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Research Article

Radiative Impact of Fireworks at a Tropical Indian Location: A Case Study

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During Diwali festival, extensive burning of crackers and fireworks is made. Weeklong intensive observational campaign for aerosol study was carried out at a representative urban location in the eastern Indo-Gangetic Plain (IGP), Varanasi (25.3°N, 83.0°E), from October 29 to November 04, 2005 (Diwali on November 01, 2005), to investigate behavioral change of aerosol properties and radiative forcing between firework affected and nonaffected periods. Results show a substantial increase (~27%) in aerosol optical depth, aerosol absorption coefficients, and aerosol scattering coefficients during affected period as compared to non-affected periods. Magnitudes of radiative forcing at top of atmosphere during affected and non-affected periods are found to be $+10 \pm 1$ and $+12 \pm 1\ \mathrm{Wm}^{-2}$, respectively, which are -31 ± 7 and $-17 \pm 5\ \mathrm{Wm}^{-2}$, respectively, at surface. It suggests an additional cooling of ~20% at top of atmosphere, ~45% cooling at surface, and additional atmospheric heating of $0.23\ \mathrm{Kday}^{-1}$ during fireworks affected period, which is ~30% higher than the non-affected period average.

1. Introduction

Importance of aerosols in regional and global climate has gained wide knowledge base during the last couple of decades. General impact of these aerosols is to cool the atmosphere and to compensate the atmospheric warming caused due to enhanced greenhouse gases. However, atmospheric warming due to aerosols is also noticed when absorbing particles, such as black carbon (soot) and/or mineral dust, are present [1, 2]. Significant heating to the atmosphere may play a crucial role in various boundary layer processes under favorable atmospheric conditions [3]. The presence of such aerosols is higher in the atmospheric boundary layer [4], but they are also reported in the free troposphere till stratosphere. Boundary layer aerosols are characterized as short-lived and showed spatiotemporal variation in mass and number concentrations. Depending on weather condition and location, the regional variability in physical, chemical, and optical characteristics of aerosols is influenced by mixing various types of aerosols, produced by different natural and/or anthropogenic processes [3, 5], for example, aerosol production from biomass burning [6], biogenic production [7], industrial effluents [8], and so forth. The impact of aerosol is also found to be associated with climatic elements [9].

During recent decades, there have been a number of studies to characterize aerosols on local scale; however, studies on instant increment of aerosols within 1-2 days, due to fireworks, are available for only a few locations, for example, during New Year event [10], Millennium festival [11], Diwali festival [12–14], and so forth. Further, studies reported for firework generated aerosols are more inclined towards the impact of firework generated, gaseous as well as particulate, pollutants on health [15, 16], air quality [12–14, 16, 17], number and mass concentration [10, 11], and

interrelationship between gaseous pollutants and particles [10, 18], but the impact of fireworks generated aerosols on climate in terms of atmospheric forcing has never been assessed for any location so far.

The present study is an attempt to understand the changes in optical characteristics of aerosols and also to understand changes in radiative impacts that are caused due to mixing firework generated aerosols in the ambience. Data for this intensive observation period (IOP) was collected for an urban location in Indo-Gangetic Plain (IGP), Varanasi (25.3N, 83.0E, 76 above mean sea level), during October 29 to November 04, 2005 (Diwali was celebrated on November 01). The objectives of the work are to broaden our understanding towards the effect of fireworks on climate and also to quantify their impact in terms of radiative forcing. To the best of our knowledge, this is the first time to report the impact of firework generated aerosol on radiative balance and heating of the atmosphere.

2. Site Description, Weather, and Data

Varanasi is a representative urban station in the central part of IGP. Varanasi is amongst few locations in India for which the column ozone and solar ultraviolet radiation are observed along with surface weather parameters, by the office of India Meteorological Department (IMD) at BHU, Varanasi, for the purpose of global database at World Ozone and Ultraviolet Radiation Data Centre (WOUDC). Weather parameters for the present study are obtained from surface weather observatory being managed by IMD, BHU, Varanasi.

Surface weather parameters and aerosol optical depths (AODs) are collected at every half-to-one hour interval during the entire campaign that includes the pre- and post-Diwali period. Weather was mostly calm and stable during the IOP. Mean sea level pressure during this period varied from 1011 to 1016 hPa and wind was mostly calm. For the IOP, daily maximum and daily minimum surface temperature and relative humidity varied from 29.0 to 31.0°C, 11.1 to 19.0°C, and 67% to 89%, respectively. General weather of Varanasi during IOP is, however, shown in Figure 1.

Multiwavelength AODs have been collected using MicroTOPS-II. The MicroTOPS-II used in this study was compared with another set of MicroTOPS-II at the National Physical Laboratory, New Delhi (NPL), before IOP. MicroTOPS-II at NPL was calibrated at Solar Light Company, USA, in 2004. More details for comparison, however, can be found elsewhere [19]. AODs were measured at 340, 500, and 870 nm wavelengths (full width at half maximum: ±2–10 nm) and signals at 936 and 1020 nm are used to compute columnar water vapor (CWV). As per Morys et al. [20], pointing accuracy of the MicroTOPS-II is better than 0.10 and long-term stability of the filter used in the instrument is better than 0.1 nm per year. In order to check the repeatability of the instrument, frequent observations were taken at about 11 seconds interval on a fairly clear forenoon of October 30, 2005. This series of observation showed average and standard deviations of AODs at 340, 500, and 870 nm as 1.213 ± 0.013, 0.967 ± 0.009, and 0.403 ± 0.005, respectively, over ~7 minutes of continuous measurements. This suggests that the observations made during IOP are consistent and can be considered as possessing good quality.

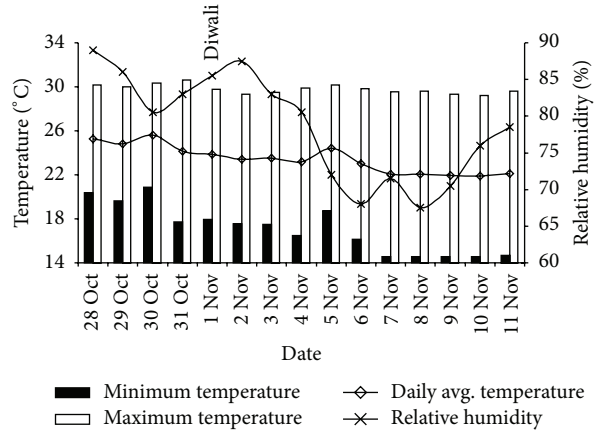

Figure 1: Weather parameters from October 28 till November 11, 2005 at Varanasi.

The spectral variations of AODs provide useful information on columnar size distribution of aerosols, which can be represented by Ångström power law [21] as,

$$\tau_a(\lambda) = \beta\lambda^{-\alpha}, \quad (1)$$

where $\tau_a(\lambda)$ is AOD at wavelength λ (in μm), β is turbidity coefficient, and α is Ångström exponent (AE). α is a good indicator of size range of the dominant particle population in an aerosol sample [22, 23], and turbidity coefficient (β) indicates total aerosol loading, which is equal to aerosol optical depth (τ_a) at 1.0 μm wavelength.

First order derivative of α (i.e. α') is a derived parameter, which is calculated using more than two wavelengths. This parameter is useful for the estimation of type of aerosols [19]. In the present study, α' is computed using AODs obtained at central wavelengths of 340, 500, and 870 nm.

3. Methodology

AODs, single scattering albedo (SSA), and asymmetric parameter (AP) are crucial aerosol properties for the estimation of aerosol direct radiative forcing (DRF). Since direct measurements of SSA and AP were not available at Varanasi, these parameters have been estimated using standard procedures (described in next section) of Optical Properties of Aerosols and Clouds (OPAC) model [24].

3.1. Estimation of Aerosol Optical Parameters. OPAC model provides wide range of optical and microphysical properties of aerosols pertaining to 61 discrete wavelengths (between 0.3 and 40 μm), eight values of RH, and various aerosol compositions. We have followed an approach that uses the available measurements as anchoring point in standard continental average aerosol model of OPAC, which is then fine-tuned to match the measurement in order to derive optical properties of aerosols (see [5] for details). As measured

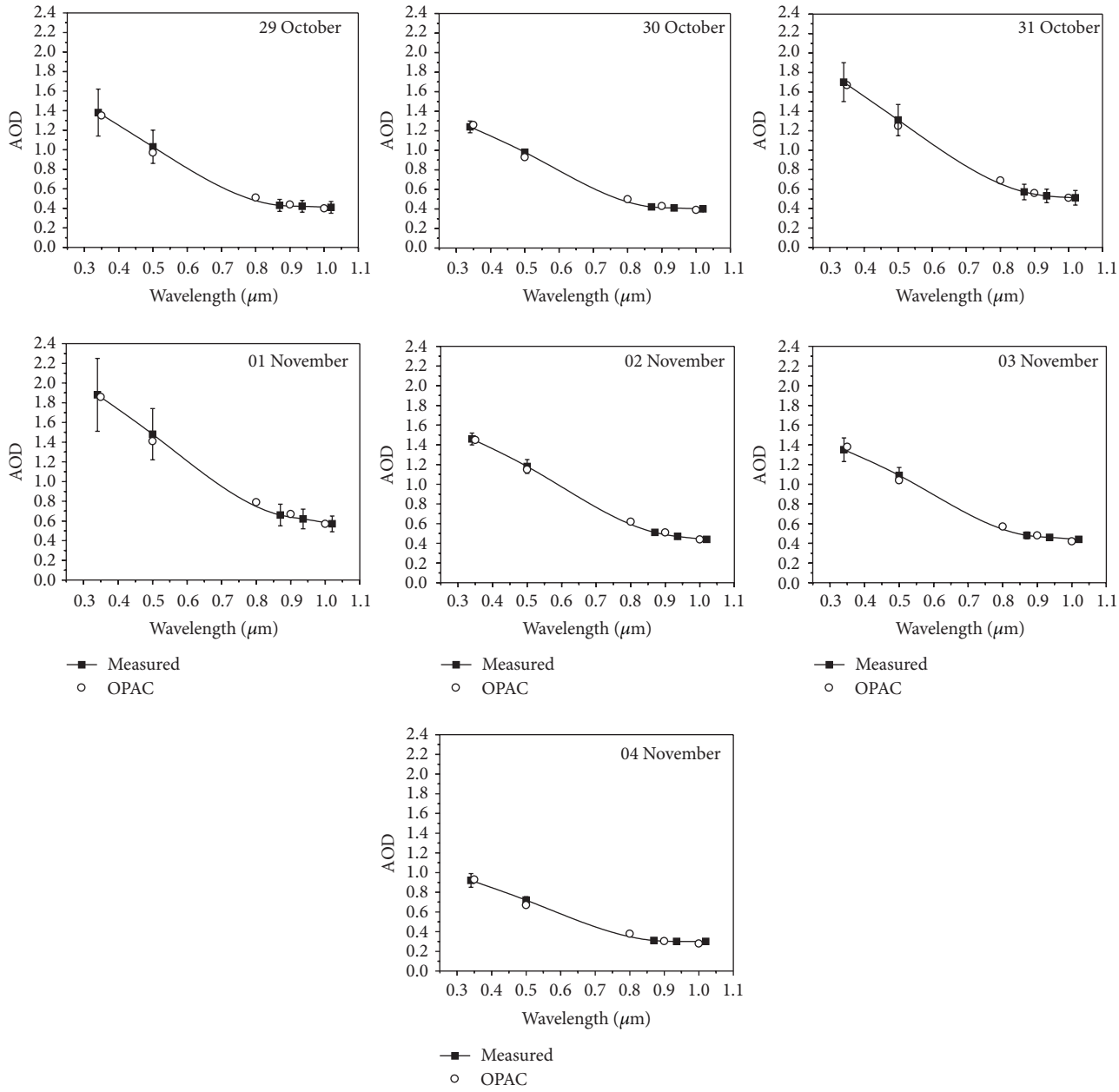

Figure 2: Comparison between measured and model (OPAC) derived spectral AODs for intensive observation period (IOP, October 29 to November 04, 2005).

aerosol composition over the station was not available during the study period, we have assumed possible composition in the OPAC model. Once an appropriate atmosphere is generated in OPAC model, measured AODs from MicroTOPS-II were used as a reference to constrain other crucial aerosol optical parameters (i.e., SSA and AP). Comparison of OPAC derived and measured spectral AODs are shown in Figure 2. Modelled spectral AOD values were found to be lying within standard deviations of measured spectral AODs, for all the days during IOP. Difference between observed and modelled values was found within 5%.

Using the above-mentioned approach, OPAC model is run for each day of IOP. Though this is an alternative method to derive crucial aerosol optical parameters in the absence of observations, it is an established and widely used method in the literature ([5] and references therein). In this method, however, there are chances of uncertainties due to vertical aerosol distribution. In the absence of vertical aerosol profiles, as in the present case, the surface aerosol properties are attributed to column properties, assuming vertical profiles in OPAC model, as suggested by Srivastava et al. [5]. Additionally, uncertainties may also be generated due to OPAC accounted external mixtures of different aerosol

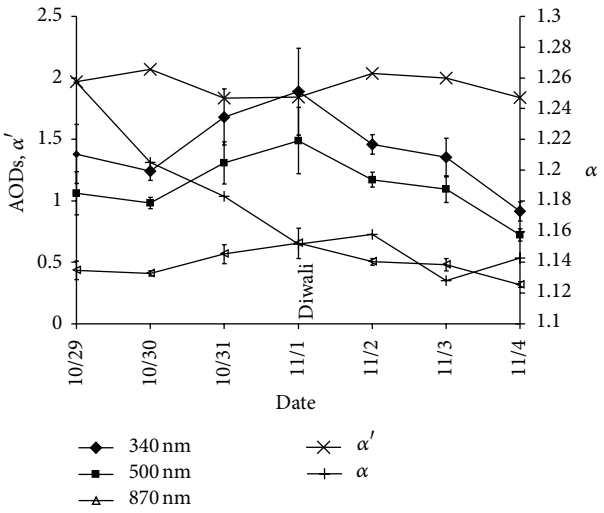

Figure 3: Day-to-day variability in AODs (340 nm, 500 nm, and 870 nm), AE (α, 340–870 nm), and α' for IOP.

components to form aerosol types. Being an urban station in the central part of IGP, the probability of internal mixing or coating of aerosols may be possible, which can deliver certain uncertainties in the end result.

3.2. Estimation of Aerosol Direct Radiative Forcing. Aerosols are significant contributors to direct radiative forcing (DRF). Some of these particles, for example, BC and mineral dust, show absorbing nature [1, 2] and contribute significantly to the warming of lower atmosphere due to short-wave absorption [25]. In the present study, net flux is computed in the shortwave region (0.30–3.0 μm), separately for top of atmosphere (TOA) and surface, with and without aerosols, using the Santa Barbara DISORT atmospheric radiative transfer (SBDART) model [26]. The input parameters for SBDART model are spectral AOD, SSA, and AP, which are either measured or obtained by OPAC model. SBDART uses six standard atmospheres to consider vertical profiles of atmospheric parameters, such as average temperature, pressure, water vapor, and ozone density [26]. Location of Varanasi falls in the tropical classification, which is characterized by average water vapor of 4.117 g cm^{-2} and average columnar ozone of 253 DU. These data are close to observations over Varanasi during October-November months. Surface albedo over the station was considered to be 0.18, which is slightly less in comparison to Kanpur (an industrial city situated ~300 km away from Varanasi) [27].

Diurnal average of aerosol direct radiative forcing (DRF) at TOA and at surface is estimated by computing the difference in net radiative fluxes, with and without aerosol, respectively, at TOA and surface. The difference between TOA and surface forcing is considered as atmospheric forcing (ΔF), which represents the amount of energy trapped or absorbed by aerosols within the atmosphere and which is available to be transformed into heat.

4. Results and Discussion

4.1. Aerosol Optical Characteristics. Figure 3 shows measured AOD at 340, 500, and 870 nm wavelengths, along with the Ångström exponents (α), computed for the wavelength pair of 340–870 nm and α' (computed with the help of wavelength pairs 340–500 nm and 500–870 nm). By and large, opposite behavior is observed between AOD and α [12, 28, 29]. AOD was found to increase (with decreasing α) from October 30 till November 01 (Diwali) and decrease (with increasing α) on subsequent days (Table 1 and Figure 3). Results suggest enhanced loading of aerosols during Diwali period, most probably due to excessive burning of firework and crackers [10–12, 30]. α' is a parameter that provides information on types of aerosol in the aerosol population [19]. Positive α' is an indicator of fine/accumulation-mode particles dominance, whereas negative α' suggests dominance of coarse-mode aerosol particles [19, 31–34]. Table 1 shows that α' is positive during IOP indicating persistent dominance of fine-mode particles during all these days; however, it was the lowest on Diwali. It suggests that IOP is dominated by fine mode particle; but there is inclusion of other fine mode particles due to burning of fireworks during Diwali day. Babu and Moorthy [30] also found enhanced AODs during the event of firework, which was caused due to enhanced presence of black and organic carbon, generated by burning of different types of crackers and fireworks during Diwali. Singh et al. [12] have reported enhancement of 5.7% and 5.5% for AOD_{340} and AOD_{500}, respectively, during Diwali at Kanpur.

The variations in OPAC derived parameters, such as absorption coefficients, scattering coefficient, and SSA at 500 nm (SSA_{500}), are also shown in Table 1. In general, the behavior of scattering coefficient was found similar to that of absorption coefficient and AOD, but it was different to that of AE. Scattering and absorption coefficients were found to be maximum (461.6 and 24.2 Mm^{-1}, resp.) on Diwali. The type of aerosols which contribute maximum to the scattering coefficient may include water-soluble inorganic species, such as sulfates and nitrates, arising from emissions of SO_2 and NO_x, and contributions from fossil fuel and biomass combustion sources. However, those aerosol types that contribute maximum to the absorbing coefficient may include BC, which is largely associated with firework [30].

Since scattering and absorbing type of aerosols are well mixed in the real atmosphere, their ultimate effect in terms of heating/cooling of the atmosphere depends on SSA of aerosol population. For the present case, minimum value of SSA_{500} (≈0.95) was observed on November 02, the next day of Diwali. It suggests extended influence of absorbing particles emitted due to burning of fireworks during Diwali night [10, 11, 30], which was affective till the next day. Absorbing aerosols are found to be associated with lower SSA values [35].

Spectral variations of average AOD, absorption coefficient, scattering coefficient, and SSA are shown in Figures 4(a)–4(d), respectively, for affected (October 31, November 01 and 02) and nonaffected (October 29, 30, November 03 and 04) periods. Significant differences in all the parameters were observed at all the wavelengths, for affected and nonaffected periods. It is found that AOD increased with

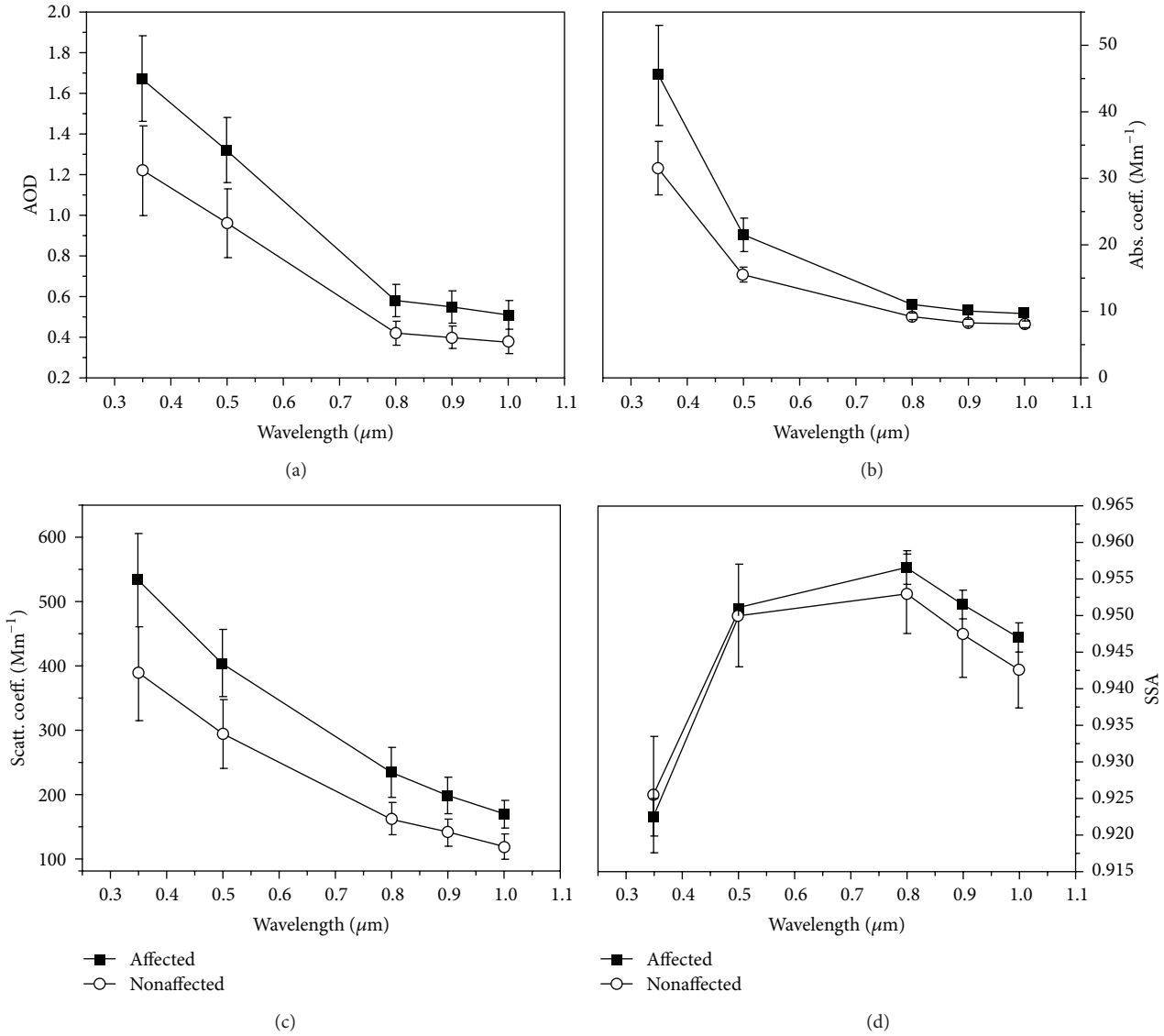

Figure 4: Spectral variation of (a) AOD, (b) absorption coefficient, (c) scattering coefficient, and (d) SSA for firework affected (October 31, November 01 and 02, 2005) and nonaffected periods (October 29, 30, November 03 and 04, 2005).

Table 1: Daily mean values of AOD, column water vapor and AE, absorption coefficients, scattering coefficients, and SSA from October 29, 2005, to November 04, 2005.

Days (2005)	Category	AOD_{500}	$AE_{340-870}$	CWV (cm)	Abs. $coeff._{500}$ (Mm^{-1})	Scatt. $coeff._{500}$ (Mm^{-1})	SSA_{500}
October 29	NA	1.06	1.26	1.63	15.58	320.20	0.954
October 30	NA	0.98	1.21	1.34	15.01	303.20	0.953
October 31	AF	1.31	1.18	1.39	20.80	406.20	0.951
November 01	AF	1.49	1.15	1.61	24.23	461.60	0.950
November 02	AF	1.17	1.16	1.58	18.70	351.10	0.950
November 03	NA	1.10	1.13	1.51	17.03	338.10	0.952
November 04	NA	0.72	1.14	1.45	14.08	218.10	0.954

NA: nonaffected, AF: affected.

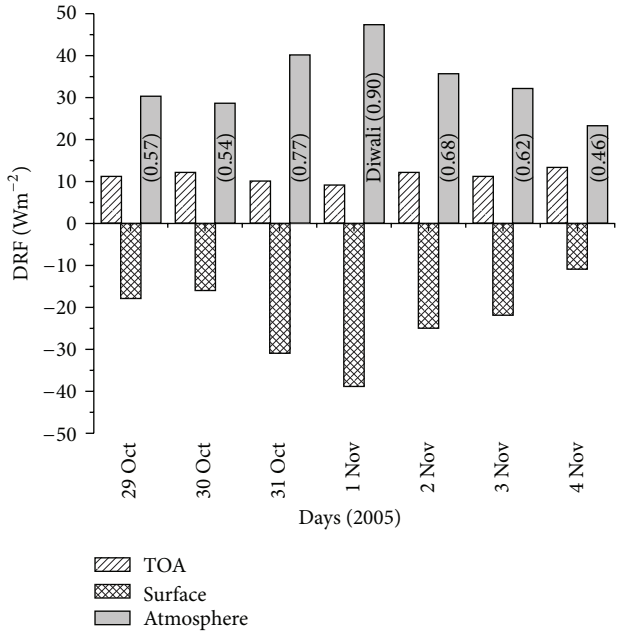

Figure 5: Day-to-day variability in the estimated direct radiative forcing at the TOA, surface, and in the atmosphere. The heating rate values are given in parentheses within respective bars.

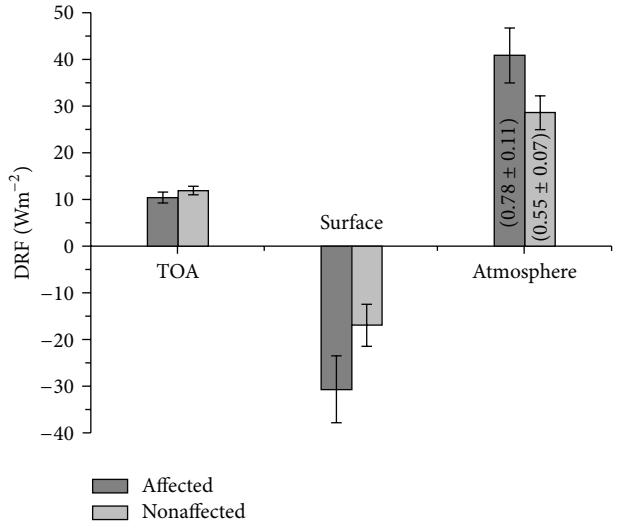

Figure 6: Comparison of estimated direct radiative forcing at the TOA, surface, and in the atmosphere for firework affected and nonaffected periods. Atmospheric heating rates are given in parentheses in the respective atmospheric forcing bars.

the advent of Diwali and reached to its maximum value on November 01 (Diwali) for each wavelength (Figure 3). The burning of fireworks and crackers invariably contributes to the anthropogenic aerosols [12, 14] and increases AODs [36]. AODs at all other wavelengths were found to increase for firework affected period (Figure 3). Average AOD_{500} for affected period shows the value of 1.3, which is ~27% higher than the nonaffected period average. Similar increment in absorption coefficient (21.2 Mm^{-1}, increase of 27.4%) and scattering coefficient (406 Mm^{-1}, increase of 27.4%) was also noticed for firework affected period in comparison to nonaffected period. It is to be mentioned here that, apart from the emissions of absorbing aerosols, different water-soluble species (like sulfate, nitrate, etc.) are also emitted from fire crackers burning, which are of scattering in nature. As a result, an enhancement in both absorption and scattering coefficients was observed. For the same period, however, AE had decreased by 6.2%.

4.2. Aerosol Radiative Forcing and Implications to Atmospheric Heating Rate. Broadband aerosol direct radiative forcing (DRF) at the TOA, surface, and in the atmosphere for each day during IOP is shown in Figure 5. Negative value of surface forcing implies a net cooling effect, whereas positive value for TOA and within atmospheric implies a net warming effect. Significant day-to-day variability was observed in surface and atmospheric forcing values. The surface and atmospheric forcing was maximum (−38 and 47 Wm^{-2}, resp.) on Diwali (November 01), whereas aerosol DRF at TOA was minimum (9 Wm^{-2}) on Diwali.

Average aerosol DRF estimated at TOA, surface, and in the atmosphere, during affected and nonaffected period, is shown in Figure 6. Magnitudes of forcing at TOA during the affected and nonaffected periods were +10 ± 1 and +12 ± 1 Wm^{-2}, respectively; however, the forcing at surface was −31 ± 7 and −17 ± 5 Wm^{-2}, respectively. These estimates indicated an additional cooling of 2 Wm^{-2} at the TOA (~ 20%) and 14 Wm^{-2} at the surface (~45%) during firework affected period. Results could be due to enhanced loading of aerosols (absorbing and/or scattering type) over the station during firework period. Apart from the aerosol loading of absorption/scattering type aerosols, TOA and surface forcing are also sensitive to the albedo of the underlying surface [37]. The atmospheric forcing values during affected and nonaffected periods were estimated to be +41 ± 6 and +29 ± 4 Wm^{-2}, respectively, which translate to an additional atmospheric warming of +12 Wm^{-2} during firework affected period.

The higher value of surface cooling and strong atmospheric heating in the atmosphere suggests their association with various aerosol properties, for example, size range and chemical composition of aerosol population, and raises several climatic issues [4, 9, 38, 39]. An important aspect in this regard is the aerosol-generated atmospheric heating rates, which can be calculated from the first law of thermodynamics and hydrostatic equilibrium as

$$\frac{\partial T}{\partial t} = \frac{g}{C_p}\frac{\Delta F}{\Delta P} \times 24\,(\mathrm{hr/day}) \times 3600\,(\mathrm{sec/hr}), \qquad (2)$$

where $\partial T/\partial t$ is heating rate in kelvin per day ($Kday^{-1}$), g/C_p is lapse rate, g is acceleration due to gravity, C_p is specific heat capacity of air at constant pressure (1006 $Jkg^{-1}\,K^{-1}$), ΔF is atmospheric forcing due to aerosols, and ΔP is atmospheric pressure difference, which was considered to be 300 hPa in the present case.

The estimated atmospheric daily heating rates during the study period are also shown in Figure 5 (in parenthesis). Heating rates are found to be increased to higher magnitudes (0.90 $Kday^{-1}$) on Diwali, which decreased afterwards to attain a lower magnitude (0.46 $Kday^{-1}$) on November 04. Average atmospheric heating rate was found to be 0.78 ± 0.11 $Kday^{-1}$ for the affected period, which is approximately 30% higher than the nonaffected period (average about 0.55 ± 0.07 $Kday^{-1}$). Considering the nonaffected period to represent normal atmospheric conditions, atmosphere is found to be heated up by 0.23 $Kday^{-1}$ due to enhanced aerosol loading related to burning of fireworks.

5. Conclusions

Increase of particulate number density is a common feature during fireworks burning event. During Diwali festival, fireworks are burnt in peak duration of 1-2 hours. An intensive observation program was conducted from October 29 to November 04, 2005 (Diwali on November 01.) at an urban location in Indo-Gangetic Plain, Varanasi, India, to study the optical properties of aerosols, radiative forcing, and atmospheric heating rates caused due to Diwali fireworks.

Study shows enhancement of ~27% in the values of AOD_{500}, absorption coefficients, and scattering coefficients for firework affected period in comparison to nonaffected period. Estimated top of atmosphere and surface forcing were found to be $+10 \pm 1$ and $-31 \pm 7\,Wm^{-2}$, respectively, for firework affected period and $+12 \pm 1$ and $-17 \pm 5\,Wm^{-2}$, respectively, for nonaffected periods. The estimated forcing caused an additional cooling of ~20% at top of atmosphere and ~45% at surface due to enhanced loading of aerosols (absorbing and/or scattering type) over the station during firework period. The resultant atmospheric forcing was $+41 \pm 6$ and $+29 \pm 4\,Wm^{-2}$ during firework affected and nonaffected periods, respectively, which exerted an additional atmospheric heating of ~0.23 $Kday^{-1}$ during firework affected period. In view of increasing population and extensive use of fireworks (and crackers) in major urban locations, the routine measurements of aerosols will certainly be helpful to understand the additional burden of aerosols caused due to fireworks burning. Such observations are also useful for understanding their impact on regional climate.

Acknowledgments

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