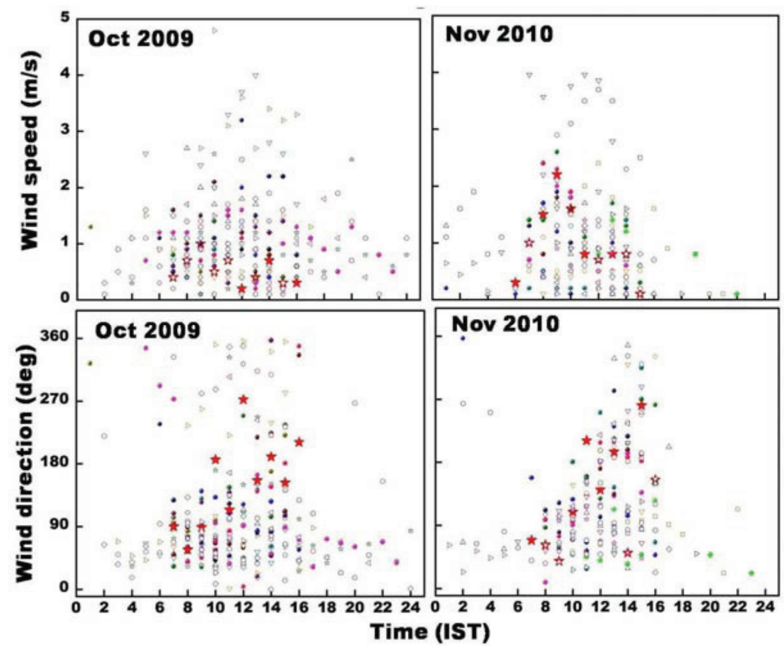

Figure 2b. *Diurnal evolution of wind speed and direction for all the days of October 2009 and November 2010. The red stars represent the wind speed/direction for the Diwali days.*

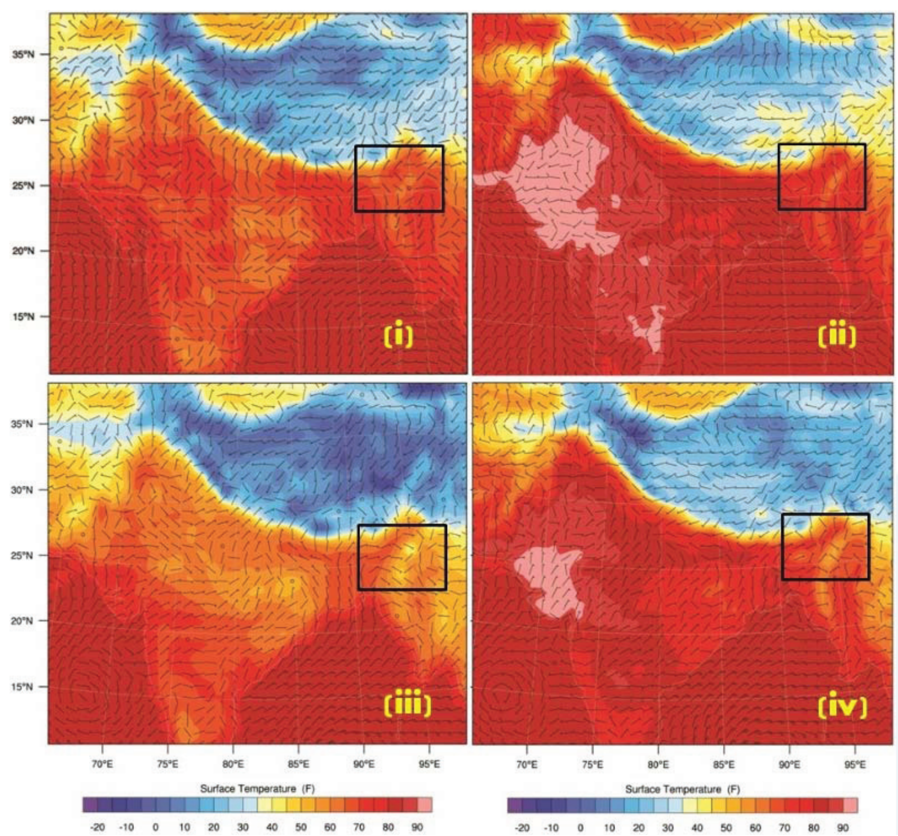

Figure 2c. *The synoptic wind pattern over the Indian region simulated using WRF–ARW for the Diwali days of October 2009 (top panels) and November 2010 (bottom panels) at 5:30 h (i and iii) and at 17:30 h (ii and iv). The study region is shown within the black box.*

3. Results

3.1. Particulate matter and black carbon mass concentrations

The temporal variation of PM_{10} and $PM_{2.5}$ concentrations during Diwali, post–Diwali days and background monthly average values are shown in Figure 3a and Figure 3b for the years 2009 and 2010 respectively. On the Diwali days, fireworks activities normally peaks in the evening to midnight hours (17:30–21:30 h). During this period, therefore, the PM_{10} and $PM_{2.5}$ levels in the Diwali days are much higher than those in the post–Diwali day as well as in the monthly average background level for both the years of observation. The maximum values of PM_{10} and $PM_{2.5}$ on Diwali day at the peak firework activity hours in the year 2009 are 165.98 μg/m^3 and 160.28 μg/m^3 respectively. The corresponding values in the year 2010 are 126.12 μg/m^3 and 123.5 μg/m^3 respectively. At the peak fire work activity hours, the average value of both PM_{10} and $PM_{2.5}$ enhances by about 5.33 and 5.74 times from the background values of 26.51 μg/m^3 and 24.05 μg/m^3 respectively for the year 2009. On the other hand in the year 2010 the enhancement is 2.50 and 2.65 times respectively from the background value of 27.22 μg/m^3 and 24.5 μg/m^3 respectively. Figure 4 shows that the number of fine aerosols on the Diwali day have increased with respect to the post–Diwali day and the background level in 2009 and 2010. This also supports the fact that the increase in aerosol number concentration is due to increase in accumulation mode particles which are mostly emitted during the fireworks. However the amount of increase in 2009 is higher compared to that in 2010 because of the fact that induction during the fireworks in 2009 was comparatively much higher as seen in Figure 3.

The diurnal variations of BC concentration measured on the Diwali day, post–Diwali day and monthly average background values are shown in Figure 5 for the year 2009 (top panel) and 2010 (bottom panel). The black carbon concentration starts to increase from 16:00 h and on an average peaks around 20:00–22:00 h after which the concentration level decreases through the night to reach the minimum level at noon, the next day. The observed increase in concentration of BC during pre–midnight hours is due to the suppression of boundary layer height. The diurnal and seasonal variations of BC concentration over the study location have been studied and reported earlier by Pathak et al. (2010) and Pathak and Bhuyan (2014). BC concentration on the Diwali days is higher than that in the post–Diwali day and monthly average background value in both the years 2009 and 2010 (Figure 5). In the year 2009 after the primary peak at ~19:00 h there was a depression in the level of BC concentration before the occurrence of a secondary peak at ~23:30 h. While in the year 2010 the Diwali day BC concentration showed a regular pattern. The increase in BC concentration at peak hours of firework activity is 1.21 and 1.66 times from the background value for the years 2009 and 2010 respectively.

3.2. Percentage contribution of $PM_{2.5}$ to PM_{10} and BC to PM_{10} fraction

To estimate the contribution of $PM_{2.5}$ and BC to the PM_{10} concentrations we calculated the percentage contribution of $PM_{2.5}$ to PM_{10} and the ratio of BC to PM_{10} for the Diwali day, post–Diwali day and background monthly average values for the years of 2009 and 2010 and the results are presented in Figure 6. The contribution of $PM_{2.5}$ to PM_{10} during the Diwali days exceeds the post–Diwali day and background level in both the years. Percentage contribution of $PM_{2.5}$ to PM_{10} is higher in the year 2009 compared to that for the year 2010 for both the Diwali days and background level, except for the post–Diwali day when the values for both the years are nearly equal. The BC fraction for Diwali days are higher than that for the post–Diwali day and background level for the both years. The contribution of BC to PM_{10} concentration for the year 2010 is higher than that for the year 2009.

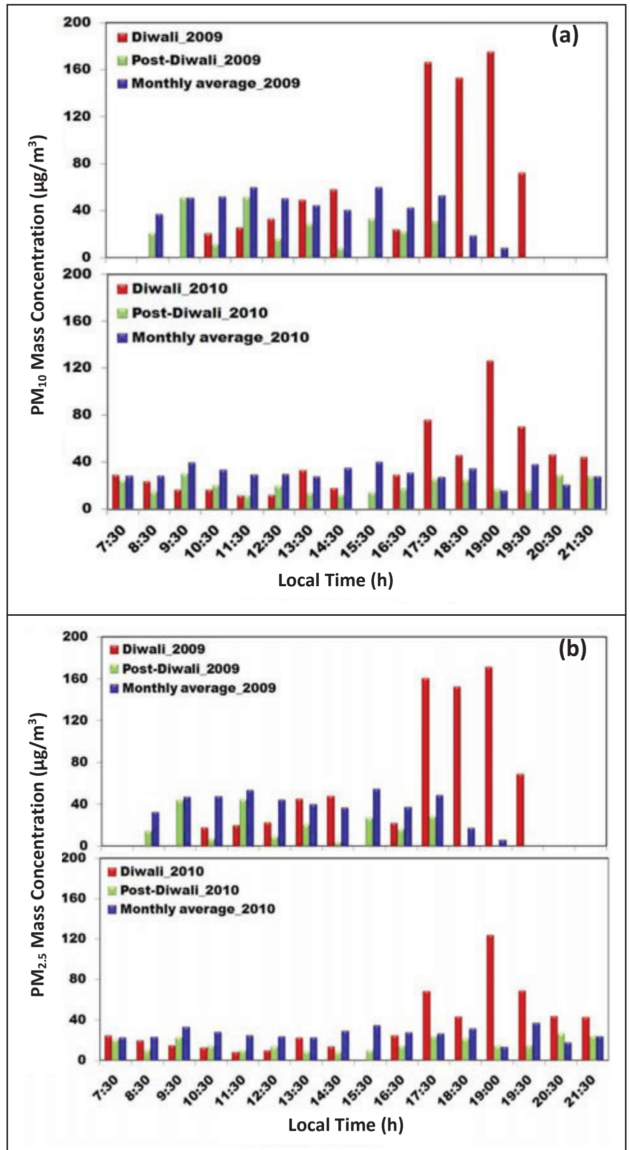

Figure 3. ***(a)*** *Diurnal variation of PM_{10} concentration for Diwali day, post–Diwali day and background monthly average value for the year 2009 (top panel) and 2010 (bottom panel) over Dibrugarh.* ***(b)*** *Diurnal variation of $PM_{2.5}$ concentration for Diwali day, post–Diwali day and background monthly average value for the year 2009 (top panel) and 2010 (bottom panel) over Dibrugarh.*

3.3. Identification of sources other than the firework activities: Long–range transport and biomass burning

To identify the possible sources of enhancement of near surface aerosol concentrations during the Diwali Festival the 5 day air mass back trajectories terminated at the study location, at 14:00 h (GMT) were computed at an elevation of 500 m above the ground level using the National Oceanic and Atmospheric Administration Hybrid Single–Particle Lagrangian Integrated Trajectory (NOAA–HYSPLIT) model (version 4) (Draxler and Rolph, 2003). These back trajectories are primarily calculated from the observed vertical wind and pressure fields. Figure 7 shows the NOAA HYSPLIT wind back trajectories on Diwali days (top panel) and for all days of October 2009 and November 2010 excluding the Diwali and Post–Diwali days (bottom panel). A close observation of these trajectories establishes that all the air masses have their origin very close to the study location at the peak hour of firework activities on the

Diwali days for both the years as well as during the normal days. However, in the year 2010 some trajectories originate at distant places. Earlier studies over Dibrugarh by Gogoi et al. (2011) and Pathak et al. (2012) have also shown mostly local confinement of air mass trajectories in addition to few mixed trajectories originating at different distant places during the same period of October–November.

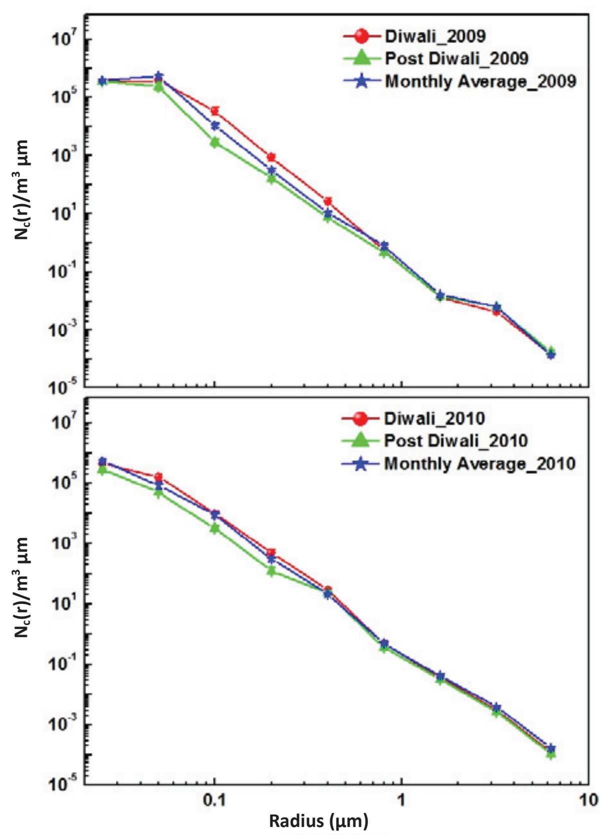

Figure 4. *Number–size distributions of PM_{10} for Diwali day, post–Diwali day and background monthly average value for the year 2009 (top panel) and 2010 (bottom panel) over Dibrugarh.*

The Moderate–Resolution Imaging Spectro–radiometer (MODIS) retrieved fire maps were used in the present study. Each of these fire maps accumulates the locations of the fires detected by MODIS on board the Terra and Aqua satellites over a 10–day period. Each colored dot indicates a location where MODIS detected at least one fire during the compositing period. Color ranges from red where the fire count is low to yellow where number of fires is large. Figures 8a and 8b show the fire maps during the festival, accumulated for the period 8–17 October 2009 and after the festival for the period 18–27 October 2009. Similarly Figures 8c and 8d represent the fire maps for the year 2010 during the festival (28 October – 7 November 2010) and after the festival (07–16 November 2010). During the Diwali period there were no significant forest fires/biomass burning present over study region in the year 2009, though there were a few burning signatures in the surrounding region in 2010.

4. Discussion

For environmental assessment, the aerodynamic diameter of aerosol particles is considered and hence PM_{10} is measured from the 3rd stage (where aerodynamic diameter <10 µm) to 10th stage of the QCM as discussed earlier. Pathak et al. (2013b) have reported temporal distribution of PM_{10} and $PM_{2.5}$ adopting the same measurement criteria. Since there is a negligible difference between the 24 h average and 7:30–22:30 h average PM concentrations, we have considered the measurements during that period as the 24 h average value in the present study for the environmental assessment. The daily average PM during the Diwali day did not exceed National Ambient Air Quality Standards (NAAQS) of India in both years of the observation (Table 1). On the other hand these concentrations are in the unhealthy category in 2009 and moderate in 2010 according to the classifications given by Guttikunda (2010) for Indian cities.

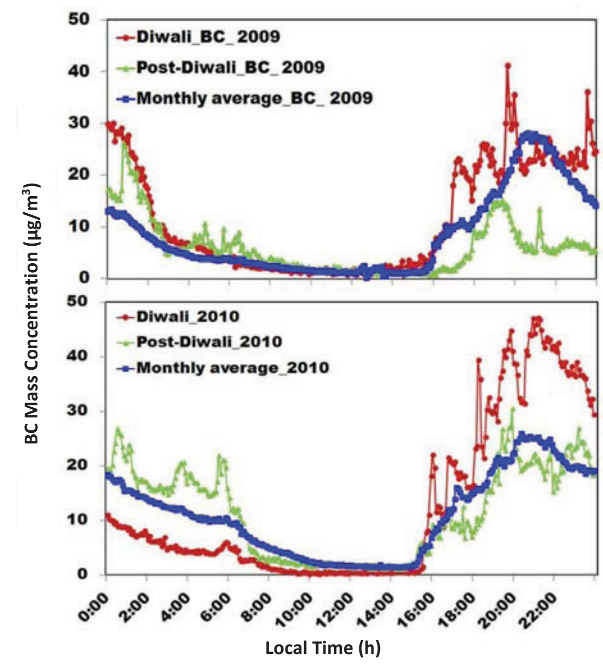

Figure 5. *Diurnal variation of black carbon (BC) mass concentrations for Diwali day, post–Diwali day and background monthly average values for the year 2009 (top panel) and 2010 (bottom panel) over Dibrugarh.*

The PM_{10}, $PM_{2.5}$ concentrations are normalized for the Diwali and post–Diwali days of 2009 and 2010 by adopting the following equation:

$$PM_{Norm} = \frac{PM_{Diwali/post-Diwali} - PM_{Background}}{PM_{Diwali/post-Diwali}} \quad (7)$$

The PM concentrations start to rise at 17:30 h, when the firework activity starts and it reaches maximum level by 19:00 h, when the firework activity peaks. The long bars of normalized PM concentrations as shown in Figure 9a clearly reveal this for the both years. The concentrations in post–Diwali day are lower than the background monthly average value, because the post–Diwali day is considered after 5 days of Diwali Festival when the effect of firework activity is completely removed. The concentrations of $PM_{2.5}$ and PM_{10} is almost similar due to the consideration of QCM size bins, 3rd to 10th stages give PM_{10} while 5th to 10th stages give $PM_{2.5}$. Further, it has been reported by Pathak et al. (2010, 2013b) that PM_{10} over the location is mainly attributed to $PM_{2.5}$ aerosols. As the location is mostly covered by vegetation there is a negligible chance of emission of coarse aerosols into the atmosphere, but high emission of biogenic volatile organic compounds, which further produce secondary aerosols that contribute to fine aerosols in the atmosphere. The PM_{10} and $PM_{2.5}$ concentrations during the Diwali days at the peak fire work activity hours show higher values in the year 2009 compared to that in 2010. This is consistent with higher level of background PM concentrations in 2009 (~43 µg m^{-3}) than in 2010 (~30 µg m^{-3}). Pathak et al. (2013b) have shown a decreasing trend of PM_{10} and $PM_{2.5}$ concentrations during 2007–2012 period (Figure 3a) in the same location with higher concentrations in October 2009 compared to that in November 2010, which were the months of Diwali Festival. In the year 2009, heavy to medium level of construction activities were going on within the University campus, where the observation site is located and in a nearby place, where a factory was under erection. This may also have a partial effect of introducing fine dust into the atmosphere, leading to higher level of background aerosols. Thus the peaks in PM concentrations during 17:30–19:00 h as in Figure 9 is due to the firework activity only as the burning of firecrackers is at maximum at this time. The firework activity in the Dibrugarh Town 5 km upwind from the observation site also contributes to the total loading under favorable wind direction.

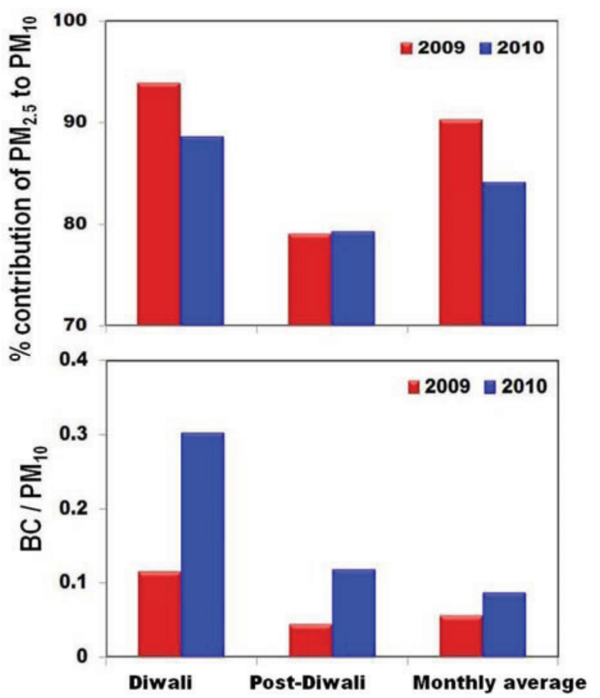

Figure 6. *Percentage contribution of $PM_{2.5}$ to PM_{10} (top panel) and fraction of BC to PM_{10} (bottom panel) for Diwali days, post–Diwali day and background monthly average values for the year 2009 and 2010 over Dibrugarh.*

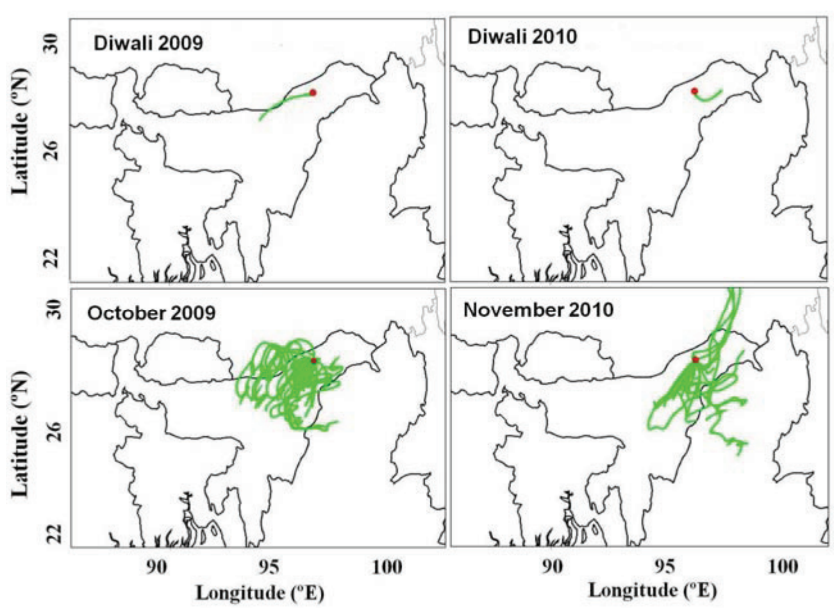

Figure 7. *Air mass back trajectories of NOAA Hysplit Model at 500 m AGL over Dibrugarh on Diwali days (17 October 2009 and 5 November 2010) and the corresponding monthly background except Diwali days for the years 2009 and 2010 respectively.*

Table 1. *24 hr average PM_{10} and $PM_{2.5}$ concentrations for Diwali, post–Diwali and monthly average and the air quality standards of India and those classified by Gutttikunda, (2010)*

PM Conc. (μg/m³)	2009			2010			Air Quality Categories (Conc. in μg/m³)				NAAQS (24 h) μg/m³
	Diwali	Post–Diwali	Monthly Average	Diwali	Post–Diwali	Monthly Average	Healthy	Moderate	Unhealthy 1	Unhealthy 2	
PM_{10}	77.62	27.16	42.86	39.84	19.68	30.27	0–40	40–80	80–120	120–200	100
$PM_{2.5}$	72.85	21.47	38.67	35.91	15.76	25.85	0–25	25–50	50–70	70–100	60

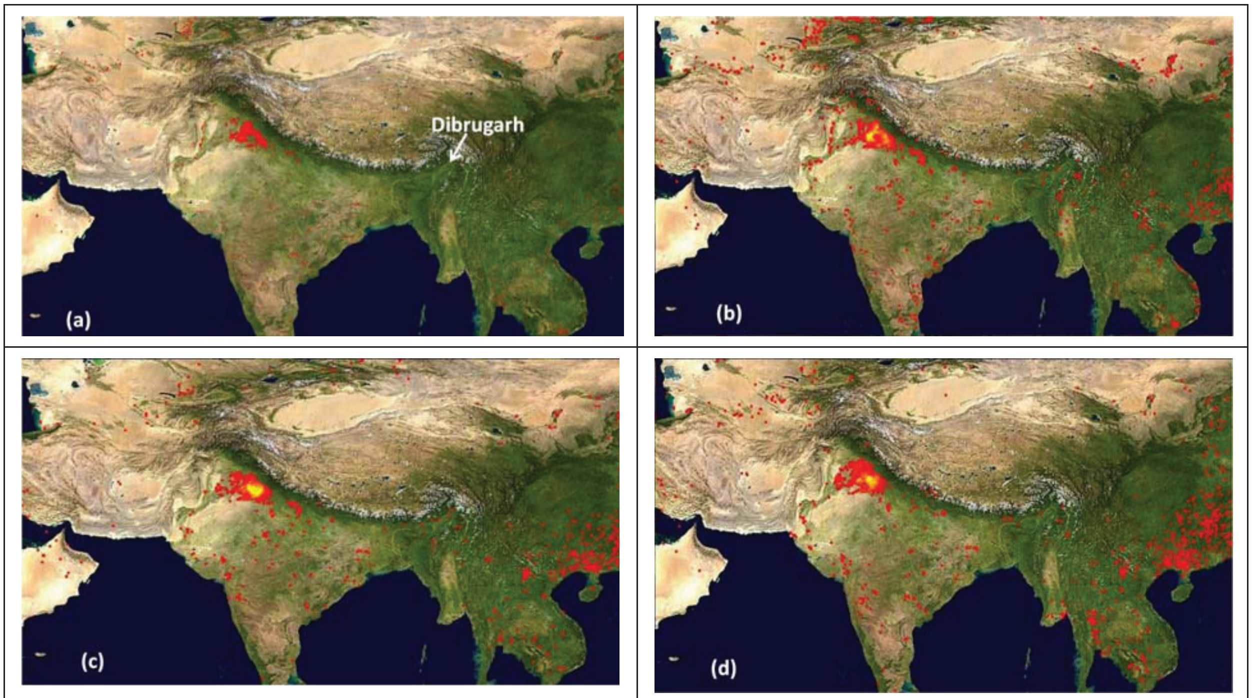

Figure 8. *MODIS Terra and Aqua fire maps during and after the festival for the year 2009* ***(a), (b)*** *and 2010* ***(c), (d)****.*

The diurnal maximum BC concentration in 2009 peaks sharply at around 19:30 h followed by a secondary peak at ~23:30 h and a depression in between whereas BC exhibits a broad peak in the year 2010 during ~18:00–22:00 h. The normal peak in BC concentration is observed during 20:00–22:00 h at the study location (Pathak et al. 2010; Pathak and Bhuyan 2014) which is also clear from the background concentration. Thus the peak in BC concentration before 20:00 h is attributed to firecracker burning. The depression in the concentration in the Diwali day in 2009 could not be ascertained. This may be due to reduction in cracker burning particularly at that period. The anomaly of the BC concentration in 2009 and 2010 may be associated with lower nighttime boundary layer height in November 2010 compared to that in October 2009, and also due to higher wind speeds and temperatures in October 2009 (Figure 2a). The shallow boundary layer is capable of holding more BC particles near the surface. Moreover, in the year 2010 Diwali was celebrated in the month of November and by then burning activities in the nearby places starts, while in October no such activities were present in the places surrounding the observation location as evident from Figure 8. This may have an impact of higher level of overall BC concentration in the year 2010, which has lead to the lower BC fraction of 10% in 2009 than that of 30% in 2010. The vertical profile of temperature also shows the stability of the atmosphere in both the years during the Diwali Festival. Further, the trajectories on the Diwali days of both the years confined locally. Thus there was no distant sources affecting the pollutant levels over the location and it can be inferred that the short term increase in mass concentration of atmospheric pollutants during Diwali days is mainly attributed to the firework activities.

Unlike BC, measured PM concentrations don't show an increase in the pre–midnight hours and also the increase in BC concentrations are not as large as that of PMs. This may be due to the fact that BC constitutes only a fraction of the total PM and during the fireworks large number of species other than BC are released which form the total PM. Thus the increase in BC concentration is not reflected in PM. This is also evident from the normalized BC concentrations presented in Figure 9b, showing no one–to–one variation with PMs as in Figure 9a. In a recent study (Pathak et al., 2013a) high increases in SO_2, NO_X and CO together with BC have been reported from the same site during the Diwali Festival in 2012. During 2009 and 2010 no trace gas measurements were available for the quantification of the gases released during the festival. Further, it may be noted that the amount firecrackers burnt during these festivals cannot be estimated.

5. Conclusions

This study shows that due to the firework activity during the Diwali Festival there is a significant enhancement of concentrations of both particulate matter and black carbon over Dibrugarh. On Diwali days the PM_{10}, $PM_{2.5}$ and BC concentrations are found to be a number of times higher compared to background levels at the peak hours of firework activity. However, this short–term high increase in the concentrations of these air pollutants during the Diwali Festivals in the years 2009 and 2010 did not cross the safety limit of Indian National Air Quality Standards, but degraded the air from clean to moderate or unhealthy.

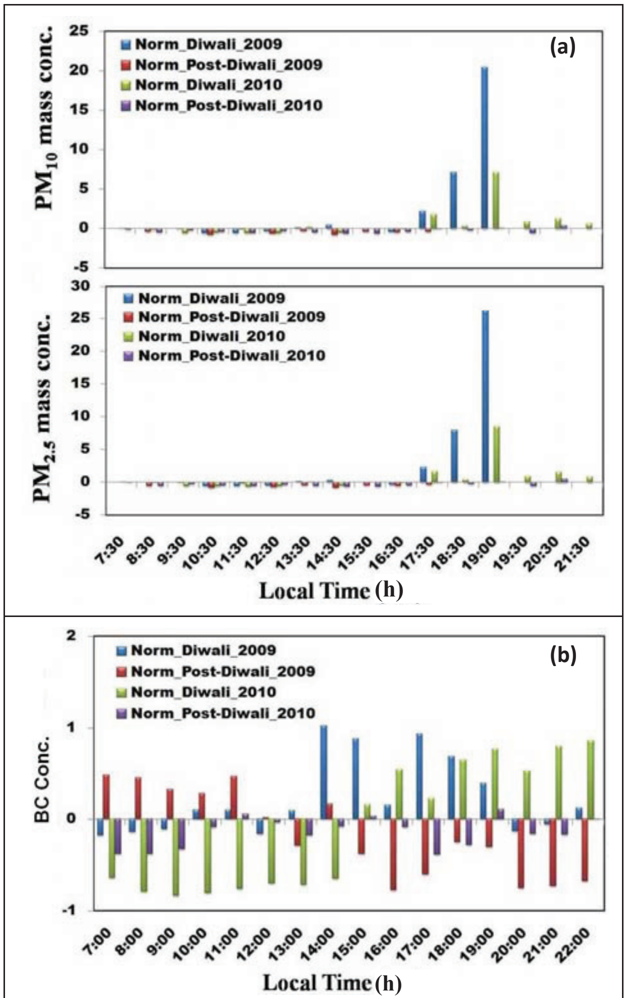

Figure 9. (a) *Normalized PM_{10} (top panel) and $PM_{2.5}$ (bottom panel) concentrations (µg/m^3) during Diwali and Post–Diwali days,* ***(b)*** *Normalized BC concentrations during Diwali and Post–Diwali days.*

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