

The impact assessment of Diwali fireworks emissions on the air quality of a tropical urban site, Hyderabad, India, during three consecutive years

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Abstract Diwali is one of the largest festivals for Hindu religion which falls in the period October–November every year. During the festival days, extensive burning of firecrackers takes place, especially in the evening hours, constituting a significant source of aerosols, black carbon (BC), organics, and trace gases. The widespread use of sparklers was found to be associated with short-term air quality degradation events. The present study focuses on the influence of Diwali fireworks emissions on surface ozone (O_3), nitrogen oxides (NO_x), and BC aerosol concentration over the tropical urban region of Hyderabad, India during three consecutive years (2009–2011). The trace gases are analyzed for pre-Diwali, Diwali, and post-Diwali days in order to reveal the festivity's contribution to the ambient air quality over the city. A twofold to threefold increase is observed in O_3 , NO_x , and BC concentrations during the festival period compared to control days for 2009–2011, which is mainly

attributed to firecrackers burning. The high correlation coefficient (~ 0.74) between NO_x and SO_2 concentrations and higher SO_2/NO_x (S/N) index suggested air quality degradation due to firecrackers burning. Furthermore, the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation-derived aerosol subtyping map also confirmed the presence of smoke aerosols emitted from firecrackers burning over the region. Nevertheless, the concentration level of pollutants exhibited substantial decline over the region during the years 2010 and 2011 compared to 2009 ascribed to various awareness campaigns and increased cost of firecrackers.

Keywords Diwali · Fireworks · Trace gases · Air quality · Pollution

Introduction

Air quality in megacities and other major population centers is a serious concern due to their high pollutant concentrations and health hazards. In recent times, short-term air quality degradation episodes are gaining increased attention of the scientific community as they considerably affect human health due to their long-term negative effects (Pope et al. 2002; Nastos et al. 2010; Samoli et al. 2011). Recreational use of fireworks to celebrate festivities all over the world is among the most unusual source of short-term

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anthropogenic pollution which causes serious health hazards. To this respect, specific air quality degradation has been reported due to bursting of firecrackers on Diwali festival in India (Kulshrestha et al. 2004; Mandal et al. 2011), Lantern festival in China (Wang et al. 2007), Independence Day in USA (Liu et al. 1997), and New Year's Day (Drewnick et al. 2006).

Diwali is one of the most important, hugely anticipated, and enormously cherished festivals celebrated across India; Diwali festival usually occurs in late October/early November and is celebrated for three consecutive days. Huge amounts of crackers and sparklers are burned mainly on the day of the festival (Diwali day) and also on the day before and after Diwali (considered as pre-Diwali and post-Diwali day). Trace gases (O_3 , SO_2 , and NO_x) and black carbon (BC) particulates emitted by fireworks generate dense clouds of smoke that contain black powder (potassium nitrate, charcoal, and sulfur). Further, depending upon the meteorological conditions, these fireworks emissions reduce visibility to a large extent and generate a dense cloud of smoke, for time intervals, up to several hours. Several studies have been performed related to Diwali fireworks over different regions in India (Babu and Moorthy 2001; Kulshrestha et al. 2004; Barman et al. 2008; Singh et al. 2010; Mandal et al. 2011). The study conducted by Barman et al. 2008 reported 5.7, 6.6, and 2.7 times higher concentrations of PM_{10} , SO_2 , and NO_x , respectively, on Diwali day as compared to their concentration on a normal day in Lucknow city, India, and they were higher than the prescribed limit of the National Ambient Air Quality Standard. Attri et al. (2001) reported nighttime formation of O_3 at the ground level even when O_3 precursors and sunlight were absent. Additionally, studies by Khaiwal et al. (2003), Nishanth et al. (2012), Thakur et al. (2010), Kulshrestha et al. (2004), Sarkar et al. (2010), and Singh et al. (2010) also highlighted the increase in pollutant levels, such as SO_2 , NO_2 , O_3 , total suspended particulate matter (TSP), trace metals, and BC aerosols during the period.

As festivals are becoming significant contributors to air pollution in India, there is increased awareness about its negative impact as well. Further, numerous environmental groups and eco clubs are coming up with their awareness campaigns and raising their voices against pyrotechnics display of fireworks during Diwali festivity celebrations. The main concern of

these campaigns includes increasing the level of awareness among the public on the toxic effects of firecrackers on human health and environment as well. As indicated by a report of the Central Pollution Control Board, New Delhi, a decreasing pattern is observed in firecrackers burning during Diwali festival due to increased awareness among the public and increasing cost of firecrackers over a period of time (<http://expressbuzz.com/cities/hyderabad/Festival-of-lights-a-quiet-affair/>).

In the present study, O_3 , NO_x , SO_2 , and BC aerosol mass concentrations were closely monitored during the festival event of Diwali for a period of 3 years (17 October 2009, 5 November 2010, and 26 October 2011, i.e., 2009–2011). Multiple satellite data products and ground-based observations were integrated in order to assess the air quality over the region.

Study area

The experimental site was located at 17.47° N and 78.58° E and at an altitude of 536 m above mean sea level, at Tata Institute of Fundamental Research—Balloon Facility (TIFR-BF), Hyderabad, Andhra Pradesh, India. The climate of this region is semiarid with a total rainfall amount of ~700 mm occurring mostly during the monsoon season in the period June–October. The climatology of this area experiences four dominant seasons, winter (December–February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November) (Badarinath et al. 2010).

Datasets and methodology

Ground-based measurements

Synchronous measurements of trace gases, viz. surface O_3 , NO_x , and SO_2 , were carried out using O_3 analyzer (49i; Thermo Scientific, USA), NO_x analyzer (42i; Thermo Scientific, USA), and SO_2 analyzer (43i; Thermo Scientific, USA) respectively. The trace gases in ambient air were measured simultaneously for every 5-min interval and averaged to attain hourly and daily concentrations.

O_3 analyzer works on the principle that O_3 molecules absorb ultraviolet (UV) light at a wavelength of

254 nm. NO_x analyzer operates on the principle that NO and O_3 react to produce a characteristic luminescence with intensity linearly proportional to the NO concentration. SO_2 analyzer operates on the principle that SO_2 absorb UV light and become excited at one wavelength, then decay to a lower energy state emitting UV light at a different wavelength. The detailed description of analyzers is presented elsewhere (Swamy et al. 2012).

In addition, continuous and near real-time measurements of BC aerosol mass concentration were carried out using an aethalometer (AE-21, Magee Scientific USA) (Cooke et al. 1997; Badarinath et al. 2009) during the Diwali period of three consecutive years, i.e., 2009–2011. More details about aethalometer use and estimates of BC concentrations can be found elsewhere (Srekanth et al. 2007; Das and Jayaraman 2011 and references therein). Furthermore, in order to quantify anthropogenic emissions, Delta C values ($\text{UVBC}_{370 \text{ nm}} - \text{BC}_{880 \text{ nm}}$) were calculated from a seven-channel BC aethalometer. The Delta C values are suggested to be a strong indicator of emissions sources, such as biomass burning, anthropogenic emissions, and forest fire emissions (Wang et al. 2011b, c, d). Besides, Gadhavi and Jayaraman (2010) highlighted that the UV channel plays an important role in separating wood smoke emissions from diesel exhausts, while the wavelength dependence of the absorption coefficient is a strong indicator of the relative influence of BC aerosols from different sources, i.e., fossil fuel or biofuel combustion (Bergstrom et al. 2002; Kirchstetter et al. 2004; Kaskaoutis et al. 2011). Meteorological parameters, viz. temperature, relative humidity (RH), wind speed (WS), and wind directions (WD), were collected from the Automatic Weather Station (AWS) installed at the experimental site.

Satellite data

CALIPSO retrievals

The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) provides new insight into the role of clouds and atmospheric aerosols (airborne particles) in regulating Earth's climate and air quality. CALIPSO has a 98° inclination orbit and flies at an altitude of 705 km, providing daily global maps of the vertical distribution of aerosols and clouds. CALIPSO was launched on 28 April 2006.

The CALIPSO payload consists of three instruments: the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), an imaging infrared radiometer, and a moderate spatial resolution wide field-of-view camera. CALIOP provides profiles of backscatter at 532 and 1,064 nm, as well as two orthogonal (parallel and perpendicular) polarization components at 532 nm. In the present study, we used level 1B datasets which contain a half orbit of calibrated and geolocated Lidar profiles including vertical feature mask (VFM), total attenuated backscatter (TAB) at 532 nm, attenuated color ratio (ACR) of bands 532 and 1,064 nm, and aerosol subtype map. The vertical resolution of the retrievals is 30 m. A detailed discussion of CALIOP data products has been described elsewhere (Powell et al. 2009).

MODIS active fire locations

Fire observations are performed four times a day from the Terra (1030 and 1230) and Aqua (1330 and 0130) platforms. MODIS fire detection is performed using a contextual algorithm (Giglio et al. 2003) that exploits the strong emission of mid-infrared radiation from fires. The algorithm uses brightness temperatures derived from the MODIS 4- and 11- μm channels. The description of MODIS fire products retrieval has been provided elsewhere (Giglio et al. 2003). We used MODIS active fire location composited for the festival period from FIRMS web fire mapper (<http://firms.modaps.eosdis.nasa.gov/firemap/>).

In addition, air mass back trajectories ending at the urban region of Hyderabad at three altitudes (300, 800, and 1,500 ma.s.l.) were calculated using the National Oceanic and Atmospheric Administration Hybrid Single-Particle Lagrangian Integrated Trajectory (NOAA-HYSPLIT) model (version 4) which includes vertical wind. This model was developed at the Air Resources Laboratory, National Oceanic and Atmospheric Administration, USA (Draxler and Rolph 2003). The NOAA-HYSPLIT model simulates the pollutant emission by releasing a fixed number of Lagrangian particles having a mass determined by the source strength. Furthermore, the pollutant concentration is calculated by dividing the sum of the particle masses of the pollutant by the volume of the corresponding user-defined concentration grid cell in which the particles reside. A detailed model description can be found in Draxler and Rolph (2003).

Results and discussion

Meteorological parameters

The meteorological parameters during the Diwali days for each year were recorded on an hourly basis by AWS located at the TIFR site, Hyderabad (Table 1). The meteorological parameters, viz. temperature ($^{\circ}\text{C}$), RH (%), WS, and WD, demonstrated small changes during the study period, suggesting minimal interference from the weather. An average temperature of 28 ± 4 , 23 ± 2 , and 25 ± 3 $^{\circ}\text{C}$ and average RH (%) of 54 ± 14 , 79 ± 15 , and 71 ± 16 % were observed on Diwali days during 2009, 2010, and 2011, respectively. Finally, the averaged WS was low, ranging from 1.6 ± 0.4 to 2.5 ± 0.9 ms^{-1} confined to southeast direction. The local meteorological conditions can significantly influence the trace gas concentrations through the mechanisms of dispersion of pollutants, i.e., enhanced convection, strong surface winds, etc., that can dilute the emissions of firecrackers. However, such large differences in the local meteorology are not seen in the studied years.

Variation in air pollutants

Ozone

Surface O_3 is a secondary air pollutant formed through a set of photochemical reactions involving $\text{NO}_x = \text{NO} + \text{NO}_2$ and volatile organic compounds (Racherla and Adams 2008; Lin et al. 2007). This section analyzes diurnal variation (for afternoon and night hours only) of trace gases over Hyderabad for pre-Diwali, Diwali, and post-Diwali days in comparison to a normal day. The extensive use of fireworks seems to be related to short-term variation in trace gases concentrations and urban air quality.

In the troposphere, O_3 is generally produced through photolysis of NO_2 in presence of solar radiation during

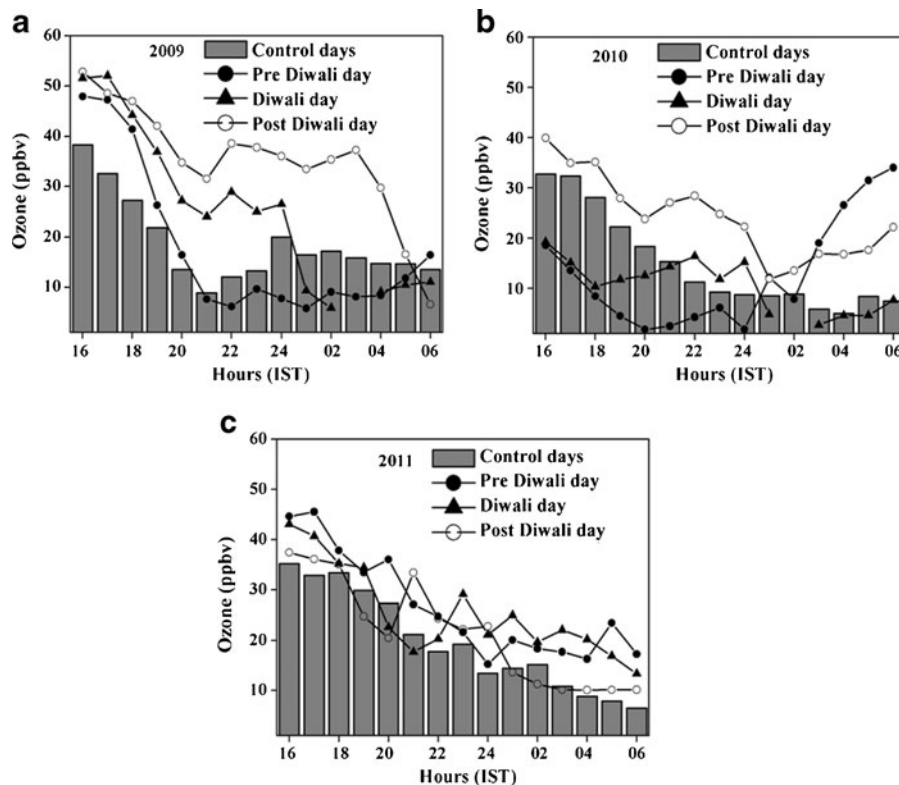
Table 1 Meteorological parameters recorded over the region during the Diwali festivity period

Meteorological variables	2009	2010	2011
Temperature ($^{\circ}\text{C}$)	28 ± 4	23 ± 2	25 ± 3
Relative humidity (%)	54 ± 14	79 ± 15	71 ± 16
Wind speed (ms^{-1})	1.6 ± 0.4	1.5 ± 0.3	2.5 ± 0.9
Wind direction ($^{\circ}$)	SE	SE	SE

daytime and gets destructed by titration with NO to produce O_2 and NO_2 . Nevertheless, at nights, there is no possibility of O_3 formation due to the lack of sunlight and absence of induced photochemical reactions. On the other hand, Attri et al. (2001) revealed the formation of nighttime O_3 in absence of NO_x and sunlight ascribed to pyrotechnics display of fireworks. However, there are very limited measurements in the literature regarding O_3 formation due to fireworks emission during the nighttime.

Continuous measurements of O_3 concentration were carried out at TIFR site, Hyderabad, India for the Diwali festivity period. The averaged O_3 data for 7 days before and after the Diwali period is considered as control day. Furthermore, the O_3 concentrations on control, pre-Diwali, Diwali, and post-Diwali days were compared to characterize the role of Diwali firework emissions effects on the urban air quality. Figure 1 shows the temporal variation of nighttime O_3 concentration for the aforementioned days during (a) 2009, (b) 2010, and (c) 2011. As expected, O_3 exhibits a general decreasing trend towards nighttime in absence of sunlight. This is more evident on control days, whereas during pre-Diwali, Diwali, and post-Diwali days, O_3 concentration increased at late night in 2009 and 2010. The O_3 concentrations during control days varied in the range of 5 to 35 ppbv (2009–2011). However, the nighttime surface O_3 levels showed a significant increase on the evening of pre-Diwali day (during 2009) from 1600 to 2100 Indian Standard Time (IST), reaching a maxima of ~ 47 ppbv marked by fireworks burning and further restored to its normal level at 2200 IST (Fig. 1a). The increase in nighttime surface O_3 concentrations continued on Diwali day and post-Diwali day as well and attained its maximum level of ~ 55 ppbv during the period. Despite the differences in O_3 concentration levels for each year, the O_3 concentrations during Diwali festivity days are much higher than those observed on respective control days, especially at night hours, i.e., from ~ 2000 to 0400 IST. Previous studies by Nishanth et al. (2012) and Attri et al. (2001) also reported significant increase in nighttime O_3 concentrations due to firecrackers burning during the festivity period. This nighttime formation of O_3 could be explained with linear relationship between the amount of combustible material present in the firecrackers and cumulative O_3 (Attri et al. 2001). Firecrackers, when burned, emit a compelling proportion of light which

Fig. 1 Temporal variation of nighttime O₃ concentration on control, pre-Diwali, Diwali, and post-Diwali days during **a** 2009, **b** 2010, and **c** 2011

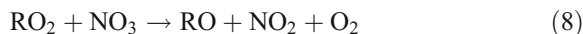


enables the reaction $O_2 + O \rightarrow O_3$ which helps in nighttime O₃ formation. The significant differences observed in the O₃ concentrations from year to year are partly attributed to local meteorological conditions, i.e., boundary layer height, wind field, and also to local emissions and secondary O₃ formation.

Furthermore, Nishanth et al. (2012) suggested a new scheme of nighttime O₃ formation on the basis of emission spectra derived from UV-visible spectrophotometer. The authors analyzed emission spectra of three different sparklers and powders and found that UV wavelengths were absent in the emissions spectra of all six samples. The study summarized that nighttime O₃ formation does not follow the scheme explained by Attri et al. (2001), as the emissions are usually restricted to the visible and infrared regions. Additionally, the authors suggested the following set of reactions (1–5) for nighttime enhancement of NO_x due to fireworks emissions:



Alkanes found in the gas phase during firecrackers burning may react with the OH radical in presence of O₂ to form alkylperoxy (RO₂) radicals. This RO₂ further reacts with NO₃ radicals to form NO₂. NO₂ is further photolyzed in presence of the fireworks flash in order to generate O₃:



In contrast, analogous increase in nighttime O₃ concentrations was not observed on pre-Diwali days during the years 2010 and 2011 (Fig. 1b and c). Nighttime O₃ levels registered an increase in Diwali and post-Diwali days, attaining a maximum level of ~45 ppbv during 2010 and 2011. This distinct decrease in firework-related pollution levels during 2010 and 2011 in comparison to 2009 were attributed to the increased attentiveness amid youngsters (newspaper publicity against

firework-related pollution), increased cost of firecrackers, and meteorological conditions.

Oxides of nitrogen

Figure 2 shows the temporal variation of nighttime NO_x concentration on control, pre-Diwali, Diwali, and post-Diwali days during (a) 2009, (b) 2010, and (c) 2011. The nighttime concentration of NO_x showed a significant increase on pre-Diwali and Diwali days in 2009; however, it exhibits lower values on the post-Diwali day. The maximum concentration of NO_x reached up to ~ 20 ppbv at 2100 IST on pre-Diwali day in 2009. However, during the Diwali festivity period in 2010 and 2011, NO_x concentration showed a peak up to ~ 15 ppbv, suggesting a considerable decrease (33 %) when compared to the previous year.

BC aerosol mass concentration

BC is a form of particulate air pollution produced due to incomplete combustion of fossil fuels and anthropogenic

emissions (Ramanathan et al. 2001). It constitutes a major pollutant over Indian urban centers and densely populated regions (Tripathi et al. 2005; Badarinath et al. 2009; Sreekanth et al. 2007 among many others). All these studies and many others agree to a pronounced diurnal variability of BC aerosols over Indian cities with primary morning and secondary evening peaks. This diurnal variability is obvious in the present analysis (Fig. 3a–c), since the BC concentrations are higher on normal days during the evening hours (2000–2100 IST). However, compared to normal days, the BC concentrations exhibit much larger values during Diwali festivity days, especially in 2009, while in 2010 and 2011, the diurnal variation seems similar to that of normal days, with little higher values of BC. Furthermore, on the Diwali day (2009), the nocturnal BC concentration increased up to four times by attaining a maxima of $\sim 12 \mu\text{g m}^{-3}$ during ~ 2400 IST and remained high till the next morning ~ 0600 IST which was attributed to the fireworks episode. Subsequently, BC concentration showed an immediate decay in nocturnal peak values on post-Diwali day and reached up to $\sim 6 \mu\text{g m}^{-3}$, corresponding to decline in firecracker

Fig. 2 Temporal variation of nighttime NO_x concentration on control, pre-Diwali, Diwali, and post-Diwali days during **a** 2009, **b** 2010, and **c** 2011

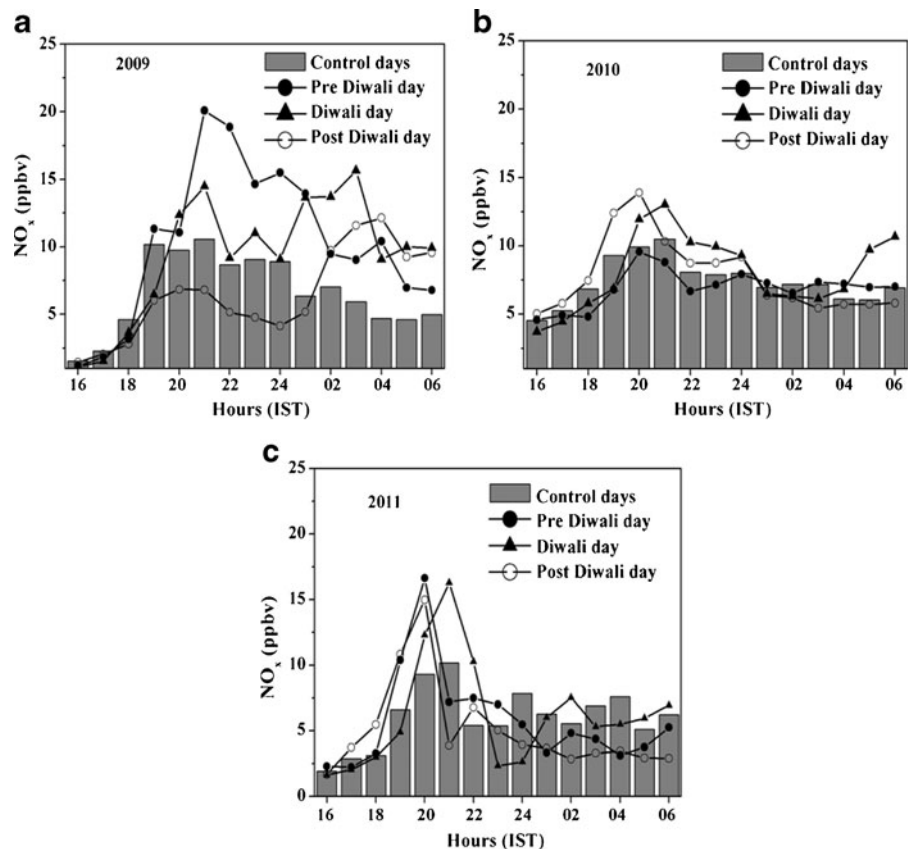
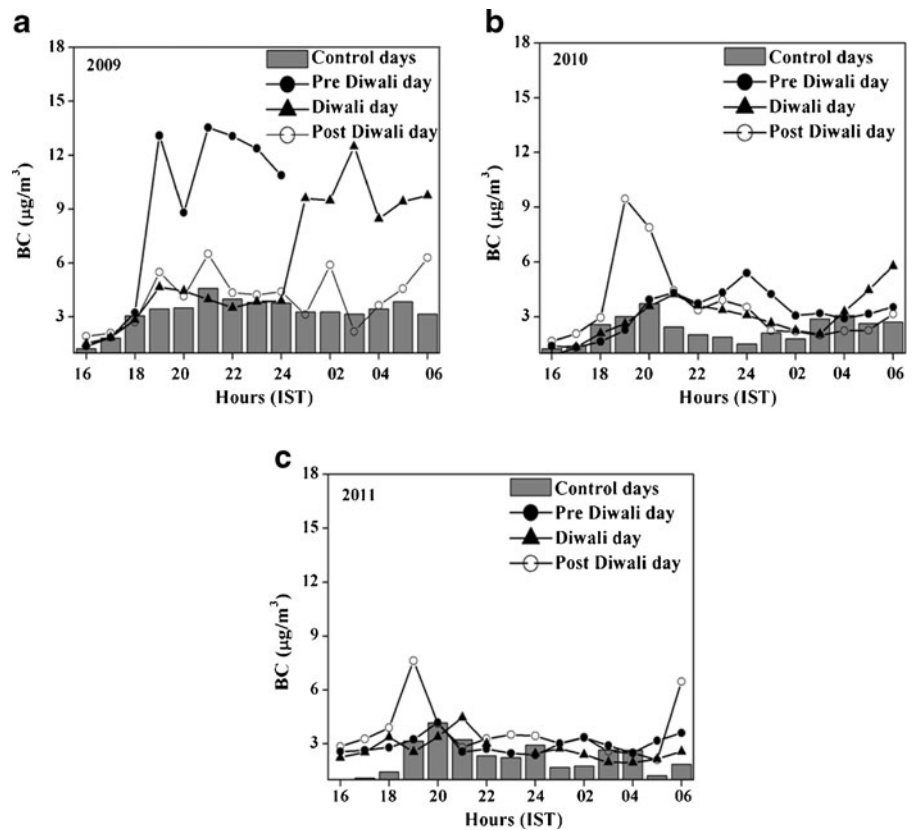


Fig. 3 Temporal variation of nighttime BC concentration on control, pre-Diwali, Diwali, and post-Diwali days during **a** 2009, **b** 2010, and **c** 2011



bursting activity. In contrast, BC concentration did not show an increasing trend during Diwali festivity periods in 2010 and 2011. The larger concentrations of BC aerosols during Diwali days is a direct consequence of the burning of fireworks over the urban region and surroundings, leaving a material of incomplete burning within the lower troposphere, which cannot be diluted at nighttime due to lower boundary layer. Babu and Moorthy (2001) also reported threefold to fourfold increase in BC concentration associated with extensive fireworks during the Diwali festival. Similarly, Vecchi et al. (2008) studied the physical and chemical properties of air pollutants emitted during the firecrackers burning episode in Milan, Italy and found that elemental carbon and organic carbon were major contributors of the particulate matter (PM) pollution.

Subsequently, Delta C values were calculated from $BC_{370\text{ nm}}$ and $BC_{880\text{ nm}}$ using the expression: $UVBC_{370\text{ nm}} - BC_{880\text{ nm}}$, in order to qualitatively indicate the anthropogenic emissions (Wang et al. 2011a, c, b). In general, UV absorption enhances at 370 nm relative to 880 nm and this enhanced absorption could serve as an indicator of combustion

particles (Wang et al. 2011a). Figure 4 shows the Delta C values in box charts during 2009–2011 on control, pre-Diwali, Diwali, and post-Diwali days. The daily averaged Delta C values are higher during the Diwali festivity days compared to control days, indicating wider variation towards higher values. The

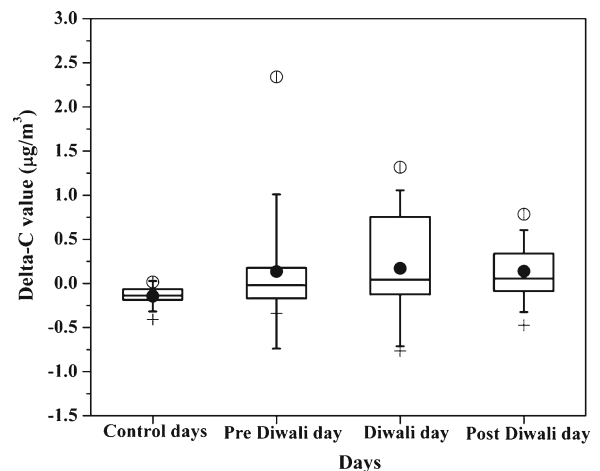


Fig. 4 Variation of Delta C values during 2009–2011 on control, pre-Diwali, Diwali, and post-Diwali days

elevated Delta C values observed during Diwali days suggested modification in the mixture of BC sources. Therefore, the positive values of Delta C observed during Diwali days denote the presence of smoke over the region (Wang et al. 2011a; b, c). On the other hand, Fig. 5 illustrates the MODIS-derived active fire locations confirming the absence of forest fires/biomass burning/wood burning in Hyderabad and surrounding regions during the Diwali period and, therefore, the rise in Delta C values during the festivity period was attributed to fireworks display rather than biomass burning over the region.

Sulfur dioxide (SO_2)

SO_2 is a major air pollutant with hazardous effect on human health. SO_2 is produced through diverse

activities, viz. fossil fuel combustion, volcanic eruption, and biomass burning. Temporal variation of nighttime SO_2 concentration is shown in Fig. 6 for control, pre-Diwali, Diwali, and post-Diwali days during the years (a) 2009, (b) 2010, and (c) 2011. The nighttime SO_2 concentrations were significantly increased during the Diwali festivity days compared to the control days. Furthermore, during the Diwali days of 2009 and 2010, the nocturnal SO_2 concentration increased up to 20 ppbv, while relatively low concentrations were observed in 2011. Figure 7 illustrates the correlation between measured NO_x and SO_2 concentrations during the Diwali period for the year 2010. A high correlation coefficient of $r^2=0.74$ between NO_x and SO_2 concentrations highlighted the probable origin of these pollutants from the same emission sources

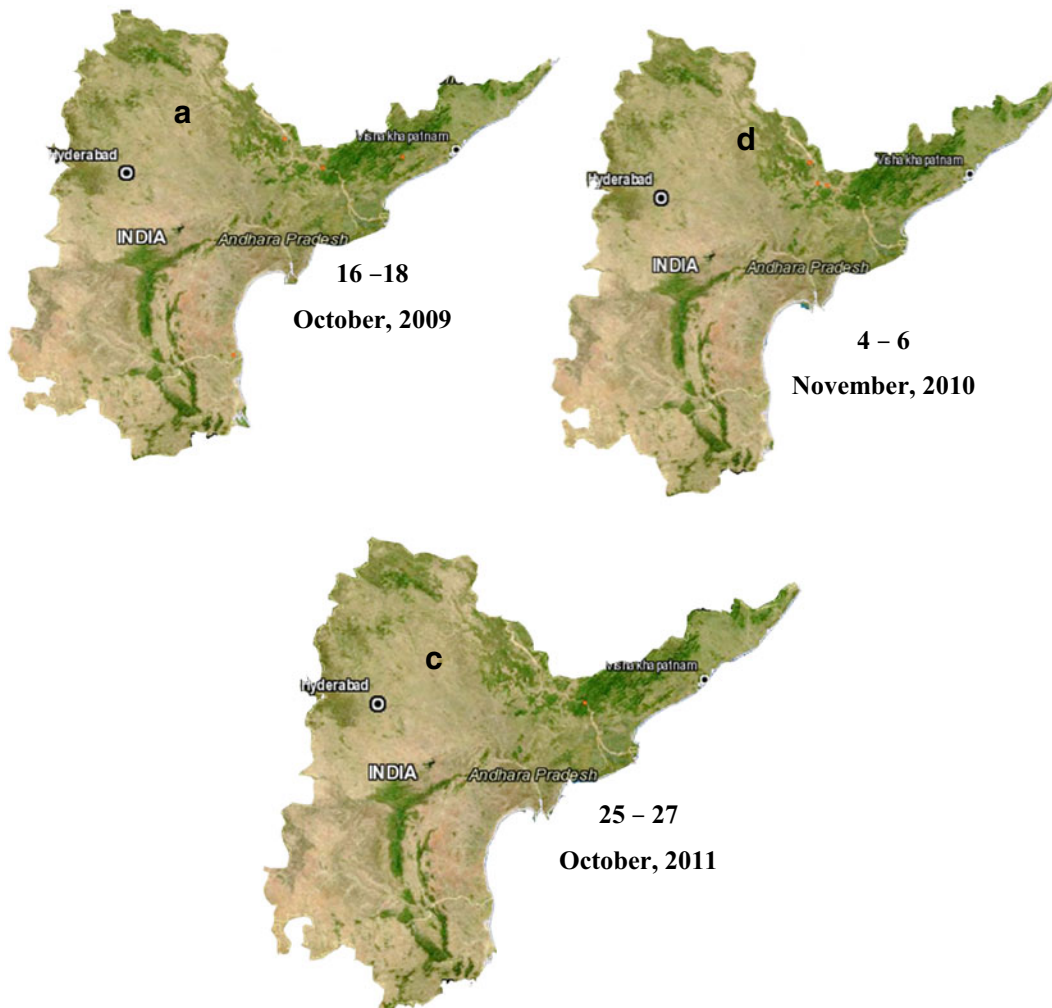
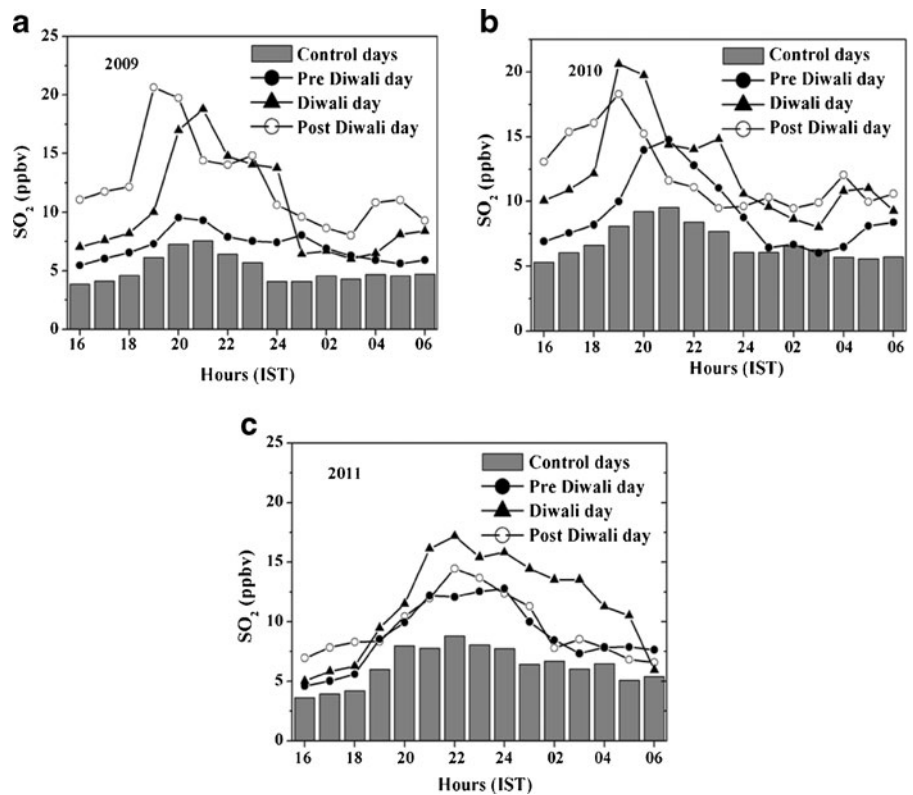


Fig. 5 MODIS active fire locations over the Indian region during **a** 16–18 October 2009, **b** 4–6 November 2010, and **c** 25–27 October 2011

Fig. 6 Temporal variation of nighttime SO₂ concentration on control, pre-Diwali, Diwali, and post-Diwali days during **a** 2009, **b** 2010, and **c** 2011



(Geng et al. 2009). Therefore, the high correlation between these two pollutants (NO_x and SO₂) is mostly attributed to the fireworks emissions during festivity celebrations.

The ratio of concentrations of SO₂ to NO_x (RSN = S / N index) is used to determine the source of pollutant emissions. The S/N index is generally independent

of meteorological conditions (Tasdemir et al. 2005) and helps in describing source origin contribution on air pollution. The daily S/N ratio was calculated during Diwali days (4–6 November) for the year 2010 (Fig. 8). Nirel and Dayan (2001) suggested that the very low values of the S/N ratio below 0.48 were associated with high traffic density. The daily average of the S/N index varied from 0.70 (control day) to 2.76

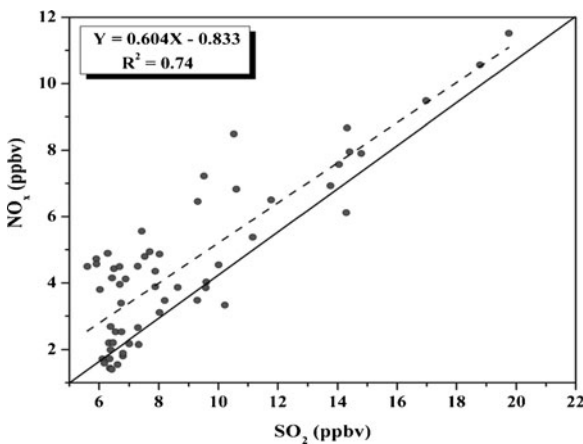


Fig. 7 Scatter plot between NO_x vs SO₂ on pre-Diwali, Diwali, and post-Diwali days during November 2010

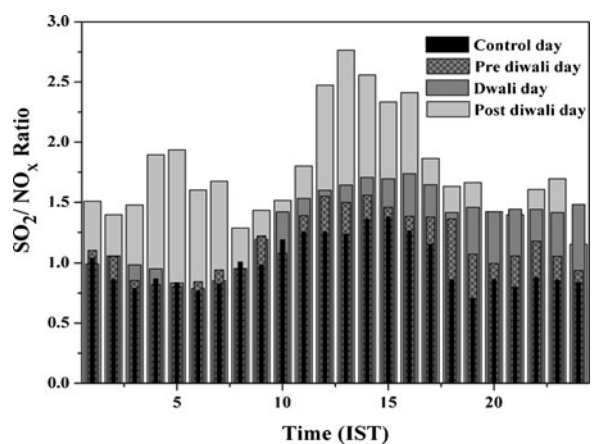


Fig. 8 Variation of SO₂/NO_x ratio on pre-Diwali, Diwali, and post-Diwali days during November 2010

(post-Diwali day). Relatively high values of the S/N ratio during the Diwali period compared to control days confirmed the presence of firework emissions. Further, the S/N ratio higher than 0.48 suggested the point sources of anthropogenic emission containing high amounts of sulfur (Nirel and Dayan 2001; Aneja et al. 2001; Goyal and Sidhartha 2003) over the region. Singh et al. (2010) reported that the daily average concentration of SO_2 before Diwali varied from 6 to $18 \mu\text{g m}^{-3}$, which increased dramatically (29 to $75 \mu\text{g m}^{-3}$) during Diwali day.

Average nighttime variation of air pollutants

Averaged nighttime variations of O_3 , NO_x , and BC concentrations on control, pre-Diwali, Diwali, and post-Diwali days during 2009–2011 are shown in Fig. 9a–c. The vertical bars express 1 standard deviation from the mean. The results indicate increased concentrations of all air pollutants (O_3 , NO_x , and BC) during the festivity period attributed to firecrackers burning. A net increase of 62.5, 57, and 133 % in 2009, 4, 15, and

50 % in 2010, and 37, 17, and 25 % in 2011 has been observed for O_3 , NO_x , and BC, respectively, on the Diwali day when compared to the control day. However, the significant finding is that the averaged concentration of the previously mentioned pollutants remained high even after the Diwali festival, suggesting that atmospheric cleansing after burning of firecrackers needs more than 1 day. This fact highlights the significant contribution of the additional pollutant emissions during festival days in India that further deteriorates the urban air quality. The significant variations of the pollutant observed during different years are strongly linked with the local meteorological conditions, i.e., average mixing layer height, temperature inversions, WS, and WD, convection activities, and how close the measuring site is to extensive firecrackers burning. The analysis reveal that O_3 , NO_2 , and BC concentrations increased significantly the day before Diwali and reached the maximum concentration on the day of the festival. A recent study by Nishanth et al. (2012) also reported an increase in atmospheric pollutant levels attributed to firecrackers burning episodes during the

Fig. 9 Average variation of nighttime **a** O_3 , **b** NO_x , and **c** BC on control, pre-Diwali, Diwali, and post-Diwali days during 2009, 2010, and 2011

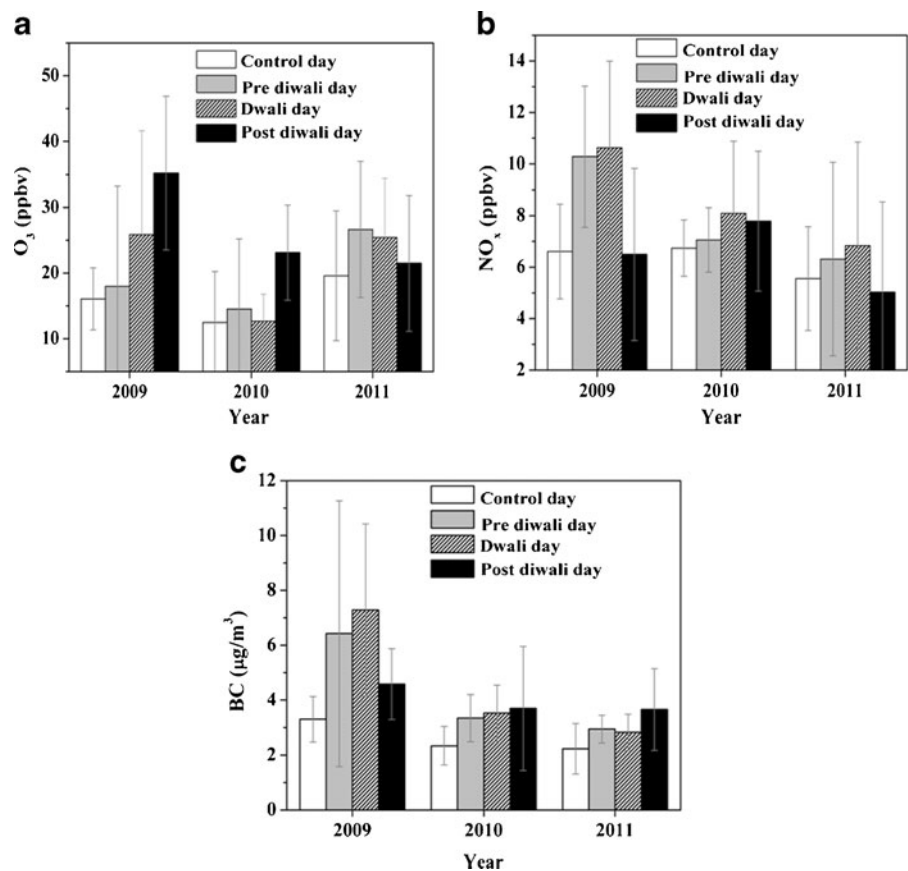
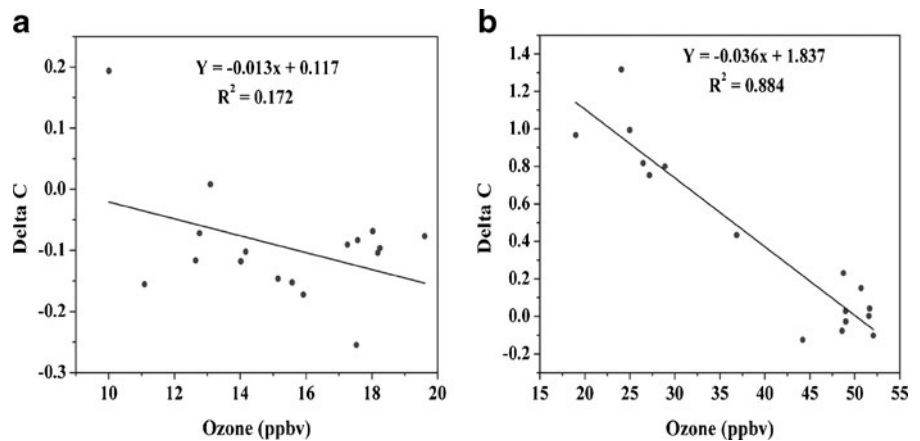


Fig. 10 Scatter plot between O₃ (in parts per billion by volume) and Delta C (in micrograms per cubic meter) on **a** control days and **b** Diwali days



Diwali festivity period. Additionally, Singh et al. (2010) showed that the diurnal variation of TSP, PM₁₀, SO₂, and NO₂ concentrations exhibited a slight increase during nighttime on the Diwali festivity period over Delhi, which seems to be associated with increased firework events during the night. However, the lower values of these pollutants in the daytime during the Diwali day might be attributed to decreased vehicular traffic on account of the public holiday and also there was no contribution from fireworks.

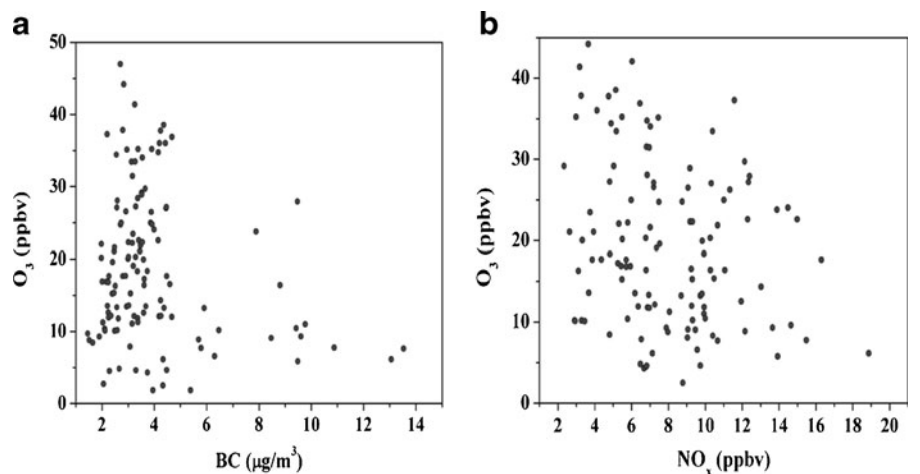
Correlation analysis

Scatter plot between O₃ concentrations and Delta C values separated for (a) control days and (b) festivity period is shown in Fig. 10a and b. In general, O₃ and Delta C are inversely correlated for both the cases with the coefficient of determination $r^2 = -0.172$ and -0.884 for control days and festivity period, respectively (Fig. 10a and b). Obviously, both O₃ and Delta

C values are very different during Diwali days, expressing a more intense negative correlation. This indicates the enhanced presence of smoke aerosols (high Delta C values) associated with lower tropospheric O₃.

The relationship of O₃ and BC PM for the Diwali festivity period during 2009–2011 is presented in Fig. 11a. Generally, O₃ shows a negative correlation with BC characterized by a poor coefficient of determination. However, during the Diwali festival, metals are predominantly found in the particle load and carbon concentration remains in lower mass ratios, as described by Agrawal et al. (2011). More specifically, they performed scanning electron microscopy energy-dispersive X-ray spectroscopy analysis for morphological characterization of aerosol diameters and shape correction factors and found that carbon concentration in the sample of Diwali day was ~25.07 % of the total particle load, while higher concentration of metals leads to lower mass ratios of BC. Figure 11b represents the

Fig. 11 Scatter plot between **a** BC (in micrograms per cubic meter) and O₃ (in parts per billion by volume) and **b** NO_x (in parts per billion by volume) and O₃ (in parts per billion by volume) for Diwali festivity period during 2009–2011



relationship of O_3 concentrations as a function of concentration of NO_x for the Diwali period during 2009–2011. In highly polluted conditions, O_3 – NO_x represents negative slopes with poor correlation coefficients (Lal et

al. 2008); however, there seems to be no relationship between O_3 and NO_x , suggesting that photochemical production was not a source of O_3 during the festivity period.

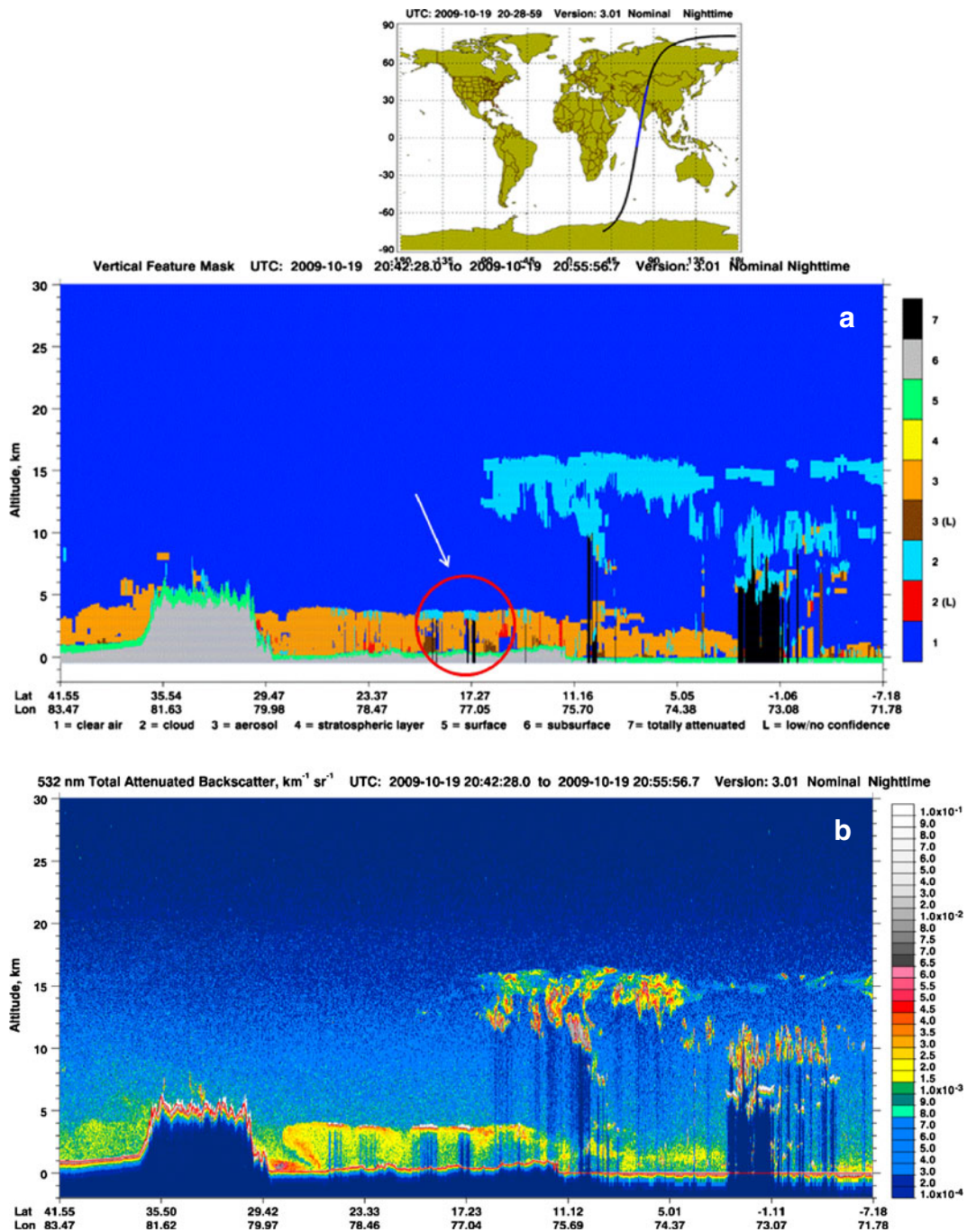


Fig. 12 **a** VFM, **b** attenuated total backscatter profiles (in kilometers per steradian) at 532 nm, **c** ACR, and **d** aerosol subtyping plot showing six aerosol types on 19 October 2009 over India, obtained from CALIPSO observations

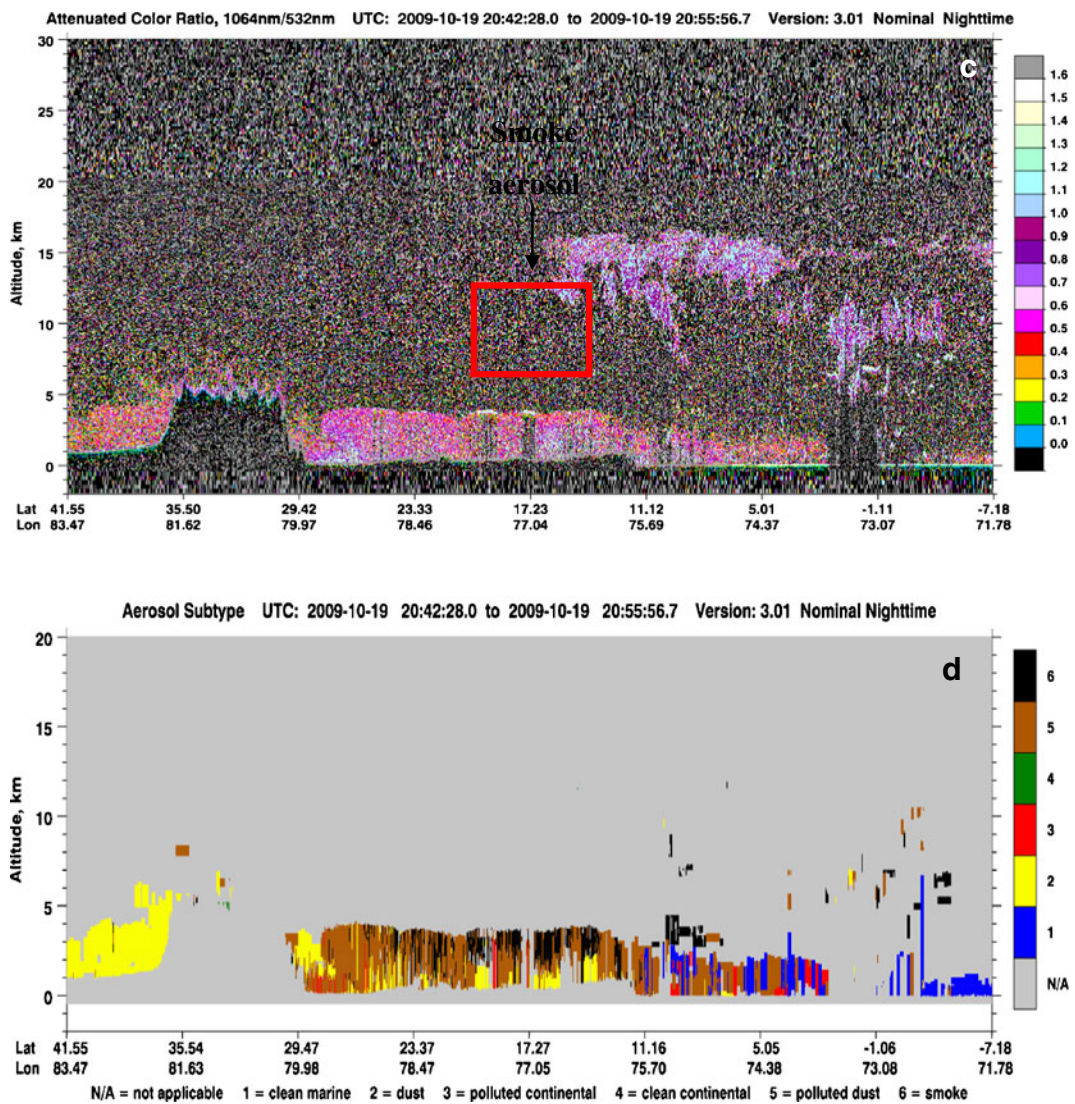


Fig. 12 (continued)

Satellite data analysis

In the present study, CALIPSO Lidar observations are used to identify the vertical distribution of fireworks emissions during the Diwali period. Figure 12a–d shows the CALIPSO overpass trajectory (moving southwards) for nighttime conditions accompanied with (a) VFM which highlights the signals into seven categories, (b) the profile of TAB at 532 nm covering the central part of India and urban Hyderabad on 19 October 2009, and (c) aerosol subtype image as obtained from the CALIPSO observations of several parameters (Guleria et al. 2011). The hours of the

nighttime overpass are shown in the upper x-axis of the figure, while the information for the coordinates of the overpass (longitude and latitude) is given at the lower x-axis of the figure. The nighttime CALIPSO overpass was at 2042 to 2055 hours Coordinated Universal Time (UTC), mainly covering parts of central India and the surroundings of Hyderabad (around 17.27° N, 77.05° E, circle shown in the VFM image). The VFM image (Fig. 12a) reveals a strong vertical structure of aerosol layers at the altitude of 2–4 km over the urban region of Hyderabad. A thick aerosol layer that intermingled with scanty clouds is observed over the whole Indian subcontinent southern of the

Himalayan slopes. The TAB image (Fig. 12b) shows an extended thick aerosol layer ($1.5\text{--}4\text{ km}^{-1}\text{sr}^{-1}$) covering most of the satellite track extending up to $\sim 4\text{ km}$. CALIPSO also provides estimation of the backscatter Angstrom exponent between 532 and 1,064 nm named ACR (Fig. 12c), which provides information on the size and shape of aerosol particles (Liu et al. 2008). The ACR values over Hyderabad and surroundings were found to be in the range of 0–1.5, suggesting the presence of anthropogenic and smoke aerosols (Liu et al. 2008), attributed to fireworks emissions/smoke aerosols. This is also verified from Fig. 12d which shows the vertically resolved aerosol subtype map (Omar et al. 2009). According to this analysis, the aerosol type over Hyderabad and surroundings is a mixture of polluted dust (mainly at the lower altitudes) with smoke aerosols at the upper levels. The detection of smoke aerosols from CALIPSO profiles indicates the significant influence of the road fires and the fire-crackers burning during Diwali festivals in India as

well as their significant contribution to the enhancement of the aerosol load and the deterioration of air quality over the urban areas.

MODIS images have proven its greater importance in monitoring natural calamities, such as forest fires, cyclones, dust storms, volcanoes, etc., over the globe. Figure 5a–c shows the composite of MODIS active fire locations over Andhra Pradesh, India, corresponding to the Diwali festivity period during (a) 16–18 October 2009, (b) 4–6 November 2010, and (c) 24–26 October 2011, respectively. It can be highlighted from the figure that, during the Diwali festivity period, minimal or no fires existed over the region, suggesting towards air quality degradation due to fireworks episodes over the region.

Air mass back trajectory analysis

The possible transport pathways of atmospheric constituents of trace gases and atmospheric aerosols are often examined by Lagrangian-based particle trajectory models

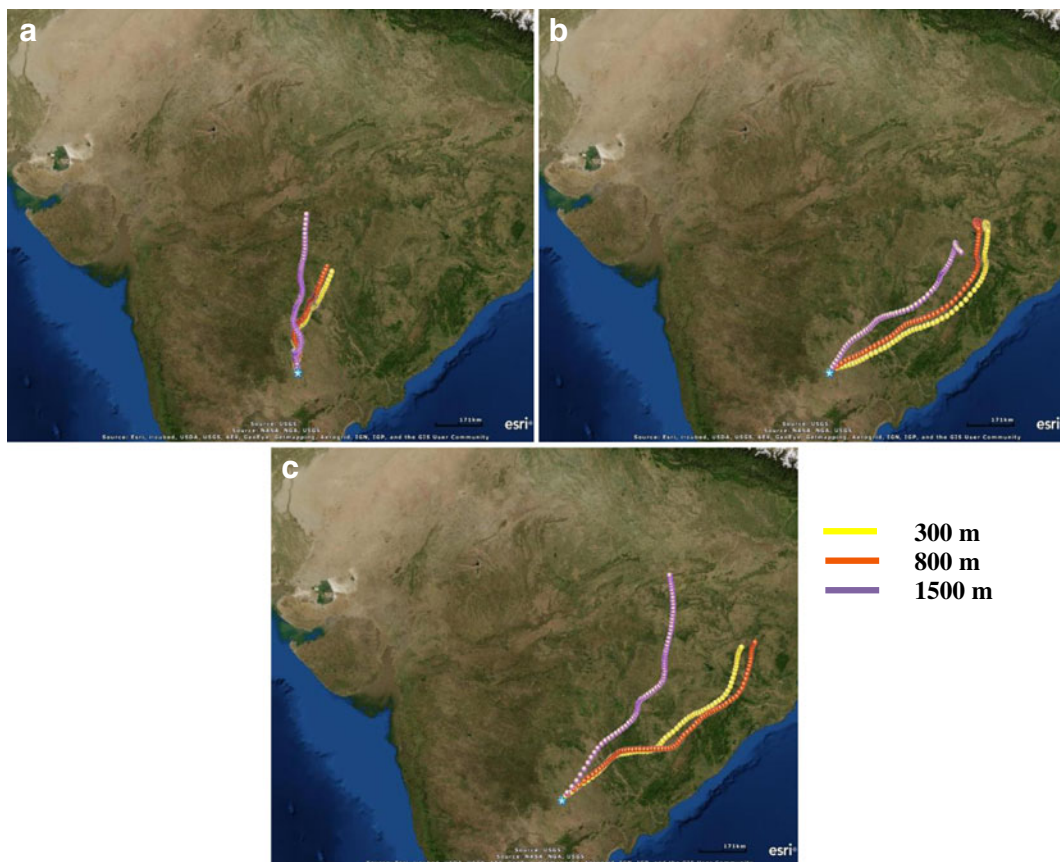


Fig. 13 NOAA-HYSPLIT 3 days wind back trajectories at 1800 UTC ending above the urban region of Hyderabad on **a** 17 October 2009, **b** 5 November 2010, and **c** 26 October 2011

(White et al. 2006). These back trajectories are primarily calculated from the observed wind and pressure fields. These have been often used as the basis for O₃ climatologists. In the present study, back trajectories are calculated using the Air Resources Laboratory's HYSPLIT model (v4.8) (<http://www.arl.noaa.gov/ready/hysplit4.htm>) (Draxler and Rolph 2003). NOAA-HYSPLIT wind back trajectory were computed hourly for 72 h (3 days) such that the trajectory terminated at TIFR-NBF, Hyderabad at 1800 hours to commensurate with the atmospheric observations at different elevations, i.e., 300 m (red), 800 m (blue), and 1,500 m (green) above ground level. Figure 13 shows the NOAA-HYSPLIT wind back trajectories on Diwali days, i.e., (a) 17 October 2009, (b) 5 November 2010, and (c) 26 October 2011. A close examination of these trajectories demonstrated that all the air masses have their origin over the north of the study site. However, as noticed from Fig. 13, there were no forest fires/biomass burning present north of the study region; hence, the increase in atmospheric pollutants were attributed to the Diwali fireworks episode.

Conclusions

The present study investigates the influence of Diwali fireworks episodes on urban air quality of Hyderabad for 2009–2011. The enhanced NO_x concentration in the presence of visible radiation due to firecrackers burning during the Diwali festivity period favored nighttime production of O₃ even in the absence of photochemical reactions. The O₃ concentration showed an average increase of 57 %. NO_x and BC concentration also followed twofold to threefold increases on Diwali day compared to control days. Furthermore, the S/N index also assisted in identifying the source appointment of harmful anthropogenic emissions containing higher quantity of sulfur from firecracker burning during the festivity period. The total attenuated aerosol backscatter from CALIPSO confirmed the extended thick aerosol layer up to ~4 km, mainly consisting of smoke aerosols emitted from firecrackers burning over the region.

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