Large inter annual variation in air quality during the annual festival ‘Diwali’ in an Indian megacity

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ABSTRACT

A network of air quality and weather monitoring stations was established under the System of Air Quality Forecasting and Research (SAFAR) project in Delhi. We report observations of ozone (O3), nitrogen oxides (NOx), carbon monoxide (CO) and particulate matter (PM2.5 and PM10) before, during and after the Diwali in two consecutive years, i.e., November 2010 and October 2011. The Diwali days are characterised by large firework displays throughout India. The observations show that the background concentrations of particulate matter are between 5 and 10 times the permissible limits in Europe and the United States. During the Diwali-2010, the highest observed PM10 and PM2.5 mass concentration is as high as 2070 µg/m3 and 1620 µg/m3, respectively (24 hr mean), which was about 20 and 27 times to National Ambient Air Quality Standards (NAAQS). For Diwali-2011, the increase in PM10 and PM2.5 mass concentrations was much less with their peaks of 600 and of 390 µg/m3 respectively, as compared to the background concentrations. Contrary to previous reports, firework display was not found to strongly influence the NOx, and O3 mixing ratios, with the increase within the observed variability in the background. CO mixing ratios showed an increase. We show that the large difference in 2010 and 2011 pollutant concentrations is controlled by weather parameters.

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Introduction

The World Health Organization (WHO) and the World Bank have reported in Indian megacity, Delhi, as the second most polluted megacity in the world with respect to particulate pollution (World Bank, 2004). The high levels of pollutants are mainly due to its large population and economical growth. Delhi and its National Capital Region (NCR) are India’s largest and the world’s second largest agglomeration with a population of about 22.2 million in 2011. The city of Delhi itself is the seventh most populated metropolis in the world. Delhi has a population density of 11,297 km−2 and a decadal population growth rate of 20.96%, one of the highest in the world (Census of India, 2011). This rapid urbanization and related industrialization have caused an increase in the number of vehicles, industrial units and power plants in the Delhi and NCR over the last two decades. More than 400,000–450,000 private and commercial vehicles are annually added to Delhi and NCR, which had more than 1.74 million total vehicles in 2011 (www.delhi.gov.in).

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Diwali is an Indian festival celebrated in October or November every year with huge firework displays across the India over 5 days, with the main event falling on the third day. In the past, several studies have reported an increase in trace gas and particle pollutions during the Diwali period in Delhi, Lucknow, Hisar and Howrah (Barman et al., 2009; CPCB, 2010; Ganguly, 2009; Perrino et al., 2011; Ravindra et al., 2003; Thakur et al., 2010; Kulshrestha et al., 2004; Singh et al., 2010). Jiang et al. (2014) also observed that significant and short-term impacts on fine particles (PM2.5) due to firework display on the days of Lunar New Year, Lunar Fifth Day, and Lantern Festival in 2013. However, all studies in the literature are limited by a coarse geographical or temporal resolution.

Fireworks used during the festival typically consist of paper tubes filled with organic, non-metallic and metallic elements (charcoal, sulphur, silicon, boron, aluminium, magnesium titanium), oxidizing agents (nitrate, chlorates), reducing agents (sulphur, charcoal), colouring agents (strontium or lithium, copper, barium, sodium, iron or charcoal) and a binder (dextrin) (Schwartz et al., 1996; Drewnick et al., 2006; Vecchi et al., 2008). Large scale fireworks cause emission of various pollutants including sulphur and charcoal compounds, trace gases, traces metals and particulate matter (Ravindra et al., 2003; Kulshrestha et al., 2004; Wang et al., 2007; Perrino et al., 2011).

In this study, we report the observations of trace gases and particulate matter in the Delhi and NCR during the Diwali festival in 2010 and 2011. This work expands on the previous studies by reporting the first high geographical resolution observations using a large air quality monitoring network within Delhi and NCR enabling increased understanding on the distribution of the pollutants resulting from firework displays.

1. Site Description and Measurements

Delhi and NCR are situated, on an average, at a height of 216 m above mean sea level and covers ~1483 km² of industrial area including the suburban towns of Gurgaon, Faridabad, Noida and Ghaziabad. The System of Air quality Forecasting and Research (SAFAR) programme, a network of air quality monitoring stations (AQMSs) and automatic weather station (AWS), was setup in and around the NCR (http://safar.tropmet.res.in/) in 2010. This project was initiated...
by Ministry of Earth Sciences (MoES). The World Meteorological Organisation’s (WMO) Global Atmosphere Watch Urban Research Meteorology and Environment (GURME) project has since recommended the SAFAR project as a pilot project for Indian and the Asian regions, underlining its importance. The simultaneous measurements of ozone (O₃), nitrogen dioxide (NO₂), carbon monoxide (CO) and particulate matter (PM), along with meteorological parameters from 14 stations were made, thus enabling investigations into the temporal and geographical variation of each pollutant and their impact on human health during the Diwali festival. The geographical distribution of the stations is shown in Fig. 1, with more details about their names and locations are in Table 1. It should be noted that all the stations were not continuously used, with more locations operational in 2010 as compared to those in 2011.

Each AQMS comprised of commercially available analyzers housed inside walkway shelters. Ozone was measured with a photometric Ozone UV analyzer (Thermo-49i, Thermo Scientific, USA, precision ~0.4 ppbV). Calibration of the O₃ analyzer was done on every alternate day using an inbuilt O₃ calibrator, photometric Ozone UV analyzer (Thermo-49i, Thermo Scientific, USA) housed inside walkway shelters. Ozone was measured with a carbon aethalometer (Model AE31, Magee Scientific Corporation, USA). The particulate matter was measured using Beta Met-One analyzers (BAM1020, Met One Instruments, Inc., USA) which have a detection limit of 1 μg/m³ and an inbuilt calibration unit. Meteorological parameters, i.e., global radiation, wind speed, wind direction, temperature, relative humidity, pressure and rainfall were recorded with the AWS at every station. All the instruments used at the AQMS sites are US Environmental Protection Agency approved. The raw data was collected at a resolution of 5 min at the sites and then binned at 1 hr intervals after a quality check for further analysis and comparisons. Correlation analyses between observed data in different stations are presented in Table 2. Although there are large differences between the sites because of their location either close to or further from busy traffic roads, all the sites show a similar trend for the O₃, CO, NO₂, BC and O₃ between IITM-D (Indian Institute of Tropical Meteorology, Delhi), MDNS (Major Dhyanchand National Stadium) and DU (Delhi University) sites respectively (Beig et al., 2013).

### Table 1 – Details of the AQMS and AWS measurement sites in Delhi during the Diwali periods in 2010 and 2011.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sites in Delhi</th>
<th>Abbreviation</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Commonwealth Games Village</td>
<td>CG-V</td>
<td>28.60 77.27</td>
</tr>
<tr>
<td>2</td>
<td>Central Road Research Institute</td>
<td>CRRI</td>
<td>28.55 77.28</td>
</tr>
<tr>
<td>3</td>
<td>Sir C. V. Raman Industrial Training Institute, Dheerpur</td>
<td>CVR</td>
<td>28.73 77.20</td>
</tr>
<tr>
<td>4</td>
<td>Directorate of Training and Technical Education, Pitampura</td>
<td>DTTE</td>
<td>28.70 77.16</td>
</tr>
<tr>
<td>5</td>
<td>Delhi University</td>
<td>DU</td>
<td>28.69 77.21</td>
</tr>
<tr>
<td>6</td>
<td>Guru Teg Bahadur Hospital</td>
<td>GTB-H</td>
<td>28.68 77.31</td>
</tr>
<tr>
<td>7</td>
<td>Indira Gandhi International Airport</td>
<td>IGI-A</td>
<td>28.56 77.09</td>
</tr>
<tr>
<td>8</td>
<td>Indian Institute of Tropical Meteorology, Delhi</td>
<td>IITM-D</td>
<td>28.64 77.17</td>
</tr>
<tr>
<td>9</td>
<td>Indian Meteorological Department — Ayanagar</td>
<td>IMD-A</td>
<td>28.48 77.13</td>
</tr>
<tr>
<td>10</td>
<td>Indian Meteorological Department — Lodhi Road</td>
<td>IMD-LD</td>
<td>28.59 77.24</td>
</tr>
<tr>
<td>11</td>
<td>Major Dhyanchand National Stadium</td>
<td>MDNS</td>
<td>28.61 77.23</td>
</tr>
<tr>
<td>12</td>
<td>National Mineral Development Corporation</td>
<td>NMDC</td>
<td>28.62 77.19</td>
</tr>
<tr>
<td>13</td>
<td>National Centre for Medium Range Weather Forecasting, Noida</td>
<td>NOIDA</td>
<td>28.63 77.36</td>
</tr>
<tr>
<td>14</td>
<td>Tyagaraj Sports Complex</td>
<td>TSC</td>
<td>28.57 77.21</td>
</tr>
</tbody>
</table>

AQMSs: air quality monitoring stations; AWS: automatic weather station.

### Table 2 – Correlation coefficients between observed data in different stations.

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Correlation coefficients with respect to CG-V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Institutional (DU)</td>
</tr>
<tr>
<td>PM₁₀</td>
<td>0.8983</td>
</tr>
<tr>
<td>PM₂·₅</td>
<td>0.9062</td>
</tr>
<tr>
<td>NO₂</td>
<td>0.7490</td>
</tr>
<tr>
<td>CO</td>
<td>0.6693</td>
</tr>
<tr>
<td>O₃</td>
<td>0.9146</td>
</tr>
</tbody>
</table>

2. Results and Discussion

Figs. 2 and 3 show the observed variations in trace gas mixing ratios and PM₂·₅ and PM₁₀ mass concentrations at all the measurement sites. It should be noted that in 2011, most of the sites were not operational due to relocation of some stations from the sport campuses in Delhi after the CWG-2010 games. However, stations at DU had continuous data over both the periods and hence were used for a direct comparison...
between the 2 years. To quantify the effect of the additional emissions during the Diwali period, we divide the observations into three periods: (a) before the Diwali festival, (b) during the Diwali festival and (c) after the Diwali festival. These periods are marked with vertical dashed lines in Figs. 2 and 3 for direct comparison.

2.1. Trace gases

Variations in the running mean mixing ratios of NO\textsubscript{x} (24-hr mean), O\textsubscript{3} and CO (8-hr mean) for all the stations are shown in Fig. 2. The averaging period for individual pollutant was chosen to enable a direct comparison with the National Ambient Air Quality Standards (NAAQS). All the stations showed a similar variation, albeit differences were noted in their absolute concentrations. For example, the NO\textsubscript{x} mixing ratios were highest at MDNS, contributed mainly by vehicular activity considering the diurnal profile showing morning and evening traffic peaks and the proximity to some of the busiest road in Delhi, while they were at the lowest at Noida and TSC (Tyagaraj Sports Complex), a site located near vegetated areas or further outskirts of Delhi from strong NO\textsubscript{x} sources.

The NO\textsubscript{x} mixing ratios did not show any significant increase during the Diwali festival with the variations similar to before and after the festival. The highest NO\textsubscript{x} levels were in fact found before the Diwali-2010. During Diwali-2011, the NO\textsubscript{x} levels were consistently lower than those during Diwali-2010 and equal to Diwali-2010 with less increase during the Diwali festival. This result is contrary to previous reports of a strong increase in NO\textsubscript{x} during the Diwali festival (Ganguly, 2009; Singh et al., 2010).

In both, Diwali-2010 and Diwali-2011, the CO mixing ratios before the Diwali period were significantly (<5 and 2 ppmV, respectively) than during or after Diwali (5–10 and 2–5 ppmV, respectively) (Fig. 2). The mixing ratios started increasing at the beginning of Diwali period and continued this trend till the end of the observational period. Over the general increasing trend, on the main Diwali day itself (5th November 2010 and 26th October 2011), a small increase is noticed. This increase is expected due to increased emissions during the
Diwali period, and is indicative of emissions due to fireworks with a similar trend reported in previous studies (Perrino et al., 2011; Ravindra et al., 2003). However, the increase is not large compared to the long-term signal during both the years 2010 and 2011.

The mean O3 mixing ratios before and during the Diwali period were high (>50 ppb) but not enhanced by fireworks as can be seen from Fig. 2. O3 concentrations were higher at MDNS compared to most sites, similar to the NOx observations. However, in contrast to NOx, the TSC site also showed similar levels of O3 as MDNS, which can be attributed to biogenic hydrocarbon emissions from surrounding forests enhancing the production of O3 in the presence of NOx at TSC (Thakur et al., 2010; Singh et al., 2010).

### 2.2. Particulate Matter

Fig. 3 shows the variation in the daily mean PM2.5 and PM10 mass concentrations at all the sites. Small variation in the mass concentrations can be seen even before the Diwali festival during both 2010 and 2011, but most of the time the concentrations are below 400 μg/m³ for PM10 and below 250 μg/m³ for PM2.5. However, from the start of the Diwali festival, it can be seen that both PM10 and PM2.5 started increasing during both years and at the end of the festival reducing back to the background levels. A large increase in PM10 and PM2.5 was seen for Diwali-2010 on the day of the main festival when the peak mass concentrations reached to as high as 2070 and 1620 μg/m³ respectively at the DU site. After the peak, the concentrations gradually decreased to the pre-Diwali concentrations after 9th November 2010. On average, the PM10 and PM2.5 mass concentrations increased by a factor of about 4 and 7, respectively, as compared to before and after the Diwali periods. In Diwali-2010, the rate of increase in concentration was low at the beginning of festival, and the strongest increase was seen on the main festival day. Interestingly, even the ‘background levels’ for the particulate matter are about five times the guidelines recommended by WHO, European and United States environmental agencies (WHO, 2008; US Environmental Protection Agency, 2004).
Diwali-2011, although the background particulate matter concentrations were at a similar level, a large increase on main festival day was not seen. A direct comparison of the Diwali-2010 and Diwali-2011, PM$_{2.5}$ and PM$_{10}$ mass concentrations is shown in Fig. 4. The reason for a lack of an increase in the Diwali-2011, particulate matter concentrations can be attributed to the meteorological conditions. We ran the Weather Research and Forecasting (WRF) model as a part of the SAFAR project. The results show that the estimated boundary mixing layer depth was about 200 m in 2010 but more than 600 m in 2011 during the Diwali festival. The AWS wind observations also show calm conditions in Diwali-2010, leading to a trapping of the increased emissions during Diwali. In Diwali-2011, enhanced mixing layer height allowed better mixing leading to faster dispersal of pollutants and hence lower mass concentrations even though the emissions were probably similar.

In Diwali-2010, it was seen that the variations in PM$_{10}$ and PM$_{2.5}$ were nearly same but their concentrations, particularly of PM$_{2.5}$, differed from one site to another. For example, the maximum PM$_{2.5}$ on main festival day was seen at DU (~1535 μg/m$^3$), while at IGI-A (Indira Gandhi International Airport) it was much lower (519 μg/m$^3$). The maximum PM$_{10}$ mass concentration also occurred at DU followed by those at TSC, CG-V (Commonwealth Games Village), TS (Talkatora Stadium) and IGI-A. Such a significant spatial variability in the concentration of PM$_{10}$ and PM$_{2.5}$ within a short distance of 10–12 km (i.e., between IGI-A and DU sites) could have been resulted from the combined effect of local anthropogenic activity and prevailing meteorology. It should be noted that at DU, the site is surrounded by residential areas with a large population. This could result in more firework displays, compared to IGI-A, which is a tourist place located in the city centre with a smaller number of people living there. Fig. 5 shows the geographical distribution of PM$_{10}$ and PM$_{2.5}$ before, during and after the Diwali festival. It can be seen that there was a large increase in the mass concentration during the Diwali period but also the increase was much large in some
restricted areas. Overall contributions of fireworks to the total PM10 and PM2.5 calculated by subtracting their background concentrations were about 780% and 1268% respectively. The north and south of the city, which are dominated by residential areas, are affected by a larger increase than the urban centre. Fig. 5 shows smaller increases in urban centre stations MDNS, NMDS (National Mineral Development Corporation) and CG-V stations as compared to DU and TSC stations located to the north and south of Delhi urban centre. It should be noted that the absence of stations either east or west on the urban centre reduces the accuracy of the extrapolation in those directions. The distribution, highlighted by the fact that some regions show almost three times more particulate matter than others, also underlines the importance of using a network of emission inventories for studying the impact of firework displays on the population, rather than single point observations that have been used in the past which can be misrepresentative for a large portion of the population. The geographical distribution in Diwali-2011 was not possible due to the lack of continuous data at most sites due to shifting work of some stations.

### 2.3. Diurnal variations of particulates matter and trace gases

Fig. 6 shows the means of concentrations of O3, CO, NOx, PM2.5 and PM10 over the study period (27th October to 14th November, 2010) on diurnal time scale at CG-V, DU, MDNS, IGI-A, and TSC sites in Delhi. CG-V.

![Diurnal variations of particulates matter and trace gases at CG-V, DU, MDNS, IGI-A, and TSC sites in Delhi. CG-V.](image)

**3. Conclusion**

Observations of trace gases and particulate matter were made in Delhi, India before, during and after the Diwali period in 2010 and 2011. Levels of particulate matters generally remain near or just above the NAAQS threshold level for the “very unhealthy” category in the Delhi-NCR for most of the observation period, but during the 2010 Diwali festival their mass concentrations increased significantly, well above this threshold. The major reason for this large increase is the widespread firework displays which are characteristic of the Diwali festival. Significant spatial variability in the
concentration of PM$_{10}$ and PM$_{2.5}$ within a short distance of 10–12 km was observed, which is most probably due to the local anthropogenic activity. In 2011, such a large increase was not seen, which can be attributed to the local meteorological conditions.

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