Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 68 (2021) 3327–3341

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Analysis of air pollution in the atmosphere due to firecrackers in the Diwali period over an urban Indian region

Vineet Pratap [a], Upal Saha [b], Akhilesh Kumar [a], Abhay K. Singh [a,c,*]

[a] Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221005, India
[b] National Centre for Medium Range Weather Forecasting, Ministry of Earth Sciences, Noida, India
[c] DST - Mahamana Centre of Excellence in Climate Change Research, Banaras Hindu University, Varanasi 221005, India

Received 5 December 2020; received in revised form 21 May 2021; accepted 17 June 2021
Available online 24 June 2021

Abstract

Short-term investigations of atmospheric pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, and CO) were performed during the Diwali festival over Varanasi for a period of six years from 2011 to 2016. Aerosol Optical Depth (AOD) observed for the corresponding days of Diwali was found to be considerably much higher and even its value reached 2.0 for some Diwali years, which is basically almost 3-folds than the control days. The total scattering aerosol optical thickness as well as aerosol extinction co-efficient at 550 nm crossed the value of 1.0 in almost all the Diwali day cases. The associated meteorological conditions (low wind speed, declining temperature, lowered night-time boundary layer height, etc.) during the Diwali period leads to the detrimental accumulation of atmospheric pollutants near to the surface layer in Varanasi region. Moreover, PM_{10} and $PM_{2.5}$ concentrations were recorded much higher than the safer limits set by NAAQS for 24-hour mean values throughout the period of study. The concentrations of PM_{10} and $PM_{2.5}$ crossed beyond the safer limits and crossed 500 $\mu g/m^3$ (in 2015) and 450 $\mu g/m^3$ (in 2016) respectively, which is basically 5–6 times higher than the standard NAAQS limit. In comparison with the trace gases concentrations (e.g. SO_2, NO_2, O_3, and CO) on control day, it was observed higher on the respective Diwali day. Satellite data derived from MODIS (Aqua and Terra) have also been taken into account to observe and verify the unpropitious effects of fireworks for the chosen case. MODIS true-color images show dense smoke plumes and haze over the entire Indo-Gangetic Plain (IGP) on Diwali days of 2011–2016 with its continuation in the following days. Proper assessment and regular monitoring is needed in order to mitigate the localized air pollution due to this kind of festival by the local scale authority to the top-level environmentalists.

Keywords: Atmospheric pollutants; MODIS; AOD; Indo-Gangetic Plain; PM_{10} and $PM_{2.5}$

1. Introduction

The whole world is currently facing remarkable challenges in terms of the debasement of air quality due to a substantial rise in anthropogenic emissions associated with rapid industrialization, motorization, urbanization, and lack of proper awareness of air health (Fallahi et al., 2018; Tzanis et al., 2019). Air quality in megacities and other major population centers is a serious concern due to their high pollutant concentrations and health hazards

Abbreviations: AMSL, Above Mean Sea Level; AOD, Aerosol Optical Depth; AOT, Aerosol Optical Thickness; AVHRR, Advanced Very High Resolution Radiometer; BHU, Banaras Hindu University; CPCB, Central Pollution Control Board; CO, Carbon monoxide; DB, Deep Blue; GEOS, Goddard Earth Observing System; GOES, Geostationary Operational Environmental Satellite; IGB, Indo-Gangetic Basin; IGP, Indo-Gangetic Plain; IMD, India Meteorological Department; LT, Local Time; MERRA, Modern-Era Retrospective analysis for Research and Applications; MODIS, Moderate Resolution Imaging Spectroradiometer; NAAQS, National Ambient Air Quality Standards; NO_2, Nitrogen dioxide; O_3, Ozone; $PM_{2.5}$, Particulate Matter at 2.5 μm; PM_{10}, Particulate Matter at 10 μm; $PM_{1.0}$, Particulate Matter at 1.0 μm; SeaWiFS, Sea-viewing Wide Field-of-view Sensor; SO_2, Sulphur dioxide

* Corresponding author at: Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221005, India.
E-mail address: singhak@bhu.ac.in (A.K. Singh).

https://doi.org/10.1016/j.asr.2021.06.031
0273-1177/

(Gurjar et al., 2010; Upadhyay et al., 2018). Increasing population density and rapid economic growth have also inevitably resulted in high air pollutant emission levels in India (Ray and Ray, 2011; (Gurjar et al., 2016). In recent times, short-term air quality degradation episodes are drawing increased attention of the scientific community and have become a great topic of debate at all levels (Pope and Dockery, 2006; Nastos et al., 2010; Singh et al., 2010; Thakur et al., 2010; Samoli et al., 2011; Bapna et al., 2013; Bhuyan et al., 2014; Saha et al., 2014). Fireworks are extensively used worldwide to celebrate different festivals, like Diwali Festival in India (Saha et al., 2014; Sateesh et al., 2018, etc.), Lass Fallas in Spain (Moreno et al., 2007), Lantern festival in Beijing (Wang et al., 2007) and New Year celebrations in United States (Tanda et al., 2019) and Netherlands (Greven et al., 2019). The extensive uses of fire-crackers as well as sparklers during these festivals have been reported to be significant sources of anthropogenic aerosols all over the world (Mandal et al., 1997; Drewnick et al., 2006; Vecchi et al., 2008; Wang et al., 2007; Nishanth et al., 2012; Vyas and Saraswat, 2012; Cheng et al., 2014). Diwali festival falls in October/November and involves extensive burning of firecrackers in India causing a major concern for the environment. Atmospheric pollutants such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matters (PM_{10} and $PM_{2.5}$) and several other metals like aluminum, manganese, and cadmium, etc, are released in significant quantity associated with serious health hazards due to fireworks (Ravindra et al., 2003; Kulshrestha et al.,2004; Wang et al., 2007; Pachauri et al., 2013; Pathak et al., 2015; Pratap et al., 2019). Large amount of fire-sparklers and fire-crackers are used by individuals from night to late-night hours for the most part on the Diwali day and the day preceding Diwali (pre–Diwali) and after Diwali (post–Diwali) as a part of the celebration. Attri et al. (2001) in a study over Delhi have reported that the formation of ground-level ozone takes place due to the burning of color emitting sparklers during the Diwali festival. Barman et al. (2008, 2009) in a similar study reported a remarkable increase in $PM_{2.5}$ concentration in Lucknow city about celebration-induced firework activities. In another urban metropolis, Kolkata, enhancement of the mass concentrations of PM_{10} and SO_2 have been reported which is ~ 5 times compared to prescribed standard limits at this site (Chatterjee et al., 2013). Global estimates of airborne particulates unanimously identify the Indo-Gangetic Plain (IGP) as amajor aerosol hotspot which, due to its unique regional geomorphology, meteorological variation, and climatic susceptibility, has been a subject for intensive researches in the last few years (Dey et al., 2004; Ramanathan and Feng, 2009; Ramachandran and Kedia, 2010; Saha et al., 2014; Sayer et al., 2014; Chakraborty et al., 2017; Sen et al., 2017; Pratap et al., 2020; Kumar et al., 2020). Under the background of a large increase in anthropogenic emissions during the festival period, haze pollution has also been a common problem over IGP with the degradation of visibility and air quality (Sateesh et al., 2018; Ojha et al., 2020). Chakraborty et al. (2017) have also confirmed that the formation of temperature inversion takes place due to an increase in atmospheric lapse rate that in turn causes inhibition of vertical convection and trapping of air pollutants close to the surface that may enhance the lifetime of those pollutants. Limited studies are done in short-term basis for a period of six years over the Varanasi region (an urban locality in the Indo-Gangetic plains) utilizing both instruments, in-situ as well as satellite observations during the Diwali festival indicating the meteorological reasons for the increase of atmospheric pollutants during this festival season. Thus, for the present analysis, efforts were made to investigate the short term impacts of event-specific bursting of firecrackers and pyrotechnic displays on the environment through concurrent measurements of both in-situ and satellite aerosol properties over the Indo-Gangetic Plain and more specifically over an urban location, Varanasi.

2. Data and methodology

2.1. Meteorology of the site

The study site Varanasi (25°28′ N and 82°97′ E; 82.2 m AMSL, Fig. 1) represents an urban environmental location over middle-Indo Gangetic Plain, characterized by multiple sources of aerosol mainly from road dust re-suspension, commercial activities, vehicular exhausts, and biomass/waste burning (Ram and Sarin 2011; Dey et al., 2012; Guttikunda and Calori, 2013; Banerjee et al., 2015). The region characteristically experiences a humid subtropical climate with distinct seasonal variations. Seasonal distinction over the study site includes extreme hot and dry summer (March to May, ~ 37–46 °C), intense rainfall during monsoon (June to September, ~ 80% of the annual rainfall occurs during monsoon), relatively hot and humid retreating monsoon (October to November, dense fog and haze becomes prominent in night/early morning hours) and extreme cold weather during winter (December to February, ~ 5–15 °C). The climate of the study area is usually affected by a wide range of synoptic weather phenomena along with relatively flat terrain, without having any specific localized effect of oceans, mountains, or any explicit emission source. The study focuses on the retreating monsoon season when Diwali festival used to occur with every pomp and glory in the Indian region. Figure S1 represents the variation in prevailing meteorological parameters i.e. relative humidity and temperature during the study period. In the figure data for two months, i.e. October and November for all the corresponding years (2011–2016) is shown. Figure S2 describe the hourly time series of wind speed over the location, Varanasi which indicates the wind speed to be much lower (~1–2 ms^{-1}) and is appearing to be standstill than any other windy days. Both Figure S1 and S2 clearly shows calm wind speed and declining temperature which is not favorable for the dispersion of atmospheric

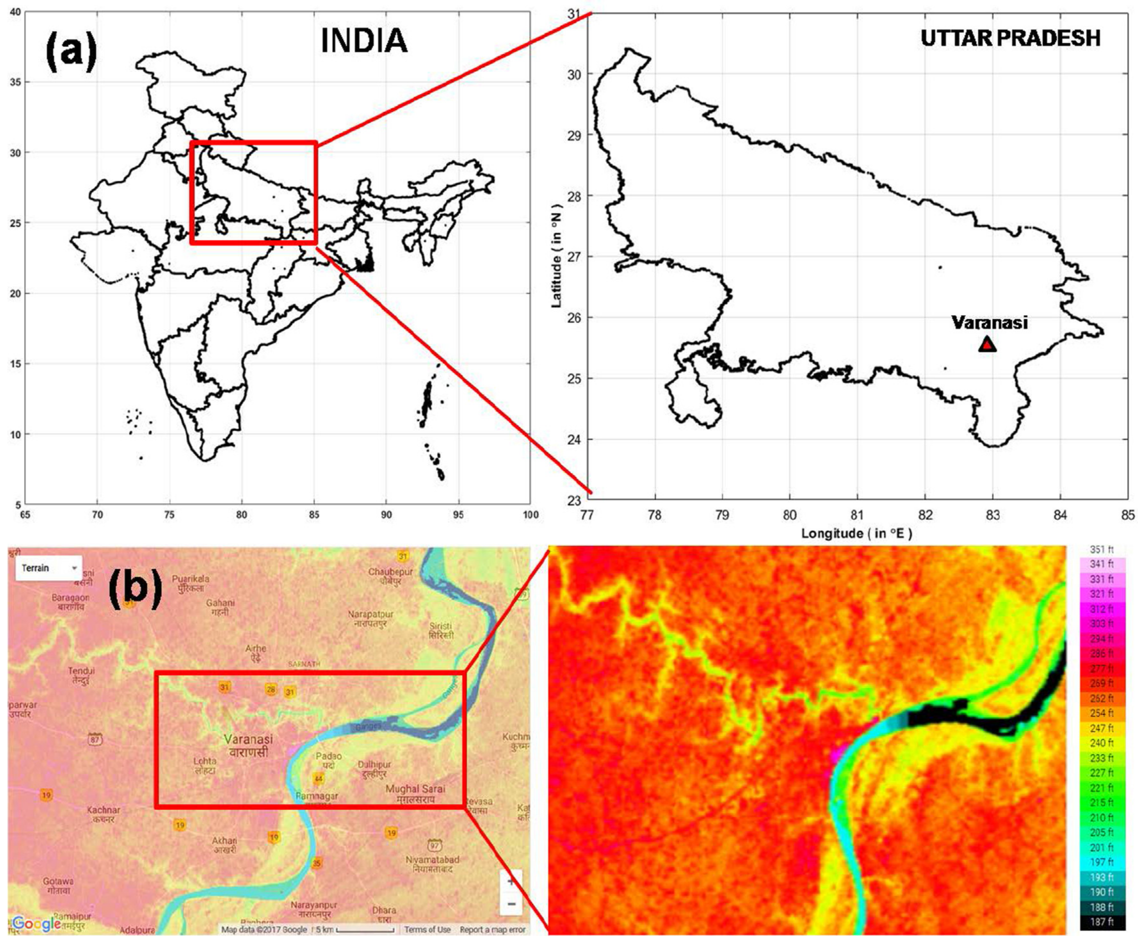

Fig. 1. (a) Political map of India, the zoomed portion in a square box is shown outside the map presenting the geographical location of Varanasi ($25^{\circ}32$ N., $82^{\circ}97$ E) showing the area of interest (red triangle) for the present study. (b) The terrain of the location, Varanasi, as obtained from Google Maps (website, https://maps.google.com), the zoomed portion in a square box represents the elevation (in feet) of the study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pollutants during the Diwali festival period which in turn makes the situation of the atmosphere worse. Not only that, the lower boundary layer in the night time will also help the air pollutants to get trapped near to the surface layer. Figure S3 indicates the hourly time series of boundary layer height, which clearly depicts that the boundary layer height falls below ~ 50 m in the night time. This is much favorable for the atmospheric pollutants to stack and remain trapped in the much below in the lower atmosphere.

2.2. Datasets, instrumentation, and methods used

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard the Terra (originally known as EOS/AM-1) and Aqua (originally known as EOS/PM-1) satellites. Daily data of MYD08_D3 v6 Aerosol Optical Depth (AOD) Deep Blue (DB) Land only product with $1^{\circ} \times 1^{\circ}$ grid spatial resolution has been retrieved from the MODIS Aqua Satellite. Deep Blue (DB) is a new MODIS retrieval algorithm, as proposed by Hsu et al. (2004, 2006) to retrieve aerosol properties over bright surfaces such as arid, semi-arid, and urban areas. The surface reflectance for aerosol retrieval is estimated for the 0.412-, 0.47-, and 0.65-μm channels based on a pre-calculated seasonal surface reflectance database created from the SeaWiFS surface reflectance products using the minimum synthesis technique (Hsu et al., 2013). Hourly time-averaged Dust Scattering AOT 550 nm - PM 1.0 μm with $0.625^{\circ} \times 0.5^{\circ}$ grid resolution has been taken from the second Modern-Era Retrospective analysis for Research and Applications (MERRA-2) reanalysis [MERRA-2 Model M2T1NXADG v5.12.4]. MERRA-2 isthe improved version of the original MERRA reanalysis (Rienecker et al., 2011) of the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. In our study, we have used the collection of true-color images of Earth, using data from NASA's MODIS flying aboard the Aqua satellites for the period of Diwali Festival. These spacecraft fly in a near-polar, sun-synchronous orbit at an altitude of 705 km. Descend and ascend of the Terra across the equator take place at 1030 LT and 1330 LT, respectively. Both satellites orbit Earth once every 98 min. MODIS measures the reflectance of visible wavelengths leaving the top of the atmosphere, centered at 645 nm (red), 555 nm (green), and 469 nm (blue) - MODIS bands 1, 4, and 3, respectively. Unlike its predecessor sensors (AVHRR and GOES) MODIS features a blue band, which allows for superior atmospheric correction and retrieval of surface reflectance values in each of the visible wavelengths with signal-to-noise ratios of 128 (red), 228 (green), and 243 (blue). The MODIS retrieved fire maps for the Diwali day were also used in the present study. Each of these fire maps accumulates the locations of the fires detected by MODIS onboard the Terra and Aqua satellites over a 10–day period. Each red-colored dot indicates a location where MODIS detected at leastone fire during the compositing period. Hourly data of u and v component of wind as well as boundary layer height is taken from ERA5 reanalysis during the corresponding Diwali festival period (four days prior and after the Diwali day to get a time series). Wind speed is calculated from the u- and v-components of wind using Climate Data Operator (CDO). The real-time archived data for atmospheric pollutant (NO_2, SO_2, CO, surface O_3, PM_{10}, and $PM_{2.5}$) concentrations over Varanasi during the Diwali festival for the period 2011–2016, were obtained from Central Pollution Control Board (CPCB), New Delhi and has been procured from the website: https://cpcb.nic.in/real-time-air-quality-data/. The one-hourly time-averaged Total Aerosol Scattering and Extinction co-efficient at 550 nm is obtained from MERRA-2 [Model M2T1NXAER v5.12.4] over the Varanasi region during 2011–2016 for the Diwali period. Meteorological parameters (temperature and relative humidity) are taken from local IMD station situated at the Department of Geophysics, BHU, Varanasi. The MICROTOPS-II sun-photometer is a portable handheld sun-photometer for direct solar irradiance measurement in different wavelengths of 440, 500, 675, 870, and 936 nm. The hourly data of Aerosol Optical Thickness at 500 nm had been taken during the Diwali festival period for the years 2011–2016 over Varanasi at our Department of Physics., Institute of Science, Banaras Hindu University, India.

3. Results and discussion

In the present work, characteristics of aerosol and variability of particulate matters during Diwali over Varanasi (India) for the years 2011 – 2016 have been studied. Table 1 gives a brief account of the chosen years of Diwali day, Pre-Diwali days, and Post-Diwali days used in the present analysis.

3.1. Spatial variation of aerosols and particulates during Diwali festival over the Indian region

Diwali is broadly rejoiced across India and perhaps liable for releasing a huge amount of particulates and associated pollutants into the atmosphere. For the current analysis, the spatial pattern of particulate origin and their subsequent evolution were initially examined. Mostly, similar spatial pattern with a regular rise in aerosol loading over the Indo-Gangetic Basin (IGB), particularly on Diwali days, for corresponding years was identified (Fig. 2). The figure depicts Aqua AOD (Deep Blue. Land only) at 550 nm over the Indian region during corresponding Diwali days for the years from 2011 to 2016. The entire nation exhibits a sudden upsurge of Diwali-day especially (2011–2016) AOD and PM concentrations throughout the Indo-Gangetic Plain including Varanasi (Fig. 3). Kumar et al. (2016) indicated the presence of coarse aerosols specifically dust (0.01–0.40) in most of the west and IGB region while parts of eastern and south-eastern India signify the presence of finer aerosols (0.61–1.00). Fig. 2 (a)-(f) delineates that the IGB region is governed by the higher urban aerosol loadings (AOD $>$ 1.0) during the respective festival days, when intense fireworks and crackers plunge abundant amount of aerosols in the Indian sub-continent. Singh et al. (2003) have stated enrichment of 5.7% and 5.5% for AOD at 340 nm and AOD at 500 nm, respectively, during Diwali at Kanpur city in IGB. Fig. 3 (a)-(f) also represents the increase in particulate loading over the Indo-Gangetic Plain during the corresponding Diwali festival days like AOD plots. The monotonous growth of AOD over the IGP region indicate the rise in background aerosol loading in these period due to the extensive use of firework displays, sparklers and fire-crackers which emit a lot of elemental as well as organic aerosol particles within the atmosphere. From both these figures, it can be suggested that particulate loading is increased at a much faster rate during the Diwali period which is an important consequence of the firework related activities in the Diwali festival season. The findings of Babu and Moorthy (2001) have also been corroborated with our

Table 1
Details of corresponding years of Diwali day, Pre-Diwali days, and Post-Diwali days for the present study.

Years	Pre-Diwali	Diwali	Post-Diwali
2011	21st-24th October	26th October	27th-30th October
2012	9th –12th November	13th November	14th-17th November
2013	30th October-2nd November	3rd November	4th-7th November
2014	19th –22nd October	23rd October	24th-27th October
2015	7th-10th November	11th November	12th-15th November
2016	26th –29th October	30th October	31st October – 3rd November

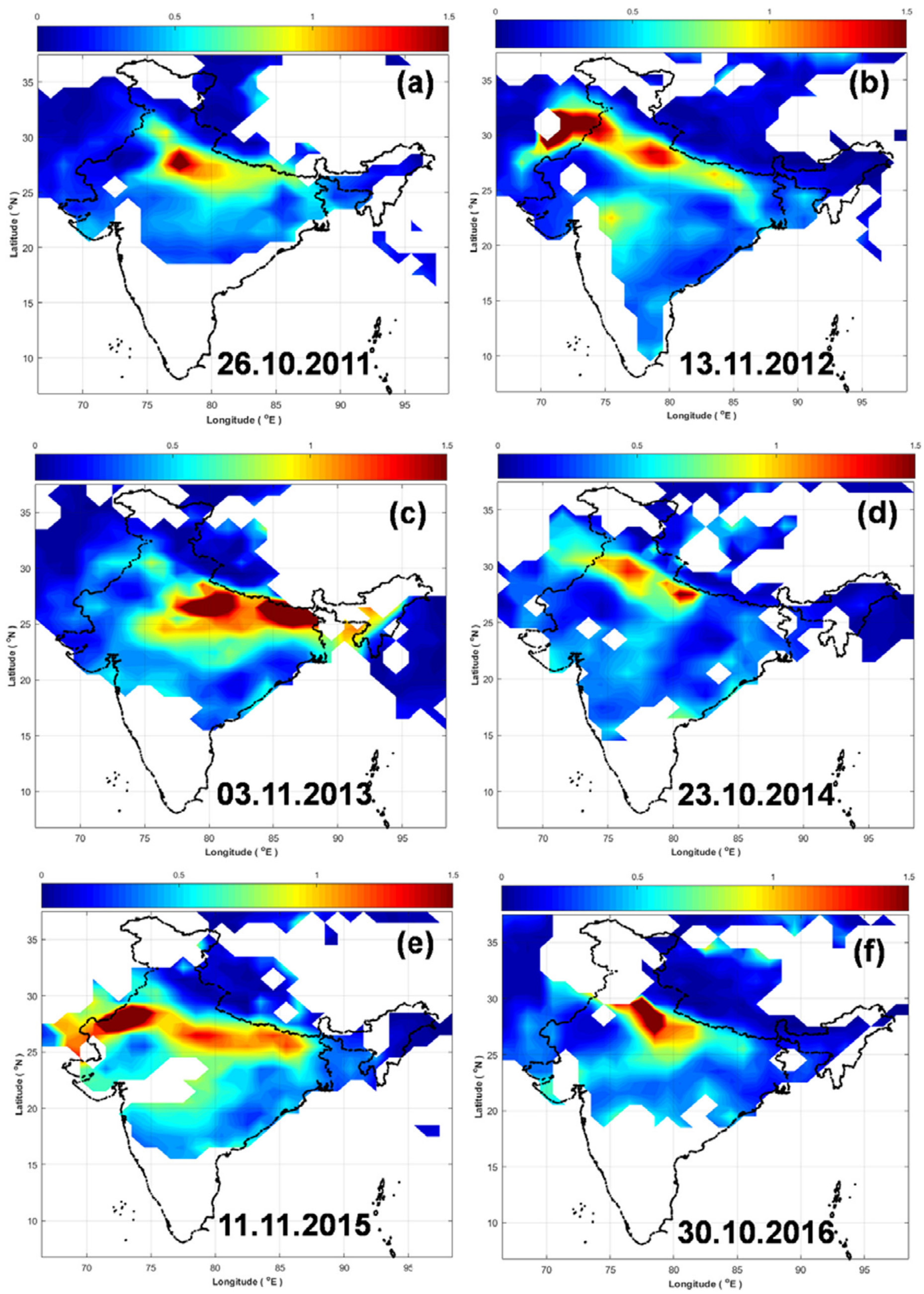

Fig. 2. Spatial distribution ofAqua AOD (Deep Blue, Land only) at 550 nm over the Indian region during corresponding Diwali days for (a) 26 October 2011, (b) 13 November 2012, (c) 3 November 2013, (d) 23 October 2014, (e) 11 November 2015, (f) 30 October 2016. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

study. They have also reported higher AODs during the Diwali event affirming the intensified presence of black and organic carbon released due to firecrackers used during Diwali pointing out that observed increase in the particulate concentration during the Diwali night is due to the suppression of boundary layer height in the pre-midnight hours of the corresponding festive days. In our case too, it has been obtained from Fig. 3 that particulate matters over IGP region during the festival period abnormally increases with a suppression in boundary layer height and calm wind speed (Figure S2 and S3).

3.2. Fate of surface aerosol loading during Diwali period in the mid-Indo Gangetic plains

AOD is often used as a proxy for pollutants in the atmosphere to accentuate the introduction of these pollutants in ambient air. Babuet al (2013) have done a long-term analysis of AOD and reported that AOD is increasing at a rate of ~ 3% per year due to increasing anthropogenic activities. Fig. 4 depicts the Aerosol Optical Depth (AOD) at 500 nm over Varanasi which clearly shows increased AOD on Diwali days for all the years and post Diwali days except

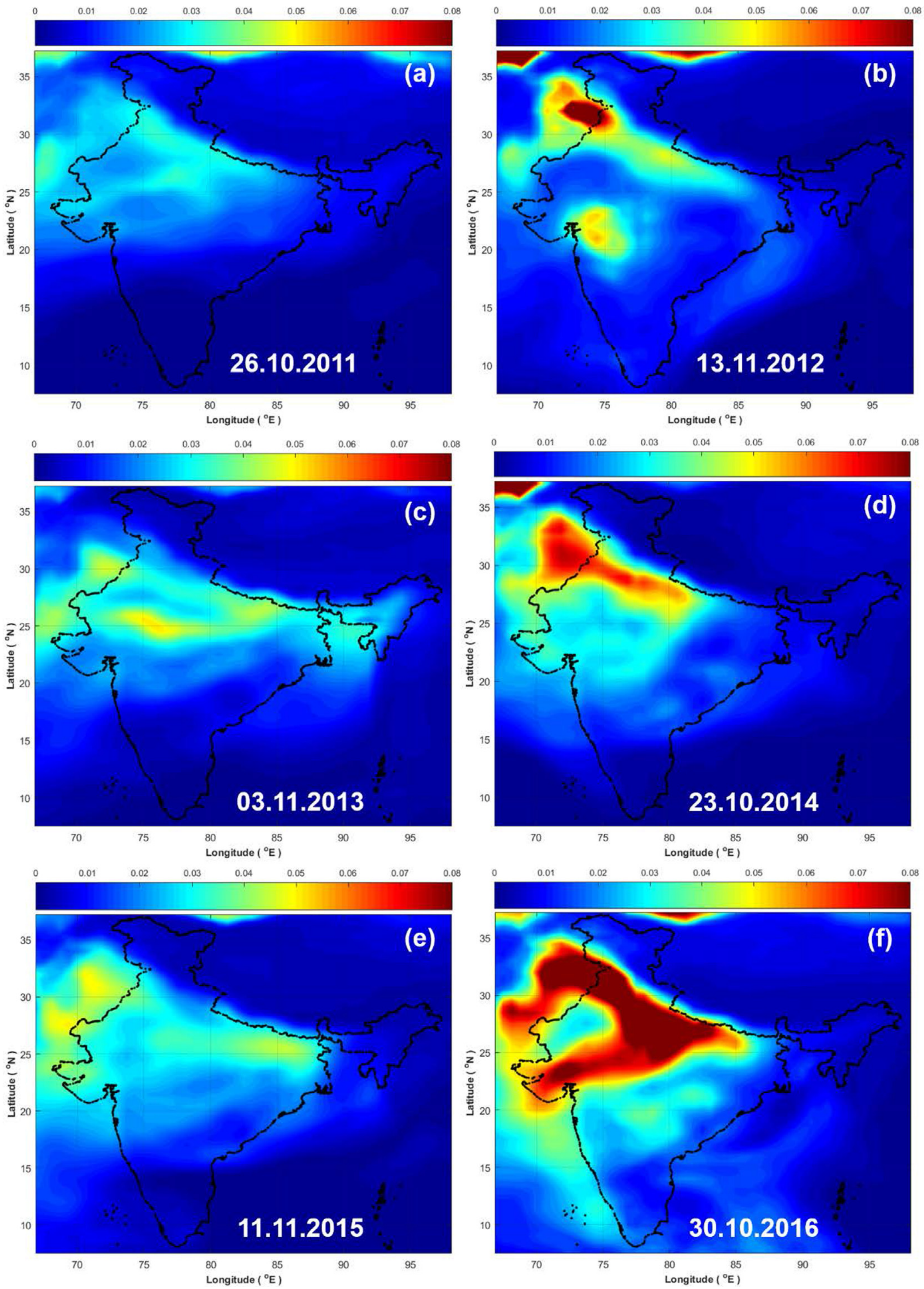

Fig. 3. Same as Fig. 2, but for Dust Scattering AOT 550 nm - PM 1.0 μm.

the year 2012 and 2013 in which they do not get enhanced after Diwali but they were found still high as compared to control days. During pre-Diwali days, AOT at 500 nm is found to be around 1.2 in 2011 which is lowered to ~ 0.8 in 2016, which indicates a declining trend in AOT distribution before Diwali. It may be noted that, on the Diwali day, AOT at 500 nm is found to be ~ 1.2 in 2011 which is further increased in the consecutive years and reached ~ 1.6 in 2016. Similar to the Diwali days, during post-Diwali days, the AOT is found to be ~1.3 and it gradually increases to ~1.8 in 2016, which indicate an increasing trend of aerosol loading in the atmosphere due to this festival. This may also be attributed to massive fireworks made during Diwali events and also the atmospheric boundary layer remains

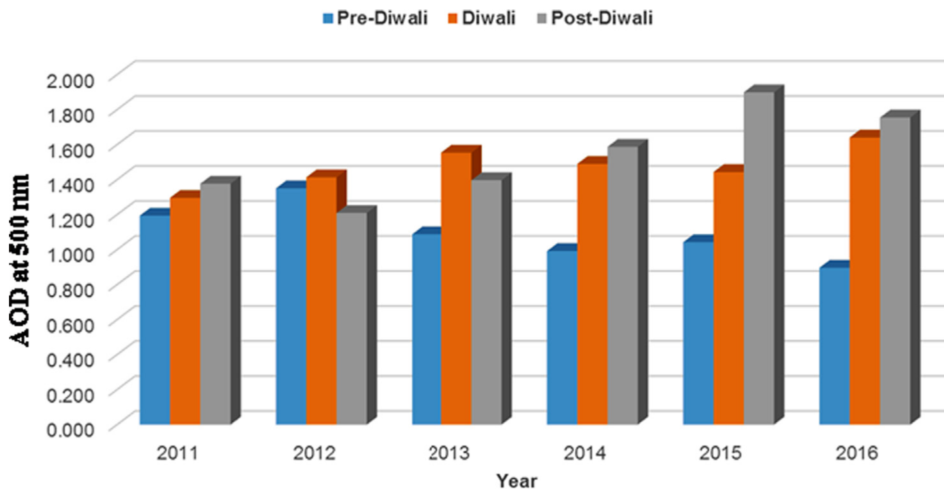

Fig. 4. Aerosol Optical Thickness at 500 nm obtained from Microtops-II Sunphotometer during pre-Diwali, Diwali, and post-Diwali days from 2011 to 2016 over Varanasi.

low in this season as compared to other seasons which further leads to the formation of an inversion layer that prohibits particulate vertical mixing (Banerjee et al., 2011a, b). Thus lower boundary layer (Figure S3) and less ventilation coefficient is a common feature of this season prompt trapping of particulates in the atmosphere as a consequence of which AOD increases during the event period. The reason for non-exceedance of AOD at 500 nm over Varanasi may be due to some local light rainfall activity occurred after the Diwali and the pollutants gets flashed off due to it. Saha et al (2014) have done similar studies on metropolitan city Kolkata during the period 2012 and 2013 and reported similar increasing trends in the behavior of AOD during this festival supporting the fact that crackers are key polluters of surroundings during this festival. Singh et al (2014) performed an extensive campaign over Varanasi during the Diwali period of the year 2005 to investigate the behavior of aerosol and reported enhanced aerosol loading during this week long event, in his study he has also mentioned the dominance of fine mode particles due to excessive burning of crackers. Several studies have been carried out to report enhanced AOD over Varanasi and other urban areas during the Diwali festival (Pratap et al., 2017; Tiwari et al., 2012; Kumar et al., 2016).

Fig. 5 (a)-(f) shows the time series of the area-averaged Total Aerosol Scattering AOT at 550 nm during pre-Diwali, Diwali, and post-Diwali days for the period of 2011–2016 over Varanasi. From this figure, it can be easily observed that in the year 2011 total aerosol scattering value is highest for the Diwali day (26th October), and then gradually starts decreasing on post-Diwali days. However, it attains the highest value two days before Diwali, which may be attributed to vehicular emissions as well. In the year 2013, it shows the highest on the next day of Diwali and then a decreasing trend. An almost similar trend is observed for the rest of the years which may be explained as a result of extensive use of firecrackers during this event which in turn injects a large number of trace gases and pollutants into the atmosphere and further degrades the surroundings. Figure S4 (a)-(f) shows the time series of the area-averaged Total Aerosol Extinction AOT at 550 nm during pre-Diwali, Diwali, and post-Diwali days for the period of 2011–2016 over Varanasi. This figure shows a similar pattern as we have observed in the case of total aerosol scattering (Fig. 5). In some Diwali seasons, like for 2012, one may see the peak of aerosol scattering AOT at 550 nm is seen in 10–11 November, while Diwali day is on 13 November. This may be attributed to the vehicular emissions (as mentioned earlier) as well as some meteorological disturbances (e.g. stagnant wind speed before Diwali due to the formation of some lows in this season, which is particularly rare). And in some cases, one may find the peak of aerosol scattering AOT as well as extinction AOT at 550 nm one or two-days after Diwali day, which may be due to extended burning of fire-crackers after Diwali, which lead to an increase in aerosol loading even at higher rate than Diwali days. Hence, the peak in the figure got suppressed due to higher values in post-Diwali days.

3.3. Variability of surface atmospheric pollutants during Diwali period over Varanasi

It is interesting to note that almost all surface monitoring stations exhibited an increase in fine particulates loading particularly on Diwali day or day following Diwali. Ravindra et al. (2003) in their research have revealed that firecrackers comprise 75% potassium nitrate, 15% carbon (C), and 10% sulfur (S). When Potassium nitrate is burnt with Carbon and Sulphur, it results in the emission of gases such as CO_2 and N_2 into the atmosphere, which when reacts with atmospheric vapor to produce SO_2 and NO_2. SO_2 is supposed to be more toxic as it gradually gets absorbed in fine particulates and gets accumulated in the lungs (Ambade and Ghosh, 2013). NO_2 is considered as a lung irritant, long exposure to this pollutant causes lung

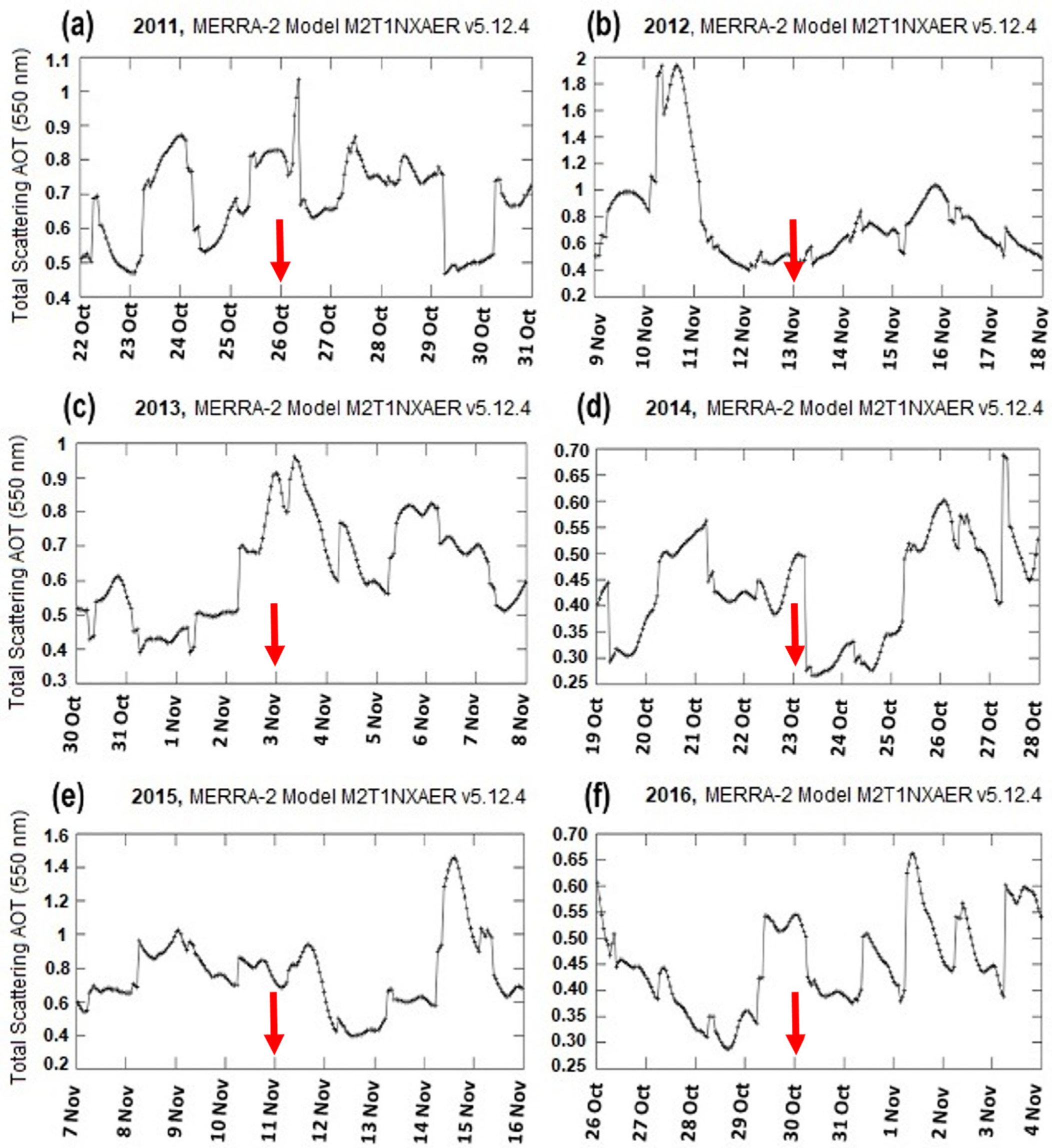

Fig. 5. Time series plots of the area-averaged Total Aerosol Scattering AOT at 550 nm during pre-Diwali, Diwali and post-Diwali days: (a) 22–31 October 2011, (b) 9–18 November 2012, (c) 30 October-8 November 2013, (d) 19–28 October 2014, (e) 7–16 November 2015 and (f) 26 October-4 November 2016 over Varanasi.

damage to residing people in the city (Dockery et al., 1993). The concentrations of NO_2 and SO_2 during Diwali for all the years are given in Fig. 6(a) and (b). Since Diwali celebration commences 2–4 days earlier of the festival day and continues for 2–4 days post-Diwali event, increased concentration of these pollutants is observed starting from pre-Diwali days and reaches its maximum on the event day and continues to be high even a few days later of this event. However, the concentrations of both NO_2 and SO_2 were found to be under the permissible limits (80 $\mu g/m^3$) as stated by NAAQS (National Ambient Air Quality Standard) but were found to be still high as compared to control days. This is attributed to the massive burning of firecrackers during the Diwali event as the emission of trace gases is associated with these fireworks. Moreover, during this festival, the emission of black carbon further leads to the formation of dense clouds which causes lower visibility (Ravindra et al., 2003; Yerramsetti et al., 2013; Saha et al., 2014). The situation remains the same for 2–3 days after Diwali and then these oxides start decreasing. Barman et al. (2008) have done similar studies for NO_2 and SO_2 and reported an increment of 2.27 and 2.82 times higher than their respective day time level over Lucknow city. Fig. 6(c) and (d) depicts a variation of Ozone (O_3) and Carbon monoxide (CO) during Diwali event for the years 2011–2016. The highest concentration of CO was observed in 2015, the concentration of CO reaches 4 mg/m^3 on the next day of Diwali which is two times greater than the permissible limit (2 mg/m^3) as stated by NAAQS. Then, after 2–4 days, CO concentration starts dwindling, however other years also witnessed the increased concentration of CO on Diwali and post-Diwali days as compared

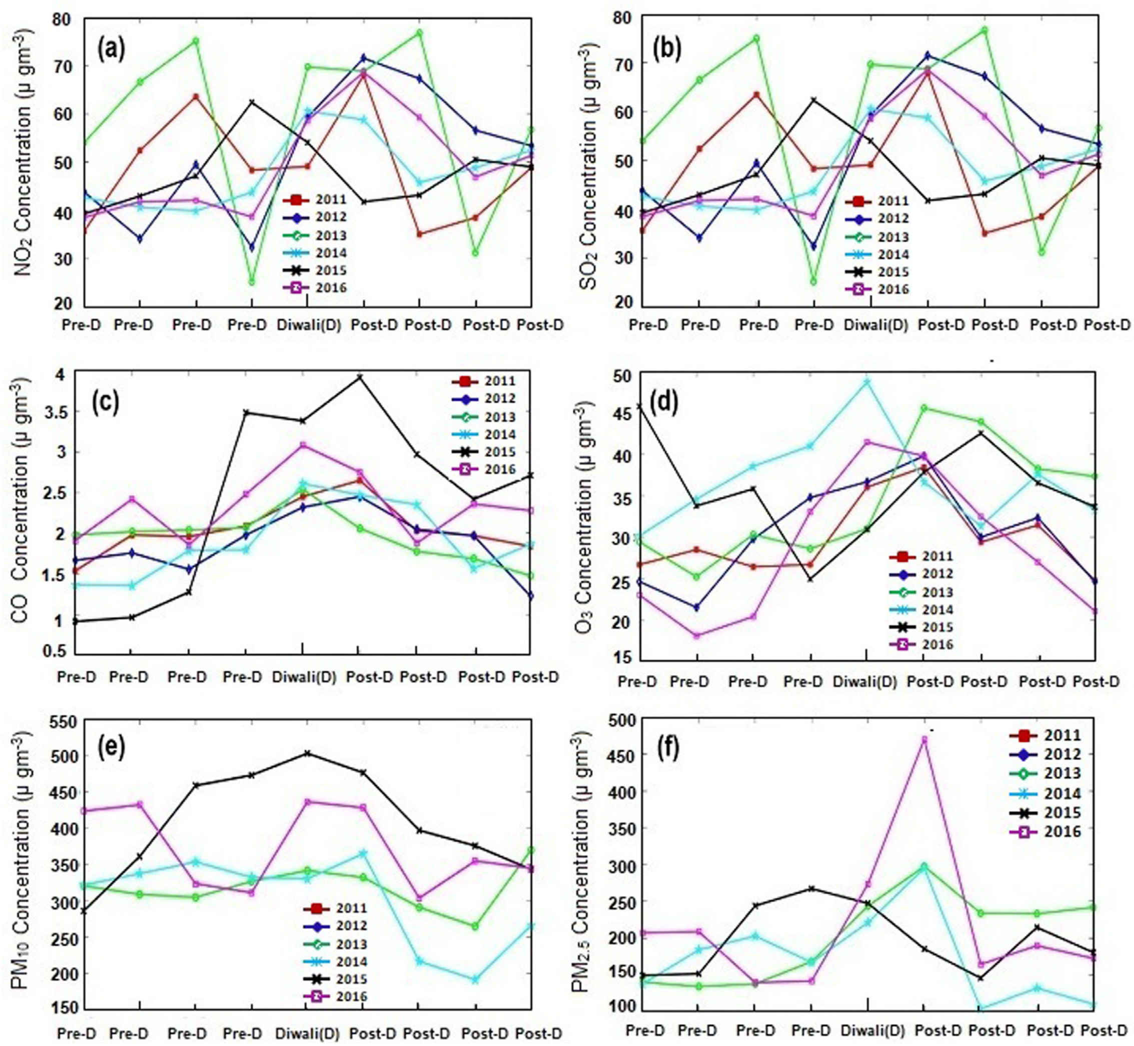

Fig. 6. Variations of the average pollutant concentrations of (a) NO_2, (b) SO_2, (c) CO, (d) surface O_3,(e) PM_{10} and (f) $PM_{2.5}$ during four days prior to Diwali [Diwali (D)] referred as "Pre-D" and four days post Diwali [Diwali (D)] referred as "Post-D" for the period of 2011–2016 over Varanasi.

to control days. Surface ozone is considered a vital secondary pollutant and its production are dependent on the intensity of solar radiation triggered by the presence of precursor gases like NOx, CO, and hydrocarbons. Ozone production is primarily controlled by the intensity of solar radiation during day time, when it is chemically removed by nitrogen monoxide (NO) and humid water vapor (Crutzen, 1979; Midya et al., 2011; Midya and Saha, 2011a, b, c; Saha et al., 2011; Attri et al., 2001). During night-time on Diwali nights, due to the burning of firecrackers, a large amount of NO_2 releases in the atmosphere which reacts with atmospheric oxygen to form nitric oxide (NO). The dazzling light emitted and extensive heat generated (exothermic reaction) during the entire process leads the atomic oxygen (produced from dissociation reaction of NO_2 and O_2) to combine with atmospheric oxygen to form ozone. In the present study, ozone concentration was found to be the highest (48 $\mu g/m^3$) for the year 2014. The study was done 4 days before Diwali festival and 4 days after the festival to get a better insight of trend of ozone concentration due to burning of firecrackers and was found that its concentration was highest on Diwali day and then after 1–2 days, it starts decreasing which confirms the fact that firework displays are the primary contributor of these pollutants in the atmosphere during Diwali festival. Atmospheric ozone exhibits high natural variability (Varotsos and Cracknell, 2004) and is highly influenced by regional/long-range transport (Beig et al., 2007). Similar work has been performed by Ganguly (2009) over Delhi for the year 2004 and 2006 in which they have reported higher concentration of ozone on Diwali day in between 5.00 am to 8.00 pm for both the years. This is because a time lag of 6–7 h is required for the precursor gases (CO, hydrocarbons, and nitrogen oxides), which are released into the air as aresilt of the ignition of firecrackers and enhanced traffic at night to produce ozone to its maximum potential (Beig et al., 2007). The ozone concentration during Diwali was found to be higher in 2013 and 2014 compared to other years; this may be accounted for higher vehicular emissions, NO_2 emission, and ignition of crackers in these years as compared to other years of consideration.

The 24-hour concentration of PM_{10} particulates was found in the range between 280 μg/m^3 to 500 μg/m^3 whereas $PM_{2.5}$ concentration was found in the range between 140 μg/m^3 to 450 μg/m^3. The unprecedented rise in both types of particulate, especially, finer particles during the festival indicates the contribution of firecrackers to be the vital reason. However, it is noteworthy that increased concentration of particulates is not only solely due to firecrackers but other local activities like vehicular emission and anthropogenic activities being responsible. The enhanced concentration of these particulates in the surroundings results in increased aerosols (AOD) for several days even after the festival which is already discussed above in Fig. 4. PM_{10} concentration was found to be the highest for the year 2015 where it starts increasing four days before Diwali and reaches 500 μg/m^3 on Diwali day and then starts decreasing after the event confirming the short-term degradation of ambient air due to intense burning of firecrackers during this festival. Chatterjee et al. (2013) have shown nighttime concentrations of PM_{10} to be 4, 7, and 5 times higher than the permissible standard of PM_{10} respectively on pre-Diwali, Diwali, and post-Diwali day. They have shown maximum night time concentration of PM_{10} aerosol on Diwali (711 μg/m^3) followed by post-Diwali (507 μg/m^3) and pre-Diwali (397 μg/m^3) day over the KKG site, a residential place in Brahmaputra Plain. $PM_{2.5}$ particles also show a similar trend i.e. its concentration is high specifically on Diwali day or post-Diwali days for all the years. But in the year 2016, it shows a sudden increase on Diwali day and reaches 480 μg/m^3, i.e.eight times higher to that of its safer limit stated by NAAQS which stands a serious concern for local public health. Thus, it is clearly evident that the bursting of firecrackers during this festival results in the induction of a large number of particulate matter and other gaseous pollutants which reduces visibility and also harmful for urban health. Since the festival is celebrated just before the commencement of the winter season the atmospheric conditions are quite stable during this time (Saha et al., 2014), and also atmospheric boundary layer is lower in this season (Figure S3) which results in the trapping of these toxic gases in the atmosphere and thus become a serious threat to dwelling people in and around the city (Perrino et al., 2011). Kumar et al. (2016) have done similar studies on Varanasi and reported an increase of 56–121% in aerosol surface mass loading during festival days due to extensive bursting of firecrackers for the year 2014. In another important study done by Barman et al. (2008), higher concentrations of PM_{10} particles were reported over Lucknow too.

Fig. 7(a)-(f) show true color images obtained from the Aqua satellite on the corresponding Diwali days of years 2011–2016 which were used to show the Earth's topography and clouds in true color like a photograph. In this figure, dark green areas show the dominance of plants over the region. In these figures, vast fumes of smoke and haze are seen over the entire Indo-Gangetic Plain where this festival is celebrated with great enthusiasm associated with extensive burning of firecrackers and light lamps which

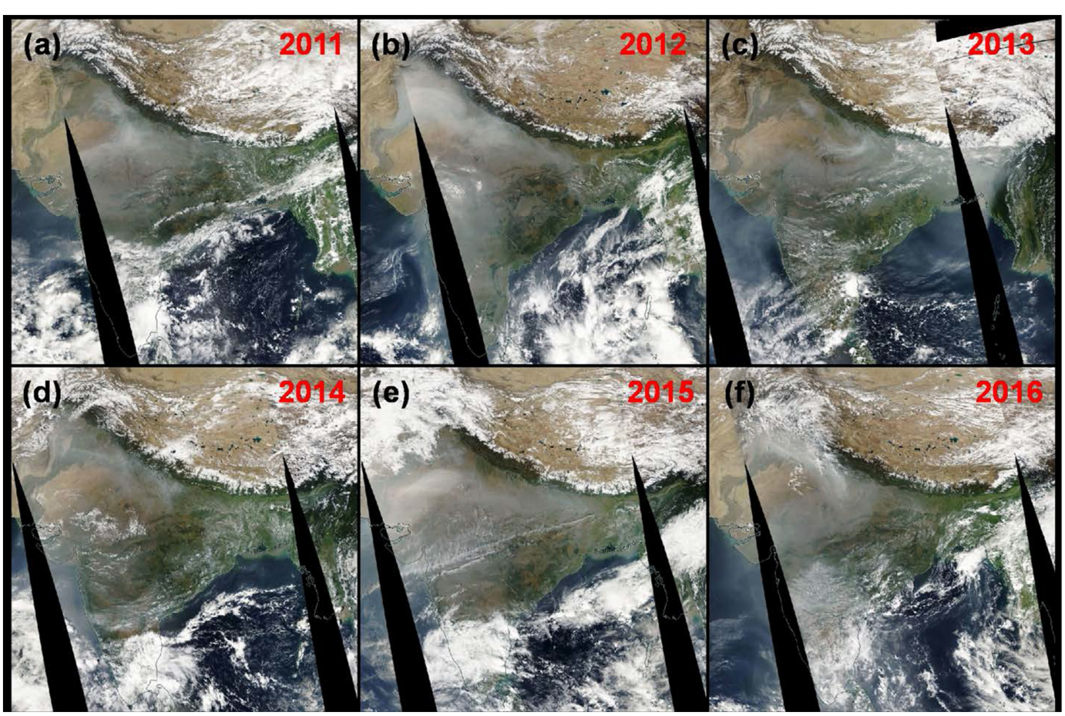

Fig. 7. Spatial distribution ofMODIS True Color Images from the Aqua satellite during corresponding Diwali days for (a) 2011, (b) 2012, (c) 2013, (d) 2014, (e) 2015 and (f) 2016.

causes short-term degradation in ambient air quality. Both haze and smoke are grey and diffuse or transparent, but the haze is usually more transparent than smoke. Haze is spread uniformly over a wide area on the map for all the years of a study indicating the dominance of pollutants and gases emanating from firecrackers vastly exploited on the festival day. Particularly for the years 2012, 2013, and 2015 vast smoke and haze can be observed over the entire country and Varanasi as well, whereas it is comparatively lower in other years of study. True color images of Pre-Diwali (4 days before Diwali) days and Post-Diwali (4 days post-Diwali) days are also shown in Figure S5 (a)-(x) and Figure S6 (a)-(x) respectively. It is indicated from the figures that in pre-Diwali days, a lesser density of smoke

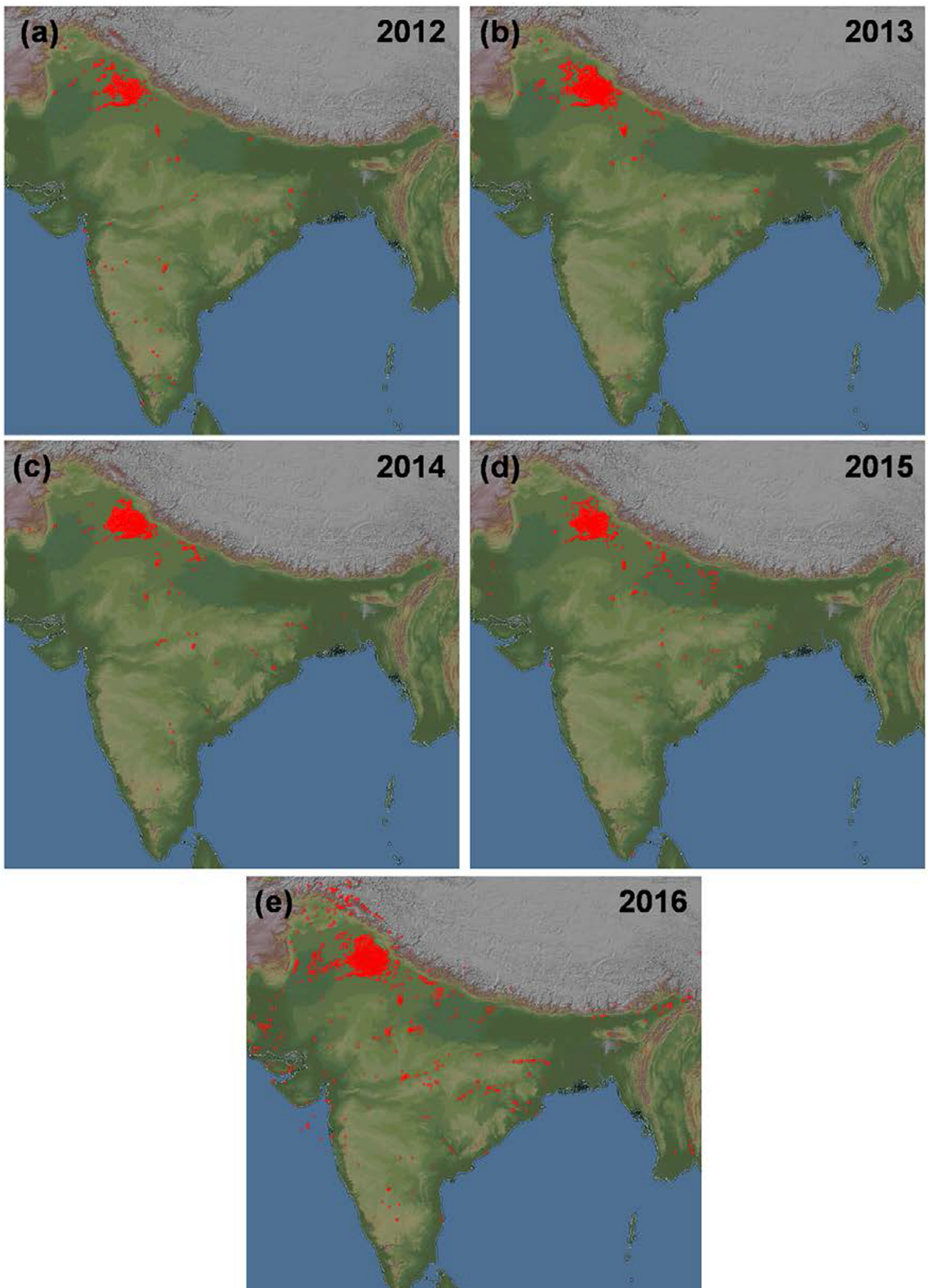

Fig. 8. Spatial distribution of MODIS Terra and Aqua fire maps during corresponding Diwali days for (a) 2012, (b) 2013, (c) 2014, (d) 2015 and (e) 2016. The data for the year 2011 is missing.

plumes was present whereas, on the day of Diwali festival and the respective following days of the event, a higher density of smoke/haze was present confirming the fireworks performed to be responsible for this plight. However, vehicular emission and other anthropogenic activities also contribute to this menace. Furthermore, MODIS-derived Terra and Aqua fire maps are shown in Fig. 8 (a)-(e) for corresponding Diwali days for the years 2012–2016. In this map, every individual red dot represents a 1 km MODIS fire active pixel. This figure shows there were no significant forest fires or biomass burning present over the study region for the corresponding days of Diwali. Pathak et al. (2015) have also shown ten-day accumulated MODIS fire maps to emphasize the contribution of aerosols from biomass burning during these days. These fires may also be attributed to anthropogenic activities i.e. agricultural crop residue burning practices associated with the rice–wheat system especially in the Punjab region where crop residue burning is in regular practice (Badarinath et al., 2009). In figures from 8 (a)-(e), spatial patterns of different parameters observed during the study for the control day (12th March 2017) over the Indian region have been shown. This control day has been chosen randomly as this day is not associated with any major anthropogenic activ-

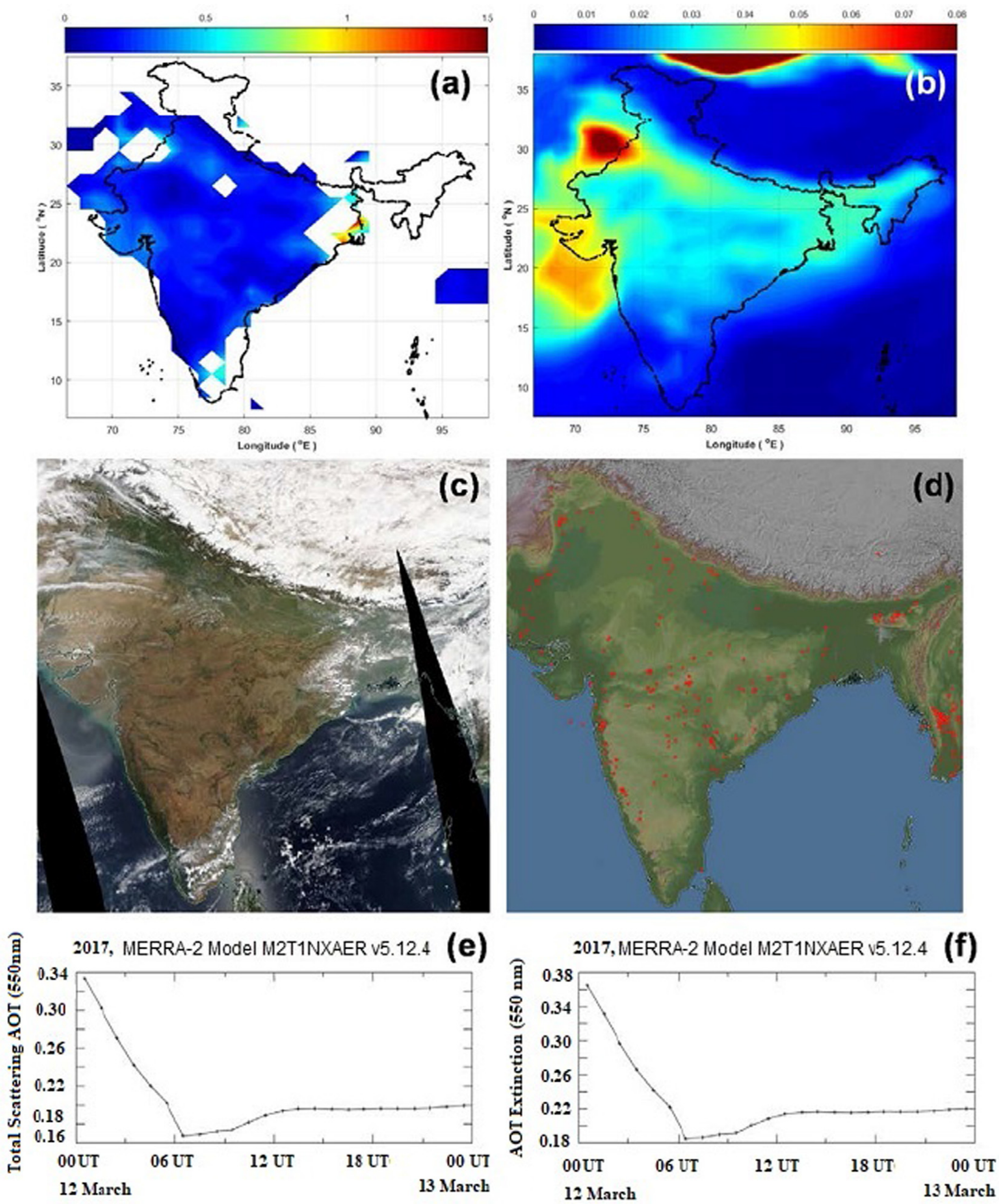

Fig. 9. Spatial patterns of (a) Aqua AOD (Deep Blue., Land only) at 550 nm, (b) Dust Scattering AOT 550 nm - PM 1.0 µm, (c) MODIS True ColorImages from the Aqua satellite, (d) MODIS Terra and Aqua fire map during a control day (12 March 2017) over the Indian region. Time series plot of the area-averaged (e) Total Aerosol Scattering AOT at 550 nm and (f) AOT Extinction at 550 nm during the control day (12 March 2017) over Varanasi region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ities like massive biomass burning or any other festival which is linked with the bursting of firecrackers that is why a lesser amount of trace gases and comparatively lower AOD value is observed on this day. Also, no dust storm event was observed in this period and for this reason, this date has been chosen for control day. Fig. 9a shows a pattern of distribution of AOD over the Indian region on a control day, a particular day on which there is no stress in the atmosphere. Here we can observe the value of AOD is approximately to be 0.5 across the country whereas it shows a sudden upsurge in the case of the Diwali event. Dust scattering AOT at 550 nm – $PM_{1.0}$ μm was also found to be less on control day (Fig. 9b) as compared to corresponding Diwali days and following days of the event of years 2011–2016. Fig. 9 c-d also indicate that IGP is particularly clean and there is no events of haze/fog due to accumulation of aerosols near to the surface layer or no stubble/biomass burning occurred in this control day. Total aerosol scattering and AOT Extinction coefficient at 550 nm indicates almost nil aerosol loading over the Varanasi region in this control day (Fig. 9 e-f). So, in general, this study deals with the potential degradation of ambient air during the Diwali festival caused by the burning of firecrackers and light lamps which is not seen on other days of corresponding years.

4. Conclusions

This study shows that short term degradation in air quality due to extensive burning of fire-crackers during Diwali festival for the years 2011–2016 over Varanasi. This study has also reported increased concentrations of trace gases. Increased concentrations of both PM_{10} and $PM_{2.5}$ particles shown on attainment of NAAQS permissible limits during the Diwali period for all the years. PM_{10} and $PM_{2.5}$ concentrations were found to be 4 to 5 times higher than their prescribed safer limits. However, concentrations of SO_2 and NO_2 remained under the permissible limit but still found higher than the control days. CO concentration was found to be two times higher for a 24 h average than the established limits of NAAQS. Surprisingly, ozone concentration was found sufficiently higher than the safe limits on all the event days and shows a decrease after the event day. Despite the huge impact caused due to the bursting of firecrackers, few studies have been performed so far to assess the health impact associated with these firecrackers. However, in some earlier studies, it has been reported that exposure to emissions of these firecrackers may lead to exacerbation of respiratory illnesses including asthma. People with pre-existing illnesses and especially children are more vulnerable to health effects caused due to exposure to emissions of firecrackers. Moreover, physical injuries such as burn injuries or damage to the eyes also cannot be denied. The sudden increase in concentrations of both primary and secondary pollutants during the Diwali festival causes lower visibility and also is a threat to people's health dwelling in the city for which local administration should take some preventive measures to avoid or mitigate such type of adverse condition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work is partially supported by ISRO, Bangalore under ISRO-SSPS to BHU, and partially by Institute of Eminence (IoE) (Scheme No: 6031) to BHU, Varanasi. The authors also thankfully acknowledge ERA5 team for providing high resolution reanalysis data on the Copernicus Climate Change Service (C3S) Climate Data Store in their website: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview. The authors also thankfully acknowledge the Central Pollution Control Board, New Delhi for providing the atmospheric pollutants data in their online portal. Authors are thankful to both the reviewers for their valuable comments and suggestions to improve the quality of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asr.2021.06.031.

References

Ambade, B., Ghosh, S., 2013. Characterization of PM 10 in the ambient air during Deepawali festival of Rajnandgaon district. India. Nat. Hazards 69 (1), 589–598.

Attri, A.K., Kumar, U., Jain, V.K., 2001. Formation of ozone by fireworks. Nature, 411 (6841), 1015-1015.

Babu, S.S., Manoj, M.R., Moorthy, K.K., Gogoi, M.M., Nair, V.S., Kompalli, S.K., Satheesh, S.K., Niranjan, K., Ramagopal, K., Bhuyan, P.K., Singh, D., 2013. Trends in aerosol optical depth over Indian region: Potential causes and impact indicators. J. Geophys. Res. Atmos. 118 (20), 11–794.

Babu, S.S., Moorthy, K.K., 2001. Anthropogenic impact on aerosol black carbon mass concentration at a tropical coastal station: A case study. Curr. Sci. 81, 1208–1214.

Badarinath, K.V.S., Sharma, A.R., Kharol, S.K., 2009. Impact of emissions from anthropogenic sources on satellite-derived reflectance. Adv. Space Res. 43 (10), 1545–1554.

Banerjee, T., Barman, S.C., Srivastava, R.K., 2011a. Application of air pollution dispersion modeling for source-contribution assessment and model performance evaluation at integrated industrial estate-Pantnagar. Environ. Pollut. 159 (4), 865–875.

Banerjee, T., Singh, S.B., Srivastava, R.K., 2011b. Development and performance evaluation of statistical models correlating air pollutants and meteorological variables at Pantnagar. India. Atmos. Res. 99 (3–4), 505–517.

Banerjee, T., Murari, V., Kumar, M., Raju, M.P., 2015. Source apportionment of airborne particulates through receptor modeling: Indian scenario. Atmos. Res. 164, 167–187.

Bapna, M., Raman, R.S., Ramachandran, S., Rajesh, T.A., 2013. Airborne black carbon concentrations over an urban region in western

India—temporal variability, effects of meteorology, and source regions. Environ. Sci. Pollution Res. 20 (3), 1617–1631.
Barman, S.C., Singh, R., Negi, M.P.S., Bhargava, S.K., 2008. Ambient air quality of Lucknow City (India) during use of fireworks on Diwali Festival. Environ. Monit. Assess. 137 (1), 495–504.
Barman, S.C., Singh, R., Negi, M.P., Bhargava, S.K., 2009. Fine particles (PM2. 5) in ambient air of Lucknow city due to fireworks on Diwali festival. J. Environ. Biol. 30 (5), 625–632.
Beig, G., Gunthe, S., Jadhav, D.B., 2007. Simultaneous measurements of ozone and its precursors on a diurnal scale at a semi urban site in India. J. Atmos. Chem. 57 (3), 239–253.
Bhuyan, P.K., Bharali, C., Pathak, B., Kalita, G., 2014. The role of precursor gases and meteorology on temporal evolution of O 3 at a tropical location in northeast India. Environ. Sci. Pollut. Res. 21 (10), 6696–6713.
Chakraborty, A., Tripathi, S.N., Gupta, T., 2017. Effects of organic aerosol loading and fog processing on organic aerosol volatility. J. Aerosol Sci. 105, 73–83.
Chatterjee, A., Sarkar, C., Adak, A., Mukherjee, U., Ghosh, S.K., Raha, S., 2013. Ambient air quality during Diwali Festival over Kolkata-a mega-city in India. Aerosol Air Qual. Res. 13 (3), 1133–1144.
Cheng, Y., Engling, G., He, K.B., Duan, F.K., Du, Z.Y., Ma, Y.L., Liang, L.L., Lu, Z.F., Liu, J.M., Zheng, M., Weber, R.J., 2014. The characteristics of Beijing aerosol during two distinct episodes: Impacts of biomass burning and fireworks. Environ. Pollut. 185, 149–157.
Crutzen, P.J., 1979. The role of NO and NO_2 in the chemistry of the troposphere and stratosphere. Ann. Rev. Earth Planetary Sci. 7 (1), 443–472.
Dey, S., Di Girolamo, L., van Donkelaar, A., Tripathi, S.N., Gupta, T., Mohan, M., 2012. Variability of outdoor fine particulate (PM2. 5) concentration in the Indian Subcontinent: A remote sensing approach. Remote Sens. Environ. 127, 153–161.
Dey, S., Tripathi, S.N., Singh, R.P., Holben, B.N., 2004. Influence of dust storms on the aerosol optical properties over the Indo-Gangetic basin. J. Geophys. Res. Atmos. 109 (D20).
Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M. E., Ferris Jr, B.G., Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. N. Engl. J. Med. 329 (24), 1753–1759.
Drewnick, F., Hings, S.S., Curtius, J., Eerdekens, G., Williams, J., 2006. Measurement of fine particulate and gas-phase species during the New Year's fireworks 2005 in Mainz. Germany. Atmospheric Environment 40 (23), 4316–4327.
Fallahi, S., Amanollahi, J., Tzanis, C.G., Ramli, M.F., 2018. Estimating solar radiation using NOAA/AVHRR and ground measurement data. Atmos. Res. 199, 93–102.
Ganguly, N.D., 2009. Surface ozone pollution during the festival of Diwali, New Delhi. India. Earth Sci. India 2, 224–229.
Greven, F.E., Vonk, J.M., Fischer, P., Duijm, F., Vink, N.M., Brunekreef, B., 2019. Air pollution during New Year's fireworks and daily mortality in the Netherlands. Sci. Rep. 9 (1), 1–8.
Gurjar R., B., Ravindra, K., Nagpure S., A., 2016. **Air pollution trends over Indian megacities and their local-to-global implications**. Atmos. Environ. 142, 475–495.
Guttikunda, S.K., Calori, G., 2013. A GIS based emissions inventory at 1 km × 1 km spatial resolution for air pollution analysis in Delhi. India. Atmos. Environ. 67, 101–111.
Gurjar, B.R., Jain, A., Sharma, A., Agarwal, A., Gupta, P., Nagpure, A. S., Lelieveld, J., 2010. Human health risks in megacities due to air pollution. Atmos. Environ. 44 (36), 4606–4613.
Hsu, N.C., Tsay, S.C., King, M.D., Herman, J.R., 2004. Aerosol properties over bright-reflecting source regions. IEEE Trans. Geosci. Remote Sens. 42 (3), 557–569.
Hsu, N.C., Tsay, S.C., King, M.D., Herman, J.R., 2006. Deep blue retrievals of Asian aerosol properties during ACE-Asia. IEEE Trans. Geosci. Remote Sens. 44 (11), 3180–3195.
Hsu, A., Reuben, A., Shindell, D., de Sherbinin, A., Levy, M., 2013. Toward the next generation of air quality monitoring indicators. Atmos. Environ. 80, 561–570.
Kulshrestha, U.C., Rao, T.N., Azhaguvel, S., Kulshrestha, M.J., 2004. Emissions and accumulation of metals in the atmosphere due to crackers and sparkles during Diwali festival in India. Atmos. Environ. 38 (27), 4421–4425.
Kumar, M., Singh, R.K., Murari, V., Singh, A.K., Singh, R.S., Banerjee, T., 2016. Fireworks induced particle pollution: a spatio-temporal analysis. Atmos. Res. 180, 78–91.
Kumar, P., Pratap, V., Kumar, A., Choudhary, A., Prasad, R., Shukla, A., Singh, R.P., Singh, A.K., 2020. Assessment of atmospheric aerosols over Varanasi: Physical, optical and chemical properties and meteorological implications. J. Atmos. Solar-Terr. Phys. 209 105424.
Mandal, R., Sen, B.K., Sen, S., 1997. Impact of fireworks on our environment. Indian J. Environ. Prot. 17, 850–853.
Midya, S.K., Saha, U., 2011a. Role of the rate of change of Total Column Ozone during different seasons on the prediction of Indian summer monsoon rainfall over Gangetic West Bengal., India. Indian J. Phys. 85 (10), 1461–1468.
Midya, S.K., Saha, U., 2011b. Rates of change of total ozone column and surface relative humidity, seasonal variations over Dum Dum (22 38′ N, 88 26′ E). Int. J. Remote Sens. 32 (22), 7891–7899.
Midya, S.K., Saha, U., 2011c. Rate of change of total column ozone and monsoon rainfall-A co-variation with the variable component of 10.7 cm solar flux during pre-monsoon period. Mausam. 62 (1), 91–96.
Midya, S.K., Saha, U., Panda, P., Kundu, A., Chaudhuri, A., Sarkar, H., 2011. Variation of total ozone concentration and rainfall over different stations of India. The Pacific J. Sci. Tech. (Spring) 12 (1), 580–590.
Moreno, T., Querol, X., Alastuey, A., Minguillón, M.C., Pey, J., Rodriguez, S., Miró, J.V., Felis, C., Gibbons, W., 2007. Recreational atmospheric pollution episodes: inhalable metalliferous particles from firework displays. Atmos. Environ. 41 (5), 913–922.
Nastos, P.T., Paliatsos, A.G., Anthracopoulos, M.B., Roma, E.S., Priftis, K.N., 2010. Outdoor particulate matter and childhood asthma admissions in Athens, Greece: a time-series study. Environ. Health 9 (1), 1–9.
Nishanth, T., Praseed, K.M., Rathnakaran, K., Kumar, M.S., Krishna, R. R., Valsaraj, K.T., 2012. Atmospheric pollution in a semi-urban, coastal region in India following festival seasons. Atmos. Environ. 47, 295–306.
Ojha, N., Sharma, A., Kumar, M. Girach, I., Ansari, T.U., Sharma, S.K., Singh, N., Pozzer, A., Gunthe, S.S., 2020. On the widespread enhancement in fine particulate matter across the Indo-Gangetic Plain towards winter. Sci. Rep. 10, 5862 (1-9).
Pachauri, T., Singla, V., Satsangi, A., Lakhani, A., Kumari, K.M., 2013. Characterization of major pollution events (dust, haze, and two festival events) at Agra. India. Environ. Sci. Pollut. Res. 20 (8), 5737–5752.
Pathak, B., Biswas, J., Bharali, C., Bhuyan, P.K., 2015. Short term introduction of pollutants into the atmosphere at a location in the Brahmaputra Plain, A case study. Atmos. Pollut. Res. 6, 220–229.
Perrino, C., Tiwari, S., Catrambone, M., Torre, S.D., Rantica, E., Canepari, S., 2011. Chemical characterization of atmospheric PM in Delhi, India, during different periods of the year including Diwali festival. Atmos. Pollut. Res. 2, 418–427.
Pope III, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution, lines that connect. J. Air Waste Manag. Assoc. 56, 709-742.
Pratap, V., Kumar, A., Singh, A.K., 2017. Short Term Air Quality Degradation by Firecrackers Used during Diwali Festival in Varanasi., India. 18158-18165. https//doi.org/10.15680/IJIRSET.2017.0609079.
Pratap, V., Kumar, A., Singh, A.K., 2019, March. Variability in air pollutants and AOD over Varanasi region for years 2005-2010. In 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC) (pp. 1-1). IEEE.https,//doi.org/10.23919/URSIAP-RASC.2019.8738590.
Pratap, V., Kumar, A., Tiwari, S., Kumar, P., Tripathi, A.K., Singh, A. K., 2020. Chemical characteristics of particulate matters and their

emission sources over Varanasi during winter season. J. Atmos. Chem. 77, 83–99.
Ram, K., Sarin, M.M., 2011. Day–night variability of EC, OC, WSOC and inorganic ions in urban environment of Indo-Gangetic Plain, implications to secondary aerosol formation. Atmos. Environ. 45 (2), 460–468.
Ramachandran, S., Kedia, S., 2010. Black carbon aerosols over an urban region, radiative forcing and climate impact. J. Geophys. Res. Atmos. 115 (D10).
Ramanathan, V., Feng, Y., 2009. Air pollution, greenhouse gases and climate change, global and regional perspectives. Atmos. Environ. 43, 37–50.
Ravindra, K., Mor, S., Kaushik, C.P., 2003. Short-term variation in air quality associated with firework events: a case study. J. Environ. Monit. 5 (2), 260–264.
Ray, S., Ray, I.A., 2011. Impact of population growth on environmental degradation: Case of India. J. Econ. Sus. Dev. 2 (8), 72–77.
Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.K., Bloom, S., 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. J. Clim. 24 (14), 3624–3648.
Saha, U., Midya, S.K., Das, G.K., 2011. The effect of the variable component of 10.7 cm solar flux on the thunderstorm frequency over Kolkata and its relation with ozone depletion mechanism. The Pac. J. Sci. Technol. 12 (1), 591–597.
Saha, U., Talukdar, S., Jana, S., Maitra, A., 2014. Effects of air pollution on meteorological parameters during Deepawali festival over an Indian metropolis. Atmos. Environ. 98, 530–539.
Samoli, E., Nastos, P.T., Paliatsos, A.G., Katsouyanni, K., Priftis, K.N., 2011. Acute effects of air pollution on paediatric asthma exacerbation, evidence of association and effect modification. Environ. Res. 111, 418–424.
Sateesh, M., Soni, V.K., Raju, P.V.S., 2018. Effect of diwali firecrackers on air quality and aerosol optical properties over mega city (Delhi) in India. Earth Sys. Environ. 2 (2), 293–304.
Sayer, A.M., Munchak, L.A., Hsu, N.C., Levy, R.C., Bettenhausen, C., Jeong, M.J., 2014. MODIS Collection 6 aerosol products: Comparison between Aqua's e-Deep Blue, Dark Target, and "merged" data sets, and usage recommendations. J. Geophys. Res. Atmos. 119 (24), 13–965.
Sen, A., Abdelmaksoud, A.S., Ahammed, Y.N., Banerjee, T., Bhat, M.A., Chatterjee, A., Choudhuri, A.K., Das, T., Dhir, A., Dhyani, P.P., Gadi, R., 2017. Variations in particulate matter over Indo-Gangetic Plains and Indo-Himalayan Range during four field campaigns in winter monsoon and summer monsoon, role of pollution pathways. Atmos. Environ. 154, 200–224.
Singh, B.P., Srivastava, A.K., Tiwari, S., Singh, S., Singh,R.K., Bisht, D. S., Lal, D.M., Singh, A.K., Mall, R.K., Srivastava, M.K., 2014. Radiative Impact of Fireworks at a Tropical Indian Location: A Case Study. Adv. Meteorol.1970728.
Singh, D.P., Gadi, R., Mandal, T.K., Dixit, C.K., Singh, K., Saud, T., Singh, N., Gupta, P.K., 2010. Study of temporal variation in ambient air quality during Diwali festival in India. Environ. Monit. Assess. 169, 1–13.
Singh, R.P., Dey, S., Holben, B., 2003. Aerosol behaviour in Kanpur duringDiwali festival. Curr. Sci. 84 (10), 1302–1304.
Tanda, S., Ličbinský, R., Hegrová, J., Goessler, W., 2019. Impact of New Year's Eve fireworks on the size resolved element distributions in airborne particles. Environ. Int. 128, 371–378.
Thakur, B., Chakraborty, S., Debsarkar, A., Chakrabarty, S., Srivastava, R.C., 2010. Air pollution from fireworks during festival of lights (Deepawali) in Howrah. India-a case study. Atmosfera 23 (4), 347–365.
Tiwari, S., Chate, D.M., Srivastava, M.K., 2012. Statistical evaluation of PM_{10} and distribution of $PM_{1\cdot0}$, $PM_{2.5}$., and PM_{10} in ambient air due to extreme fireworks episodes (Deepawali festivals) in mega city Delhi. Nat. Hazards 61 (2), 521–531.
Tzanis, C.G., Alimissis, A., Philippopoulos, K., Deligiorgi, D., 2019. Applying linear and nonlinear models for the estimation of particulate matter variability. Environ. Pollut. 246, 89–98.
Upadhyay, A., Dey, S., Chowdhury, S., Goyal, P., 2018. Expected health benefits from mitigation of emissions from major anthropogenic PM2. 5 sources in India: Statistics at state level. Environ. Pollut. 242, 1817–1826.
Varotsos, C., Cracknell, A.P., 2004. New features observed in the 11-year solar cycle. Int. J. Remote Sens. 25, 2141–2157.
Vecchi, R., Bernardoni, V., Cricchio, D., Alessandro, A.D., Fermo, P., Lucarelli, F., Nava, S., Piazzalunga, A., Valli, G., 2008. The impact of fireworks on airborne particles. Atmos. Environ. 42, 1121-1132.
Vyas, B.M., Saraswat, V., 2012. Studies of atmospheric aerosol's parameters during pre-Diwali to post-Diwali festival period over Indian semi-arid station i.e., Udaipur. Appl. Phys. Res. 4 (2), 41–55.
Wang, Y., Zhuang, G., Xu, C., An, Z., 2007. The air pollution caused by the burning of fireworks during the lantern festival in Beijing. Atmos. Environ. 41 (2), 417–431.
Yerramsetti, V.S., Sharma, A.R., Navlur, N.G., Rapolu, V., Dhulipala, N.C., Sinha, P.R., 2013. The impact assessment of Diwali fireworks emissions on the air quality of a tropical urban site, Hyderabad, India, during three consecutive years. Environ. Monit. Assess. 185 (9), 7309–7325.