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Cultural and Ritual Burning Emission Factors and Activity Levels in India

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ABSTRACT

Real-world particulate matter, organic carbon, and elemental carbon (OC and EC) emission measurements were measured for different cultural and ritual burning practices. These were (g/kg): 11.36 (OC), 0.27 (EC) and 31.04 (RPM) for Marriage Events; 27.04 (OC), 0.18 (EC) and 123.82 (RPM) for Muslim Holy Shrines; 25.99 (OC), 0.85 (EC) and 47.93 (RPM) for Buddhist Temples; and 3.47 (OC), 7.96 (EC) and 20.13 (RPM) for Hindu Temples. When projected to reasonable levels of such activities throughout India, the total annual emissions would be 72.38 Gg/yr, comparable to those from transport (165 Gg/yr), power plants (19 Gg/yr), agricultural waste burning (428 Gg/yr) and forest and savannah burning (176 Gg/yr).

Keywords: Emission factors; OC and EC fractions; Cultural and ritual performances; Combustion activities; Asian Brown Haze.

INTRODUCTION

"Brown Clouds" are caused by a mixture primary and secondary particulate matter (PM) generated from engine exhaust, biomass burning, and industrial processes (Smith *et al.*, 1983; Reiner *et al.*, 2001; Streets *et al.*, 2003; Yan *et al.*, 2006; Witham and Manning, 2007). Atmospheric elemental carbon (EC) and organic carbon (OC) are the major primary PM constituents emitted by inefficient combustion of fossil fuels and biomass (USEPA, 2012; UNEP and NOAA, 2003). EC and OC occur together in PM as soot, and their combination is important for climate change because EC absorbs solar radiation, potentially contributing to global warming (Jacobson, 2001; Jacobson, 2002; Hansen and Nazarenko, 2004; Bond and Sun, 2005; Ramanathan *et al.*, 2007). However, EC/OC soot also scatters solar radiation back into space, which may counteract the warming effect. Water-soluble OC may be mixed in liquid water, thereby modifying its optical properties and affecting the formation and surface tension of cloud droplets (Hallett *et al.*, 1989; Saxena *et al.*, 1995; Rivera-Carpio *et al.*, 1996; Saxena and Hildemann, 1997; Soto-Garcia *et al.*, 2011).

In India, large amounts of EC and OC are emitted from agricultural crop residue burning (Streets *et al.*, 2003; Vadrevu *et al.*, 2008; Gadde *et al.*, 2009; Rehman *et al.*, 2011; Sahai *et al.*, 2011), fossil fuel combustion in residential (Raiyani *et al.*, 1993; Kandpal *et al.*, 1995), industrial sectors (Sharma and Vyas, 2001; Ghose and Majee, 2003; Mishra, 2004), and transportation (Ghose *et al.*, 2004; Pal *et al.*, 2009; Nesamani, 2010; Apte *et al.*, 2011; Reynolds *et al.*, 2011), forest fires (Vadrevu *et al.*, 2006; Badarinath *et al.*, 2007; Vadrevu *et al.*, 2011) and other activities. EC and OC emission factors from religious and ritual burning activities have not been adequately characterized, nor have the amounts of material burned each year been estimated. This study measures these emissions factors, quantifies the activity levels, and estimates contributions to brown cloud formation for several types of Indian religious rituals.

There are ~3.0 million religious worship places in India, more than the number of educational and health centres in India (Ministry of Health and Family Welfare, 2011; Office of registrar general, 2012). In a Hindu marriage, the couple transits seven circuits around a Holy Fire fuelled by the materials described elsewhere (Dewangan *et al.*, 2013, 2014). Besides these ritual activities, different religion oriented worship places (Hindu Temples, Muslim Holy Shrines and Buddhist Temples) are also paid spiritual homage using flaming episodes by igniting different kinds of bio- and synthetic materials described elsewhere (Dewangan *et al.*, 2013, 2014). This study evaluates real-world emission conditions in contrast to other studies that examined emissions from specific types of incense (Lee and Wang, 2004; See and Balasubramanian, 2011) or biomass material (Yevich

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and Logan, 2003; Ito and Penner, 2005; Janhall *et al.*, 2010).

METHODOLOGY

Sampling Sites

Sampling was conducted at four different cultural and ritual places in Raipur city, District Raipur, Chhattisgarh, India: 1) Hindu Temples (HT), 2) Muslim Holy Shrines (MHS), 3) Buddhist Temples (BT) and 4) Marriage Places (MP). Raipur, the capital city of Chhattisgarh, India, is located in global scale of 21°14′22.7″N latitude and 81°38.1″E longitude (Fig. 1). Three separate examples of each of these four cultural/ritual venues were sampled when materials were burned. Description of sampling sites, the materials burned and a visual evaluation of the extent to which the burning was dominated by flaming (visible fire) or smouldering (visible smoke and embers) emissions were given elsewhere (Dewangan et al., 2013, 2014). Smouldering fires tend to contain more OC and have different optical properties relative to flaming emissions (Chen *et al.*, 2006, 2007; McMeeking *et al.*, 2009; Chakrabarty *et al.*, 2010). Concentrations of Respirable Particulate Matter (RPM, aerodynamic diameter < 5 μm), carbon dioxide (CO_2), and carbon monoxide (CO) were sampled from the smoke plumes. Before the in-plume sampling, background samples of gaseous pollutants and RPM were measured at each location for subtraction from the in-plume concentrations.

Sampling and Analysis

RPM was sampled onto 47 mm diameter quartz fibre filters (Whatman QMA) with three Envirotech Model APM 821 samplers equipped with a 5 μm 50% cut-point cyclone inlet at an average flow rate of 2.0 L/min. Three sampling units have been used in the emitted plume to evaluate field uncertainties of selected pollution parameters. The sampler inlets were moved to remain within the visible smoke plume. Quartz fibre filters pre-baked at 450°C for 5 h before sampling to remove residual carbon (Chow, 1995), were equilibrated in a controlled chamber (RH 45–55%, T 22–26°C) for 24 hours and weighed with a single pan top loading digital balance (Denver, Model, TB-2150) with ± 10 μg precision prior to and after sampling. Samples were

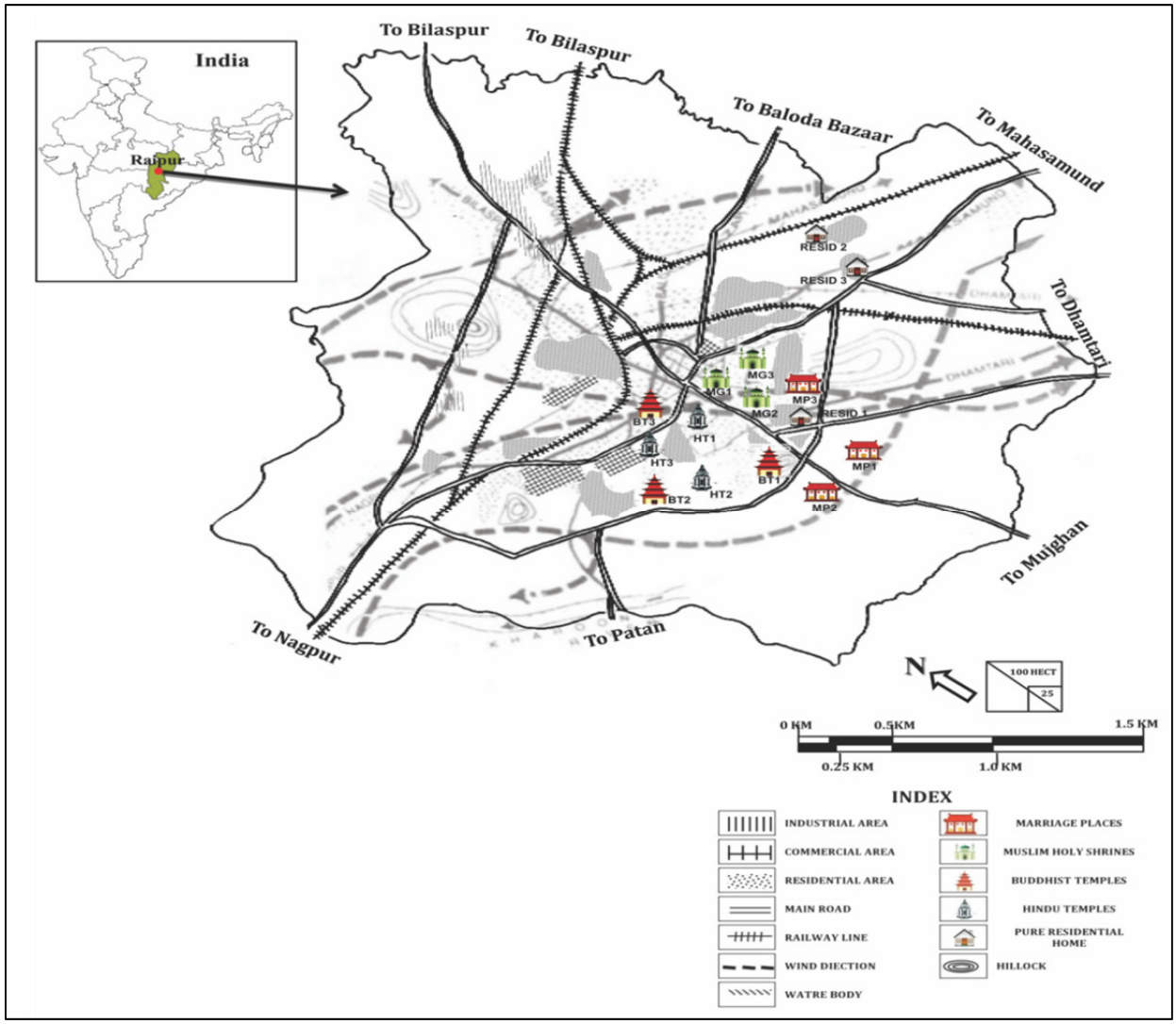

Fig. 1. Location map of cultural and ritual sites designed on the background map of wind channel over Raipur India.

stored at –4°C prior to further chemical analysis. Sample durations (min) and mass loading/filter (mg/filter) were: 215 to 320 min and 5.8 to 6.01 (MP); 120 to 150 min and 4.1–10.9 (MHS); 120 to 180 min and 2.94–3.21 (BT) and 120 to150 min and 0.16–0.3 (HT).

Five-minute CO concentrations were measured with a Non-Dispersive InfraRed (NDIR), (Langan Products Inc., San Francisco, CA, Model T15v) and CO_2 was measured with a collocated NDIR instrument (AZ Instrument Corporation, Taiwan, Model AZ 7755). Probes were placed in the smoke plumes next to the RSP inlet (Lee and Wang, 2004).

Eight carbonaceous fractions of OC and EC (OC1, OC2, OC3, OC4, OP, EC1, EC2, and EC3) were determined on 0.5 cm^2 punches taken from each sample using the IMPROVE_A thermal/optical reflectance protocol at the Desert Research Institute (Chow *et al.*, 1993; 2004; 2005; 2007; 2011). Field blank levels were determined in the same way, averaged, and subtracted from the sample measurements while propagating the standard deviation of the average blanks to compensate for adsorbed organic vapours on the quartz filters (Watson *et al.*, 2009; Chow *et al.*, 2010).

Emission Factors and Emission Rates

Emission factors are expressed as grams of pollutant emitted per gram of dry fuel burned (g/kg) (Andreae, 2001). By measuring the carbon content of the emissions, which is mostly in the form of CO_2 and CO, and estimating the carbon content in the fuel, these fuel-based emission factors can be estimated from the in-plume measurements as (Moosmüller *et al.*, 2003):

$$EF_i\ (g/kg) = \frac{\Delta C_i \times 1000\ (g/kg) \times C_{Fraction}}{(\Delta CO_2\text{-}C + \Delta CO\text{-}C + \Delta THC\text{-}C + \Delta PM\text{-}C)} \quad (1)$$

EF_i = Emission Factor of pollutant i in g/kg
ΔC_i = background-corrected concentration of pollutant i in mg/m^3
ΔCO_2-C = mass fraction of C in CO_2 in mg/m^3
ΔCO-C = mass fraction of C in CO in mg/m^3
ΔTHC-C = mass fraction of C in total hydrocarbon in mg/m^3
ΔPM-C = mass fraction of C in particulate matter in mg/m^3
$C_{Fraction}$ = carbon content in dry material

The THC and PM carbon are typically << 1% of the CO + CO_2 and can be neglected. Emission factors determined by this method are summarized in Tables 1 and 2.

Total carbon mass fraction $C_{fraction}$ in the dry matter was determined by weighted ratio of different ingredients (biomass and synthetics) used in burning processes of selected cultural and ritual activities. One of the major ingredients used in all activities is bark of Shorea rodusta and mangifera tree which has carbon stock 36.8–50% compared to other regional species (32.4%) (Ragland *et al.*, 1991; Maharjan, 2012). Other major ingredients are cow dung & urine having carbon content of 38.6–42.5% (Haq and Haq, 2006); grains (43.4–44.2%) (Gullett and Touati, 2003; Dhammapala *et al.*, 2006, 2007a, b); incense matter (43.8 ± 3.3%) (Yang *et al.*, 2007). The resulting $C_{fraction}$ of different burning mixtures of bio/synthetic matters in selected cultural and ritual activities were 52% for MP, 54% for MHS, 63% for BT, and 45% for HT.

This can be translated into total emissions by summing over the products of emission factors and activities for the different sources.

$$E_i = \Sigma M_j \times EF_{ij} \quad (2)$$

where E_i = total emissions of pollutant i (Gg/yr), M_j = amount of dry material burned (kg) for source j, EF_{ij} = emission factor of pollutant i from source j in g/kg. The process for estimating the amount of material burned is illustrated elsewhere (Chakrabarty *et al.*, 2014).

RESULTS AND DISCUSSION

Burning Characteristics of Selected Sites

In BT, candles and incense sticks dominate the burning with most of smouldering stage (upon extinction) occur in burning of incense, whereas sooting burn stage is occurred in candle (Pagels *et al.*, 2009). Incense sticks contain charcoal, glue powder, aromatic wood and bark and synthetic chemicals common to the perfume industry (Jetter *et al.*, 2002; Chang *et al.*, 2007). Candles are mostly made of paraffin, by-product of hydrocarbon. Candle emission is associated with three different modes of burning, which are defined as steady bum, unsteady bum and smoldering (Sun *et al.*, 2006; Wright *et al.*, 2007). In MHS, incense sticks and Syrax benzoin are being used for worshipping activity. Styrax benzoin, a gum of Shorea robusta tree, burn on ember; completely in smouldering phase (incomplete combustion), releases higher amount of white-brownish smoke (Dewangan *et al.*, 2013, 2014). Burning practices in MP and HT also use mostly biomaterials but in different proportions and burning phases. Solid bio-materials are mostly used in MP with flaming and smouldering episodes simultaneously, while vegetable oil is mainly used in burning practices involved with HT and mostly with flaming episodes (Dewangan *et al.*, 2013, 2014).

Emission Characterization of Burning Practices

The EFs of gaseous pollutants and RPM have been given in Table 1. The highest CO_2 EF was 1762.48 ± 159.88 g/kg for the BT, while the lowest 1378.20 ± 98.78 g/kg was found for the HT. The EF of CO_2 is much higher than that from a previous study (Wang *et al.*, 2007). The CO EF was highest at the MHS at 315.16 ± 11.82g/kg with the lowest EF of 119.16 ± 23.76 g/kg found for MP. EFs of these pollutants are entirely different from that of specific matters and in laboratory modelling scale; burning events having major ingredients of incense (MHS and BT) have shown comparable EF values of CO_2 and CO compared to earlier work on laboratory scale (Wang *et al.*, 2007). RPM EF were highest for the MHS, averaging 123.82 ± 14.85 g/kg and lowest for the HT (20.13 ± 2.05 g/kg). RPM EFs have shown higher agreement with earlier reported EFs for incense burning (Wang *et al.*, 2007). EFs of OC and EC for all sites have given in Table 2. The EFs of eight carbon

Table 1. Emission factors (g/kg) for Indian different cultural and ritual based burning activities.

Location \ Species	CO_2	CO	RPM
MP	1697.50 ± 274.49	119.16 ± 23.76	31.04 ± 5.90
MHS	1408.92 ± 6.38	315.16 ± 11.82	123.82 ± 14.85
BT	1762.48 ± 159.88	303.08 ± 26.94	47.93 ± 7.19
HT	1378.20 ± 98.78	158.23 ± 0.23	20.13 ± 2.05

Table 2. Emission Factor (g/kg) of carbon fraction in different cultural and ritual places in India.

Sites \ Species	O1TC	O2TC	O3TC	O4TC	OPTTC	OC
MP	3.01 ± 0.15	5.63 ± 0.28	1.39 ± 0.07	0.40 ± 0.02	0.93 ± 0.05	11.36 ± 0.58
MHS	17.75 ± 0.89	5.31 ± 0.27	1.85 ± 0.11	0.81 ± 0.05	1.32 ± 0.07	27.04 ± 1.38
BT	4.28 ± 0.22	16.63 ± 0.84	2.88 ± 0.16	0.95 ± 0.05	1.25 ± 0.07	25.99 ± 1.33
HT	0.22 ± 0.02	0.63 ± 0.05	0.58 ± 0.11	0.13 ± 0.04	1.92 ± 0.12	3.47 ± 0.33

Sites \ Species	E1TC	E2TC	E3TC	EC	TC
MP	1.18 ± 0.06	0.02 ± 0.0001	0.00 ± 0.001	0.27 ± 0.01	11.63 ± 0.59
MHS	1.49 ± 0.08	0.01 ± 0.001	0.00 ± 0.001	0.18 ± 0.01	27.22 ± 1.39
BT	2.05 ± 0.11	0.04 ± 0.01	0.01 ± 0.001	0.85 ± 0.05	26.84 ± 1.37
HT	0.49 ± 0.04	9.37 ± 0.49	0.01 ± 0.001	7.96 ± 0.42	11.43 ± 0.75

fractions have also been evaluated in this study. MHS and BT showed similar EFs of 27.04 ± 1.38 g/kg and 25.99 ± 1.33 g/kg, respectively. OC EFs are higher than reported values from biomass burning (5.8 ± 2.9 g/kg) (Crutzen and Andreae, 1990); fuel wood (4.4 g/kg) (Cachier, 1998); dung cake (0.25 g/kg) (Venkataraman *et al.*, 2005) and agricultural residues (3.3 g/kg) (Bond *et al.*, 2004). OC EF values for fossil fuels (coal, diesel, gasoline, kerosene and LPG) consumed in transport and residential areas (Bond *et al.*, 2004) have shown several fold lower trend compared to the present study. For EC, the highest EF was found for the HT (7.96 ± 0.42 g/kg), 3.6 times higher than reported EF values for biomass burning (2.2 ± 1.1 g/kg) (Crutzen and Andreae, 1990); six to ten-fold higher than crop residue (0.75 g/kg) (Turn *et al.*, 1997; Parashar *et al.*, 2005); two to fifty-fold higher than dung cake (0.17 g/kg) (Parashar *et al.*, 2005; Venkataraman *et al.*, 2005); twenty fold higher than charcoal consumption (Parashar *et al.*, 2005; Venkataraman *et al.*, 2005). EC EFs in the present study have shown exceptionally high levels compared to diesel fuel use (0.84 g/kg); gasoline use (0.19–5.4 g/kg); kerosene use (0.9 g/kg) and LPG use (0.2 g/kg) in transport and residential sectors (Bond *et al.*, 2004). Most of earlier studies on EFs determination for carbonaceous aerosols from cultural/ritual burning practices are focused on burning of incense sticks, whereas this study is conducted on different types of ritual burning practices involved different types of synthetic and bio-synthetic materials along with/without incense sticks. Hence the burning characteristics involved with these combustion activities have shown frequent variation in flaming and smouldering episodes; and it is one of the major reasons with higher emissions of organic aerosols in this study.

As far as EFs of eight fractions of OC and EC are concern, OC1, major marker of biomass burning (Lai, 2010) has been found to be highest in MHS (17.75 ± 0.89 g/kg) and lowest in HT (0.22 ± 0.02 g/kg). This trend might be due to the fact that combustion of Styrax benzoin, a biomaterial is predominant in MHS. EFs of OC2, OC3 and OC4 have shown higher fraction in BT (16.63 ± 0.84 g/kg, 2.88 ± 0.16 g/kg and 0.95 ± 0.05 g/kg respectively) than that in other sites due to use of fossil fuel based candle materials (paraffin wax) and incense sticks as burning material used in BT (Orecchio, 2011; Dewangan *et al.*, 2013, 2014). In case of burning practices involved with BT, candles are lightened with burning of incense sticks and quantity of incense sticks are higher compared to those of candles. Accordingly, smoke released from incense burning (smouldering phase) dominated over candle smoke; produced higher OC2, OC3, and OC4 fractions. OC2 and OC3 represent the semi-volatile organic compounds with increasing molecular weights, whereas OC4 components may consist of a mixture of high boiling point hydrocarbons e.g., PAHs (Grabowsky *et al.*, 2011; Joseph *et al.*, 2012). Pyrolyzed organic carbon (OP), an indicator of water soluble organics (Yang and Yu, 2002) has shown uniform EFs values in all sites: HT (1.92 ± 0.12 g/kg), MHS (1.32 ± 0.07 g/kg), BT (1.25 ± 0.07 g/kg) and MP (0.93 ± 0.05 g/kg). OP is associated with water soluble organic carbon (Cao *et al.*, 2004) which accounts for a large fraction (13–66%) of charring. In this study, all the selected cultural/ritual burning practices involved combustion of mainly wood material along with other natural bio-materials; responsible to enhance charring (Yu *et al.*, 2002).

On the other hand, EC fractions, reported to be the fractional masses of soot (EC2 + EC3) and char (EC1 – OP) emissions (Han *et al.*, 2009; Cao *et al.*, 2013), have shown different EF values in HT compared to other sites. Char has been observed to be dominant in emissions resulting

from burning practices involved with MP, MHS and BT, whereas soot is predominant in case of HT. EC1 was the dominant elemental carbon fraction in emissions resulting from all cultural /ritual sites except HT. In case of HT, EF of EC2 (9.37 ± 0.49 g/kg) was much higher than those measured in MP (0.02 ± 0.0001 g/kg), MHS (0.01 ± 0.001 g/kg) and BT (0.04 ± 0.01 g/kg). In HT, vegetable oil and cotton were used for burning practices which mostly consists flaming episodes; produces soot particles containing mainly EC2 (Cao *et al.*, 2013). During sooting burning stage, these materials burned with higher amount of black smoke and emit larger particles mainly consisting of agglomerated elemental carbon (Pagles *et al.*, 2009). The EFs of EC3 were lowest in all cultural/ritual sites due to absence of high temperature burning practices at ≥ 800°C (Gu *et al.*, 2010).

Annual Emission Budget

Total Indian RSP emissions from these cultural/ritual sites were 72.38 ± 4.71Gg/yr, of which 24.35 ± 2.17 Gg/yr was in the form of OC and 48.026 ± 2.529 Gg/yr was in the form of EC (Table 3). Of these, the major OC source was HT, which constituted 90% cultural RPM, 86% of cultural OC, and 100% of cultural EC emissions. Both the emission factors and the activity level for this source are high, since 85% of Indian population is Hindu and follows these cultural and cultural -ritual. OC emission sources in order of magnitude are HT > MHS > BT > MP. For EC emissions, the order is: HT > MHS >BT > MP.

Some perspective on cultural ceremony emissions relative to other Indian emissions (Lu *et al.*, 2011) is provided in Table 4. Most of the earlier studies on emission estimates from cultural activities in India are mainly focused on fireworks events mostly occurred in festivals (Kulshrestha *et al.*, 2004; Barman *et al.*, 2008); agricultural waste burning (Cheng *et al.*, 2009; Favez *et al.*, 2009; Yevich and Logan, 2003) and temple/residential incense burning (Fang *et al.*, 2002; Jetter *et al.*, 2002; Lung and Kao, 2003; Lung *et al.*, 2007; Wang *et al.*, 2007) along with transport, total residential, industries, coals, oils and forests burning (Lu *et al.*, 2011). Annual emission estimates of OC and EC from cultural and ritual places has shown 2/5th part of those estimations from transport sector in India. Interestingly, power plant (19 Gg/yr) has shown lower emissions compared to emissions resulting from cultural places. Residential bio- and fossil fuel use has shown many folds higher emission estimation of OC compared to the present study due to profuse consumption of conventional household cooking fuels in India (Ramakrishna *et al.*, 1989; Smith, 1996; Taneja *et al.*, 2008; Padhi and Padhy, 2008). In contrast to OC emission estimation, EC has shown significant annual emissions from cultural and ritual activities compared to that from transport sector.

CONCLUSION

Crude statistics of cultural and ritual activity centres and quantity of burning materials has been tabulated for Indian scenario to determine OC/EC emission estimates from these potential sources. 72.380 ± 4.701 Gg/yr estimation of total carbon fraction from cultural and ritual activity centres in India will draw sincere attention to evaluate relationship between under developing source inventories and causes of Asian Brown Haze. Variation pattern in carbon emissions with respect to their organic and elemental character has also been quantified with observations of flaming and smoldering episodes. Chief sources of brown haze has been predicted in earlier researches are domestic wood and dung fires, smoke generated during the burning of forests and agriculture residue, vehicle exhausts, power plants and factory chimneys; drawing lower trend of correlation between sources and causes of brown haze (Srinivasan and Gadgil, 2002; Ramanathan *et al.*, 2005). To address the poor correlation between atmospheric carbon levels and already established sources, emission estimation of speciated carbon fractions (OC & EC) from cultural and ritual places will be useful.

AUTHOR CONTRIBUTIONS

S.P. and R.K.C. designed and led the study, including project coordination and manuscript preparation. S.P. and S.D. were involved with field measurements and data collection in India. R.K.C. and J.R. performed optical

Table 3. Emission Budget (Gg/yr) of carbon fraction in different cultural and ritual places in India.

Species / Sites	RPM	O1TC	O2TC	O3TC	O4TC	OPTTC
MP	1.08 ± 0.211	0.105 ± 0.005	0.197 ± 0.010	0.049 ± 0.003	0.014 ± 0.001	0.032 ± 0.001
MHS	10.94 ± 1.31	1.568 ± 0.079	0.469 ± 0.024	0.164 ± 0.009	0.071 ± 0.004	0.117 ± 0.006
BT	1.14 ± 0.17	0.102 ± 0.005	0.395 ± 0.020	0.068 ± 0.004	0.022 ± 0.001	0.030 ± 0.002
HT	121.41 ± 12.36	1.311 ± 0.137	3.817 ± 0.325	3.483 ± 0.618	0.760 ± 0.212	11.581 ± 0.706
Total	134.57 ± 14.05	3.085 ± 0.226	4.877 ± 0.379	3.764 ± 0.633	0.868 ± 0.218	11.759 ± 0.715

Species / Sites	OC	E1TC	E2TC	E3TC	EC	TC
MP	0.397 ± 0.020	0.041 ± 0.002	0.001 ± 0.0001	0.0001 ± 0.00002	0.009 ± 0.001	0.406 ± 0.021
MHS	2.388 ± 0.122	0.132 ± 0.007	0.001 ± 0.0004	0.0001 ± 0.00001	0.016 ± 0.001	2.404 ± 0.123
BT	0.617 ± 0.031	0.049 ± 0.002	0.001 ± 0.0001	0.0002 ± 0.00004	0.020 ± 0.001	0.637 ± 0.033
HT	20.952 ± 1.998	2.960 ± 0.243	56.524 ± 2.945	0.078 ± 0.043	47.981 ± 2.526	68.933 ± 4.523
Total	24.354 ± 2.171	3.181 ± 0.254	56.527 ± 2.946	0.078 ± 0.044	48.026 ± 2.529	72.380 ± 4.701

Table 4. Emission Estimates of EC & OC by different burning activities in India (Gg/yr) (Source - Lu *et al.*, 2011).

S. NO.	Area	Year 2010	
		Elemental Carbon	Organic Carbon
1	Power Plant	5	14
2	Industry	227	214
3	Residential	579	1946
4	Transport	111	54
5	Coal	295	346
6	Oil	159	72
7	Biofuel	454	1792
8	Forest and Savanna Burning	19	157
9	Agricultural Waste Burning	74	354
10	Cultural and Ritual Based Burning*	48.026*	24.354*

* Data from this study.

characterization and R.K.C., S.P., S.D., J.R., J.C.C., and J.G.W. were involved with data analysis. All authors discussed the results and contributed to the manuscript.

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