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Absorbing Aerosols, Possible Implication to Crop Yield - A Comparison between IGB Stations

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ABSTRACT

The current study compares black carbon radiative effects at the densely populated plain station, Varanasi and the lesser populated plateau station Ranchi with large forest cover but with numerous open coal mines. While the measured average black carbon mass density (BC) reduces from February to March at Ranchi following an increase in convective mixing, it is observed to increase by 150% from February to March in Varanasi, as transport from northeast forest fires increases. It is observed that absorption due to black carbon of non-fossil fuel origin is prevalent throughout the day, in Varanasi, while this contribution is most significant during post sunset hours in Ranchi. Radiative forcing, estimated hourly using chemical model (to derive BC-aod) and radiative transfer model, indicates that at least 5% of the incoming radiation is always cutoff during any time of the day in Varanasi while this is about 4% in Ranchi. BC effectively causes an apparent delayed sunrise by reducing the incoming radiation on the plains of Indo Gangetic Basin (IGB) by up to 25% at the daybreak. An estimate of crop loss due to cut off in radiation, using an empirical formula for crop yield as a function of radiation, indicates a possible loss of more than a quintal per hectare considering anthesis (February) and maturity (March) periods for the winter wheat in both the IGB stations with consistently higher losses in Varanasi.

Keywords: Black carbon; Radiative forcing; Biomass burning; Coal mines; Crop loss.

INTRODUCTION

Populated tropical underdeveloped and developing countries are known for the black carbon production due to burning of easily available firewood for cooking and other daily activities. Enhanced biomass burning is bound to continue in these areas due to poor regulations that stem from various reasons such as high population intensity, political reasons, agricultural practices, easy availability of firewood from evergreen forest cover and favorable climate regime. However, knowledge of the magnitude of burning would help administration to try and control or make it efficient. In a recent study on the project, 'Surya village', it is concluded that the BC mass concentration at that place is about an order more than that in the developed countries (Praveen *et al.*, 2012), but most of the developed countries are geographically located in the mid-latitudes or extra tropics. On the other hand, urbanization, that is part of development, continues to pump into the atmosphere black carbon and other pollutants as elsewhere happening in the world. Knowledge of their partition as well as source is also needed to bring in curbing measures optimally. A review (Cheng *et al.*, 2011) of mass absorption efficiencies of elemental carbon, indicates that the urbanized areas exhibit high absorption efficiency values as compared to the rural areas (biomass burning dominated environment).

Aerosols including black carbon are the most widely varied, short-lived and their effect still remains puzzling since their interaction gets complicated with various dynamical phenomena of the atmosphere, especially the boundary layer with higher aerosol density. The complexity increases as carbonaceous aerosols are an aggregate of numerous poorly characterized species varying in their thermal, optical and chemical properties (Pöschl, 2005; Andreae and Gelencsé, 2006). Therefore, compared to other aerosols like mineral dust or sulfates, their characterization is highly difficult. An evaluation of earlier studies (Kirchstetter *et al.*, 2004) on spectral dependencies of BC, connecting source and absorption angstrom exponent, emphasizes on the difficulty to have a clear demarcation with source bifurcation or association with any typical activity as the properties tend to overlap.

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While BC characterization is complex, the radiation cutoff that it causes tend to interfere with different processes, especially during the day break, specifically affecting early morning startup time of photosynthesis and its accelerated rate thereafter. In this study we try to bring out the comparison of BC concentrations at two stations, their nature, apparent causes and the effect they could have on agriculture as IGB is known for its agriculture economy.

STATION DESCRIPTION AND DATA

The observations used for this work were collected using 7 wavelengths Magee Scientific make aethalometer (AE-31 model) during February–March, 2011 at the mining plateau station, Ranchi (23.3°N, 85.3°E) and for the same months but in 2012 at Varanasi (25.3°N, 83°E) in the central Indo Gangetic Basin, IGB (Fig. 1). According to the climatology records, (1991-2000, IMD) Varanasi (Ranchi) experiences a minimum temperature of 11.3 (12.6)°C and a maximum 26.7 (25.8)°C with a precipitation 15 (25.7) mm in February and 16.3 (17)°C, 33 (31.2)°C, 7.9 (15) mm respectively in March (www.imd.gov.in). Major crops in the districts of Varansai and Ranchi are rice and wheat that are grown in summer (Khariff) and winter (Rabi) seasons respectively. In February and March rabi crops are usually in full grown stage to be harvested in April. Varanasi is at an altitude of about 80 m AMSL and the observation site in Varanasi (Banaras Hindu University, Varanasi) is about 3 km away from the banks of the holy river Ganges. Ranchi has an average altitude of 650 m AMSL and the measurement site in Ranchi (Birla Institute of Technology, Ranchi) may qualify for semi-urban/rural type away from the town by about 12 km with considerable tree cover on both sides. The site is situated in a sprawling campus of the technical education institute with regular activities. At both stations, the aethalometer sampled air at about 5 m above ground level on the first floor of the respective buildings with identical settings at 5 minute interval averaged for that period. MODIS-Terra satellite data were used for other required inputs and parameters (like albedo, water vapor and ozone to estimate BC radiative forcing) for both stations due to non-availability of the in-situ measurements for Varanasi, though detailed complimentary measurements were available in Ranchi. Ranchi also had concurrent measurements of skyradiometer for aerosol optical depth (AOD). NOAA-Hysplit back trajectories (http://www.arl.noaa.gov/ready/hysplit4.html) were used to know the possible aerosol transport source. Period of measurement, February-March, was chosen so that, being the transition period (between winter and pre-monsoon), the effect of changing wind direction and thermal condition could be observed. Moreover, these may also be used as representative months for winter wheat crop anthesis and maturity respectively.

INSTRUMENTATION AND METHODOLOGY

The main part of Aethalometer is the optical unit (analysis chamber), which consists of an aerosol inlet, the optical source assembly, the light guides for the photo-detectors and the filter tape support. High intensity LED lamps operating at 370, 470, 520, 590, 660, 880, and 950 nm are used as light sources for the multiwavelength measurements of BC concentration. The Instrument is operated with a flow rate, 4 LPM.

Principle of Operation

The absorption of broadband light, by an absorber such as graphitic carbon with particle size smaller than the

Fig. 1. Geographical locations of Varanasi and Ranchi marked in the map. Shaded portion indicates Indogangetic Basin (reproduced from Map 3.3 appearing in the online site of acair.gov.au).

wavelength of light, is inversely proportional to the wavelength of the light used. Thus, for a given mass of black carbon (BC), the optical attenuation at a fixed wavelength, λ may be written as

$$ATN(\lambda) = \sigma(1/\lambda) \times (BC) \quad (1)$$

where (BC) is the mass of black carbon, σ(1/λ) is the 'Specific Attenuation' which is the optical absorption cross section that is wavelength dependent. The above derivation assumes that the actual optical absorption is linearly proportional to the mass of absorbing material. Details of estimation of BC mass concentration and absorption coefficient from the measured attenuation coefficient are available in Hansen *et al.* (1984) and Arnott *et al.* (2005) respectively. The misinterpretation of scattering as absorption is commonly found in all the filter based optical instruments such as Aethalometer (Bond *et al.*, 1999). The sensitivity of aethalometer is directly related to flow rate. A typical flow rate of 4 LPM with a measurement period of 5 minutes introduces a measurement noise equivalent to 50 ng m^{-3}. These corrections are taken care of while analyzing the Aethalometer data following the method discussed in Sreekanth *et al.* (2007). In general, the estimated BC has an uncertainty of ~10–15%. Uncertainties, artifacts and issues regarding measurement of BC by aethelometer are available elsewhere (Gadhavi and Jayaraman, 2010; Harrison *et al.*, 2013).

Methodology

Spectral Absorption coefficients can be obtained by the formula:

$$abs\_coef = (-1/C(\lambda) \times R) \times (A \times \log_{10}(I_2/I_1)/Q. \times \Delta t \times 100) \quad (2)$$

We used a set of MATLAB programs for obtaining absorption coefficients from 7-channel aethalometer with λ = [0.37 0.47 0.521 0.59 0.66 0.88 0.95] for seven wavelengths and C(λ) = [2.355 2.656 2.677 2.733 2.827 2.933 2.925] for the corresponding seven wavelengths.

R = 1 (unity); Δt = 5 minutes (constant); Q = 4 LPM, Flow rate; A = 1.67 sq. cm (Area of the spot),

Simplifying further by substituting the values,

$$abs\_coef = 1.66995 \times 10^{-4} \times \Delta(ATN)/C(\lambda) \quad (3)$$

Optical properties of BC are obtained using OPAC (Hess *et al.*, 1998). BC mass concentration is converted to number density (1 µg m^{-3} = 16333 particles cm^{-3}) assuming '*continental polluted'* environment with a mass density of soot as 2.1 µg m^{-3}. BC particle concentration alone is input into the OPAC model as 'soot' and all other components are ignored to obtain BC optical properties (Sreekanth *et al.*, 2007; Latha *et al.*, 2014). Since soot (absorbing black carbon) is not soluble in water, its size is insensitive to the relative humidity in the model. Monthly mean mixed layer height, obtained from Geovanni-MERRA model (1° × 1.5°) is used. The OPAC-derived BC optical properties are used in SBDART (Ricchiazzi *et al.*, 1998) to get radiative fluxes with and without BC aerosols and then BC radiative forcing at surface, top of the atmosphere as well as atmospheric absorption. Other input to SBDART like daily columnar water vapor (1° × 1°) and ozone (Aura-OMI 0.5° × 0.5°) (http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html) are obtained from MODIS-Terra (Giovanni). Details of parameter values are given in Table 1.The standard tropical profile of temperature and water vapor mixing ratio is assumed. The standard tropical profile assumes a lapse rate of temperature (–dT/dz) as 6.25° km^{-1} for 0–4 km range. Surface temperature is taken as 300°K. Sensitivity of aerosol radiative forcing to changes in typical temperature and moisture profiles (from tropical to mid-latitude winter or summer) mentioned in SBDART is reported to be insignificant (Latha *et al*, 2013). Exponential decrease of aerosol concentration is assumed. A solar spectral band of 0.3–3.0 µm and monthly mean surface albedo from MODIS-Terra is used in SBDART to compute hourly BC radiative forcing.

ANALYSES AND DISCUSSION

Spectral BC Mass Density

Mean monthly diurnal mass density expressed in µg m^{-3} measured by aethalometer for 880 and 370 nm is plotted in Fig. 2. Mass densities at Varanasi for both February and March are higher than that in Ranchi. Varanasi shows

Table 1. Parameters used in SBDART model.

Month	Water vapor, cm	Surface Albedo	Ozone (DU)
Varanasi			
Feb-first half	1.85	0.171	0.255
Feb-second half	2.0		0.252
Mar-first half	2.0	0.176	0.262
Mar-second half	1.6		0.272
Ranchi			
Feb-first half	1.1	0.172	0.248
Feb-second half	1.9		0.27
Mar-first half	2.3	0.177	0.27
Mar-second half	1.5		0.31

Note: Daily columnar water vapor (1° × 1°) and ozone (Aura-OMI 0.5° × 0.5°) (http://disc.sci.gsfc.nasa.gov/giovanni/overview/index.html) are from MODIS-Terra (Giovanni). Monthly mean surface albedo from MODIS-Terra.

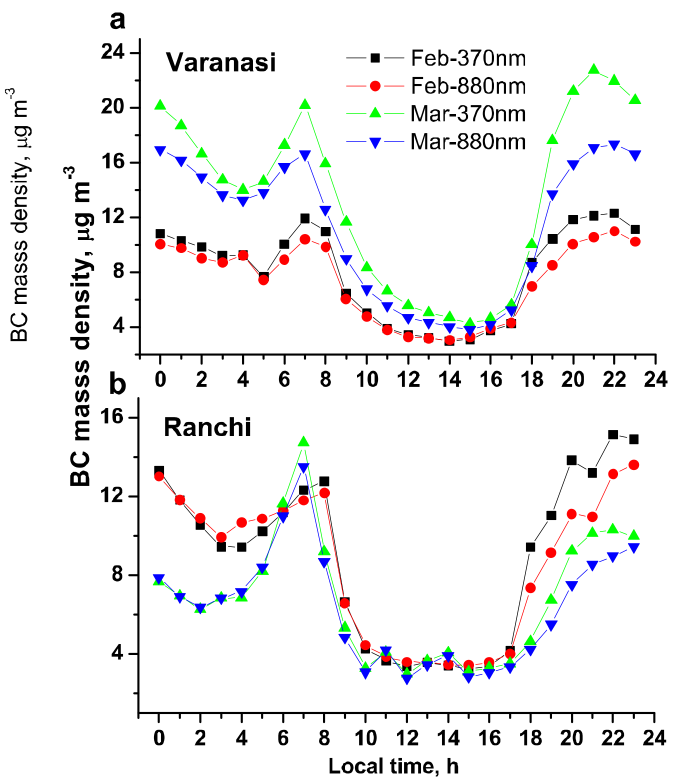

Fig. 2. Monthly diurnal variation of BC mass density in 370 and 870 nm wavelengths for February and March; a) for Varanasi (VNS) b) for Ranchi (RNC).

larger variability and concentration at 370 nm for March indicating more contribution to BC of biomass burning or organic origin. Similar to the general observation in all inhabited stations, BC diurnal variation displays morning and evening peaks along with an afternoon minimum. The nighttime BC is about double of the day-minimum in February at both stations and in March at Ranchi. At Varanasi, nighttime mean BC is about three times of the daily minimum. Daily average BC (880 nm) is 7.35 ± 2.89 µg m^{-3} and 11.27 ± 5.16 µg m^{-3} respectively at Varanasi in February and March 2012 while it is 8.51 ± 3.8 µg m^{-3} and 6.36 ± 2.9 µg m^{-3} respectively at Ranchi in February and March 2011. This has close comparison with Kharagpur as reported by Beegum *et al.* (2009) which is located in the east coast of India. BC values at Varanasi are apparently similar to that of SVLI (rural IGP) as reported by Praveen *et al.* (2012). Upadhyay and Singh (2010) reported average BC concentration in Varanasi at 14.5 µg m^{-3} for a period of 18 months, but for Ranchi monthly averages vary from 1.1 to 8.5 µg m^{-3} (Lipi and Kumar, 2014). BC exhibits a morning maximum around 0500–0800 h and evening maximum around 1800–2200 h with the day minimum between 1200 and 1400 h. For rural regions of India these variations are generally known which are associated with anthropogenic activity related to household chores with extensive biofuel usage. The general urban rush hour is for a shorter period, between 08–10 h and 17–20 h. The periods chosen for this study are also of meteorological importance as they represent night-stability breaking (08–10 h), well mixed and stability building up hours (17–20 h) for any day. Hence, we stressed upon the above time periods for further analysis. We also divided theses two months in first and second half to get an insight of transportation through back-trajectories. We used NOAA-Hysplit model to derive 5 day ensemble back trajectories for each month (February and March) ending on 7th, 14th, 21st and 28th (only 14th and 21st are shown for each month as they had significant difference), thus to observe prevalent air mass transport from probable source regions in each week. The other supporting data included in this study are the satellite derived fire counts and AOD to get an idea about the BC local source through fire and other aerosols those are present at these stations. Monthly fire count and daily AOD values derived from MODIS satellite together with skyradiometer in-situ observations of AOD at Ranchi are given in Fig. 3. Though the in-situ AOD observations are more or less at par with the February satellite output, for March skyradiometer measured AOD significantly surpasses satellite AOD at least by 50%. High fire count value in March at Ranchi supports this, but it does not reflect much in the BC mass density measurements. These differences may be caused by the disparities in measurement methodologies. It is noticeable that February with lower fire count exhibit higher BC density during late evening hours (Figs. 2 and 3). Increased human activity in connection with the National Games conducted during February within 1–2 km west of the measuring station and lower temperatures (higher stability) might have resulted in the increased BC. Numerous small local fires might be undetected by satellite though the satellite fire counts are numbered ten. The back trajectories (Fig. 4), for both the

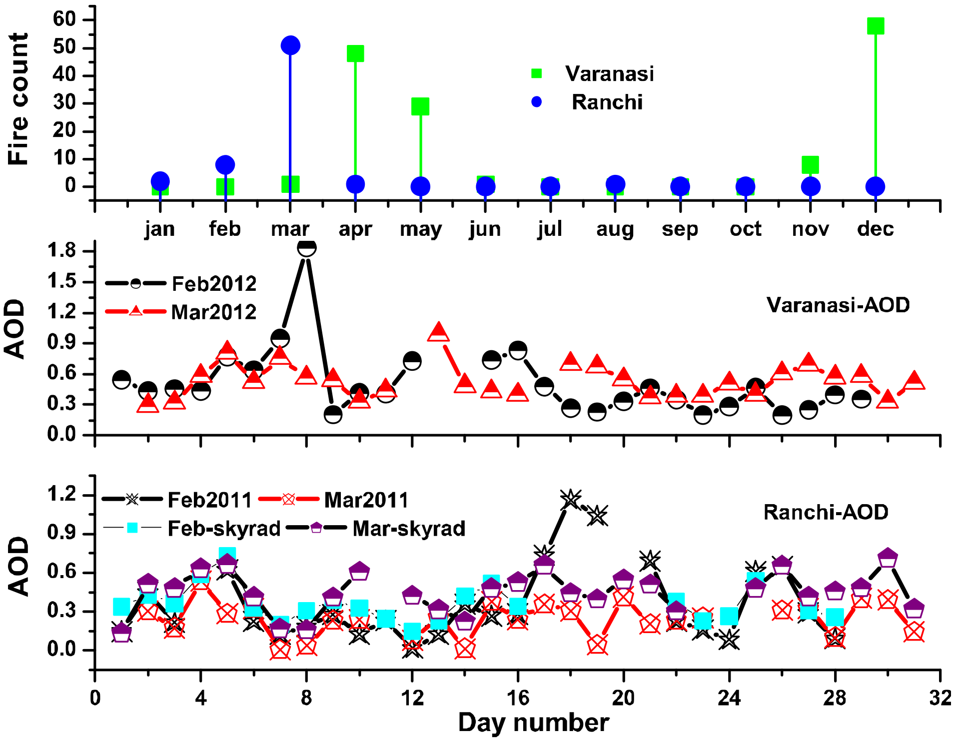

Fig. 3. Satellite derived fire count for Varanasi and Ranchi (top), AOD for Varanasi for February and March (middle), same for Ranchi along with sky-radiometer derived AOD (bottom).

stations are from northwest (NW) and winds are higher during the first half of February, capable of bringing in some amount of additional BC from small local fires ignited to fight cold in the cold NW region. Interestingly, over Varanasi fire counts are not reported till April, though the banks of 'Ganges' at Varanasi are crowded with "shamshan ghats" or open funeral pyre lighting grounds which are sources of BC. Moreover, various popular festivals happening in February and March increase the tourist influx to the station and associated anthropogenic activities. As rain events (IMD climatology) significantly reduce from February to March in Varanasi, unlike Ranchi, rain-related reduction of BC does not occur (Tang, 1996; Latha *et al*., 2014). This is reflected as an increase in BC mass density (Fig. 2). Moreover, the trajectory plots in Fig. 4 on March 14th and 21st at Varanasi clearly indicate a northeast shift. Emission inventory (Venkataraman *et al*., 2006) of open biomass burning states that forest fires are at their maximum in the northeastern (NE) states of India in March. Apart from the cremation grounds situated towards NE of the observation site acting as local source, the long range transport from forest fires also cause BC increase progressively at Varanasi as the upwind direction changes to NE. Diurnal pattern is slightly different at Ranchi in February compared to March with higher evening peak and delayed morning peak with similar day time concentrations. A significant increase in the number of fire counts fails to lift the BC levels considerably in March in Ranchi as they may not be reaching the measurement site. In the absence of low level transport, low BC concentration may be an outcome of the increase in ventilation coefficient (Gadhavi and Jayaraman, 2010).

Spectral Absorption Coefficient

The effect of biomass burning on the spectral characteristics of BC has been quantified using observations collected at a rural station in the lee side of the Western Ghats (Gadhavi and Jayaraman, 2010). There are a large number of observations of spectral absorption of BC worldwide in connection with biomass burning (e.g., Badarinath *et al*., 2009; Cheng *et al*., 2013) that indicate the influence of biomass burning on total BC absorption.

The spectral BC measurements are popularly made by aethalometer. As explained in the earlier section, aethalometer measurements assume specific cross sections and the absorption coefficients truly follow the mass density. Hence, we calculated aerosol absorption coefficient (AAC) at different wavelengths to characterize BC at these two stations. It is widely admitted that elemental/inorganic BC responds maximum to 880 nm, the organic carbon to 500 nm and brown carbon to 370nm, while measuring through optical methods and all other wavelengths respond to aromatic/carbon mixtures. Hence the slope of the spectral curve expresses the influence of carbon mixture in the total BC absorption. Our time slots (0500–0800, 1200–1400 and 1800–2200 h) are typical to characterize the influence of biomass burning; 1200–1400 h denotes generally a base level for the day and morning and evening peaks are the outcomes of household cooking/ wood/coal heaters, apart from the daily traffic surge hours. Since the back trajectory plots showed certain noticeable variations, that could be missed out on a monthly scale, we decided to analyze the AAC data fortnightly. These plots are shown side by side for both Varanasi and Ranchi in Fig. 5. The AAC at Ranchi

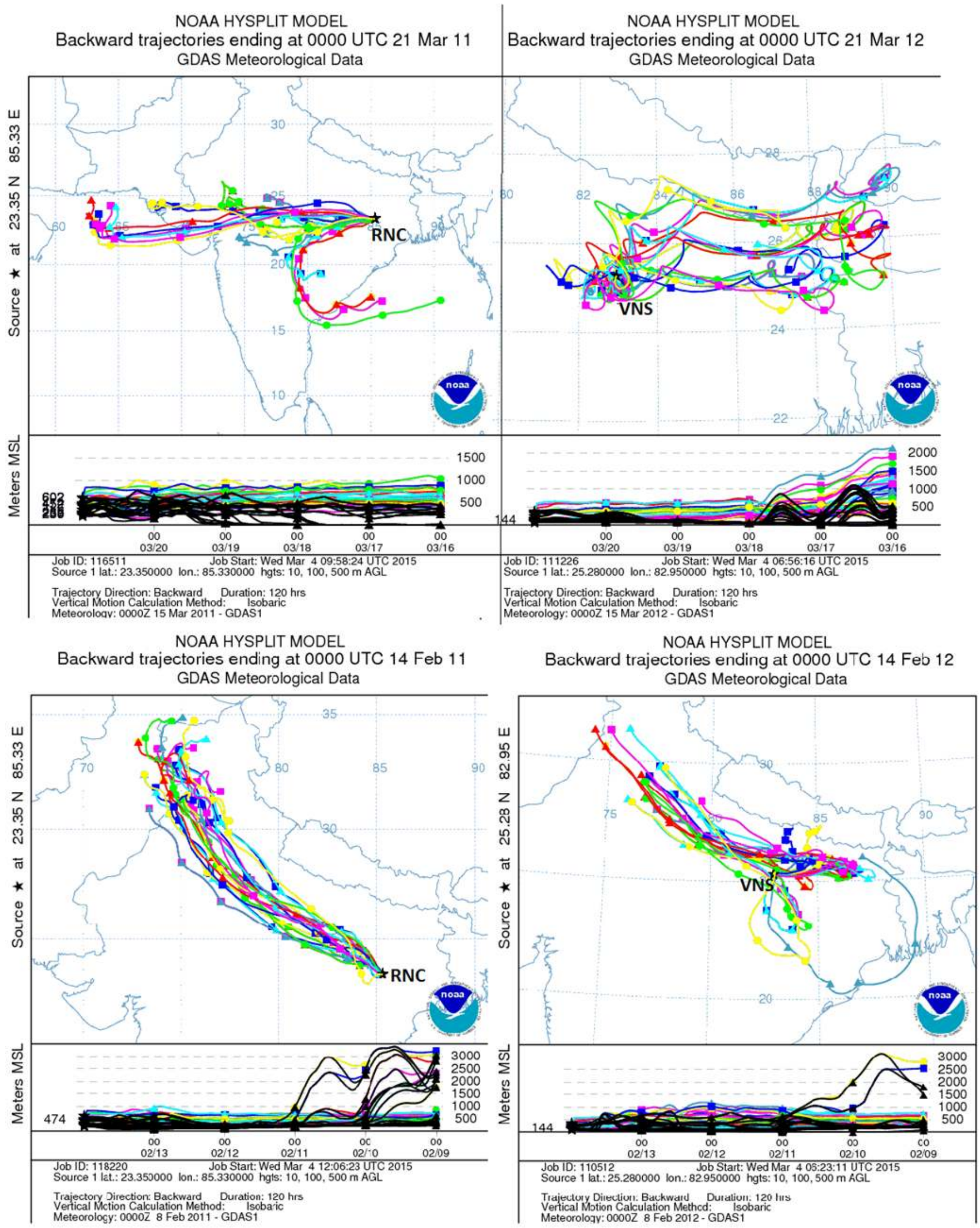

Fig. 4. Back trajectories (5 days) for Varanasi (right panel) and Ranchi (left panel) ending at 0000 UTC on 14 February 2011 (below) and 21 March (above).

for February first half (FFH) (figure not shown) is about 150% of that in February second half (FSH) for the time period 1200–1400 h. Apparently, activities in connection with 'National Games-2011', a national sports event, might have played a major role in elevating BC levels at this station during this period. Influence of biomass burning in the morning (0500–0800 h) and evening (1800–2200 h) are also more during FFH at Ranchi as indicated by the relatively higher slope of the AAC curves (Fig. 5). During FSH, (Fig. 4) winds are low and are flowing in from the vicinity and from lesser polluted regions towards the north at higher altitudes. Hence transported influx may not be significant that limits values of AAC (spectral AAC graphs not shown, instead normalized AAC are given in Fig. 5). At Varanasi, absorption due to BC is nearly equal in the first and second halves of February, the back trajectories also indicate transport from NW (Fig. 4). An increase of fire counts and shift of wind in the last week of March supports maintenance of BC at Ranchi.

Spectral curves of AAC for two sources of BC, i.e., burning

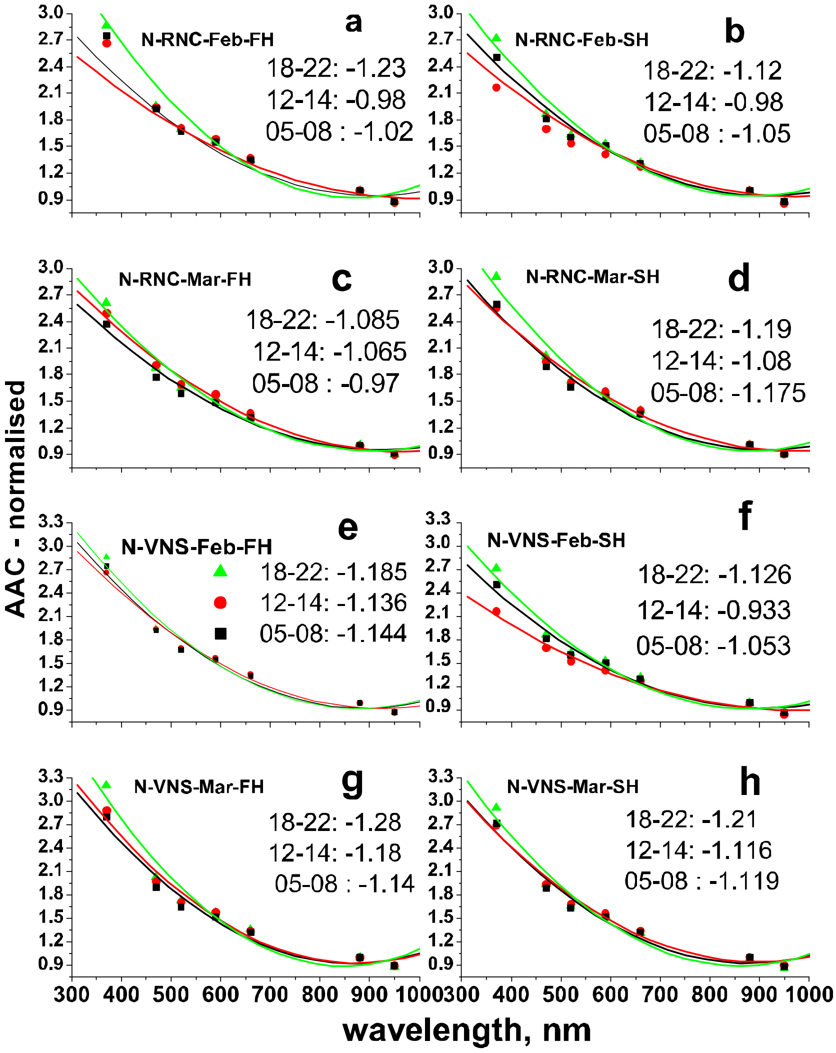

Fig. 5. Normalized absorption coefficient for Ranchi during February and March, (a–d) and same for Varanasi, (e–h); spectral absorption coefficients normalized with 880 nm. February first half (Feb-FH), second half (Feb-SH), March first half (Mar-FH) and second half (Mar-SH).

of leaves and the diesel engine are available elsewhere (Gadhavi and Jayaraman, 2010). The diesel exhaust has an almost linear spectral curve, but the fitted curve for leaf burning sources has a large curvature and exhibits about 6 times more absorption in the UV region than at 880 nm, the standard wavelength for BC (Gadhavi and Jayaraman, 2010). Normalized AAC curves (Figs. 5(a)–5(h)) show a mixed scenario in Varanasi as well as Ranchi for both the months. Biomass burning contribution is relatively low at Ranchi (Figs. 5(a)–5(d)) but different time slots are distinctly affected. Nighttime temperature and UV band absorption are seemingly well correlated, due to possible firewood/coal burning. An increase in the same during MSH, similar to FFH could be the outcome of local festivities. Varanasi is characterized by similar activities on all the three time slots except for FSH that shows slightly different slopes for each time period (Fig. 5(f)). It may be due to the limited transport under considerably low wind condition. Varanasi, being a religious locality, bio-fuel burning activity lasts the entire day, as seen by the more absorption in the UV band.

Soot particles emitted from biomass burning are reported to have values of α, angstrom exponent between 1.5 and 3 (Bergstrom *et al*., 2004; Kirchstetter *et al*., 2004; Clarke *et al*., 2007). Theoretical calculations (Bergstrom *et al*., 2002) showed that values of α will be 1.0 for small spherical particles having a uniform refractive index. For urban regions dominated by BC from fossil fuel (petroleum), it is indeed found to be 1.0 (Kirchstetter *et al*., 2004; Schnaiter *et al*., 2005; Sandradewi *et al*., 2008). However, our average values, between 370 and 880 nm, range from 0.98 to 1.23, except that values have been always above 1.0 for the Varanasi site (Table 2), an indication of more OC. Figs. 5(a)–5(h) are inscribed with the average values of α for the entire spectrum for all the three time periods for the respective duration under consideration. In FFH and FSH, α for the 1200–1400 hrs are below 1 due to the relatively lower content of OC or mixing of dust during that period. If UV and visible AAC (370–590 nm) values are only considered for calculation, α value is more than 1.5. Hence we would limit our interpretation that BC aerosols basically containing

Table 2. BC spectral characteristics and crop yield loss estimates.

parameter	Ranchi -2011				Varanasi -2012			
	F@370	F@880	M@370	M@880	F@370	F@880	M@370	M@880
AACmin,E-4 (12–14 h)	1.4	0.6	1.22	0.49	1.16	0.5	2.0	0.72
AACmax,E-4 (18–22 h)	4.97	1.79 (5–8)	4.3 (5–8)	1.71 (5–8)	4.4	1.57	7.32	2.44 (5–8)
NAACmax, 370/880 (18–22)	2.88		2.75		2.79		3.05	
AAE(370-880)(18–22)	–1.18		–1.13		–1.16		–1.245	
AAE(370-880)(12–14)	–0.98		–1.08		–0.995		–1.15	
ARF-bc, W m^{-2}	20		27.5		21		22.5	
GM, no m^{-2}	591		547		620		447	
GW, kg $spikelet^{-1}$	0.1		0.083		0.105		0.067	
Y, kg $hectare^{-1}$	79.1		70.7		83.1		57.8	

F: February; M: March; AAC: aerosol absorption coefficient; NAAC: AAC/AAC@880 nm; AAE: absorption angstrom exponent; ARF-bc: BC aerosol radiative forcing; GM: grain no per sq. meter; GW: grain weight/spikelet; Y: yield per hectare.

non-fossil fuel BC and also some definite organic BC, cannot be quantified with this study. While considering the ratios of BC at 370 and 880 nm at Varanasi, this ratio during all the three time slots are equal. In Ranchi, unlike this, the ratio is almost 1 during noon, slightly higher in the early morning and highest during late evenings (Table 2). However, these ratios point to the type of BC source, i.e., biomass burning or combustion of fossil fuel at the respective places; a domination of non-fossil based source at the Varanasi station is very much perceivable.

BC Radiative Forcing

BC radiative forcing (ARF-BC), defined as the radiation cutoff due to BC aerosols alone, is calculated as explained earlier and the results for Ranchi are shown in Figs. 6(a)–6(h) and for Varanasi are shown in Figs. 7(a)–7(h). ARF-BC, being dependent on mixing layer height, incoming solar radiation, etc., do not follow an exact variation as BC or AAC. Though daytime BC in Ranchi reduces from FFH to FSH, the ARF-BC remains similar due to other factors (Figs. 6(a) and 6(b)). On the contrary, though BC increases slightly from MFH to MSH, ARF-BC does show a slight reduction in the second half (Figs. 6(c) and 6(d)). The apparent reduction in MSH may be an artifact as monthly mixed layer heights are used for calculations, otherwise it is expected that as the incoming radiation increases, the mixed layer to grow higher and hence ARF-BC as per model calculations. The ARF-BC is calculated as hourly averages and maximum ARF-BC corresponds to BC values at noon. At 0800 h, while ARF-BC at surface/bottom at Ranchi exhibits steady small increments fortnightly, it is almost the same in Varanasi, except in MFH (Figs. 6(a)–6(c) and Figs. 7(a)–7(d)). However, peak ARF-BC (at surface) increase is felt more at Varanasi while it is rather steady at Ranchi. The maximum ARF-BC (surface) at 1200 h increases from –30Wm^{-2} in FFH to –40 Wm^{-2} in FSH and further to about –55 Wm^{-2} in March at Varanasi; at 0800 h, the increase is about 10 Wm^{-2} from February to MFH. Aerosol heating at the top of the atmosphere and atmospheric absorption also increase similarly.

To make the analysis more critical and quantitative, hourly ARF-BC (surface) is calculated and expressed as hourly % cutoff of the incoming solar radiation for 0500–0800 h and 1200–1400 h (Figs. 6(f) and 7(f)). About 25% of the incoming solar radiation is cutoff at Varanasi during 0600–0700 h with a minimum of 5% during 1200–1400 h (Fig. 7(f)). Since Varanasi is drier than Ranchi, temperature increases rapidly and so the mixed layer height. In tune with BC variation and mixed layer depth, BC-AOD calculated through OPAC increases and incoming radiation attenuation due to BC also escalates at Varanasi compared to that at Ranchi.

Here we present only ARF-BC, but other aerosols also cause a cutoff of the incoming radiation proportional to AOD. AOD based on satellite data is also higher over Varanasi in comparison to Ranchi, follows more reduction of incoming solar energy which is directly proportional to AOD. Earlier studies (Singh *et al*., 2010; Latha *et al*., 2013) have shown the importance of SSA, the ratio of scattering coefficient to extinction coefficient, which is crucially affected by absorbing aerosols (mainly BC), in increasing the aerosol radiative forcing. Since BC is higher in Varanasi, effective SSA also may be lower, increasing the effective radiation cutoff. This implies that such situations may exist at many locations of IGB. Recent aircraft observations under the RAWEX program (Babu *et al*., 2015) indicate that mean columnar SSA over Ranchi is relatively higher than that at the other IGB station, Lucknow or central India station Nagpur or even better than the western station Jaipur during winter which implies relatively more radiative forcing over these stations and higher associated impacts.

Effect of Radiative Forcing on Crop Yield

It is well recorded that photosynthesis (Bonan, 2008) in plants is at its peak immediately after sunrise, hence their productive cycle. The finding of the current study is that BC alone can delay the sunrise by reducing the radiation up to 25% during early morning, which is a serious situation for IGB where economy is largely dependent on agriculture. Such a reduction in energy could easily reduce the 'sunlit time'/ energy receiving time duration, required for plant functions that could obviously result in lesser flowering, lowering carbon fixing, hence the yield, on repeated occurrences. Unlike natural calamities or pest attack, this gradual loss of

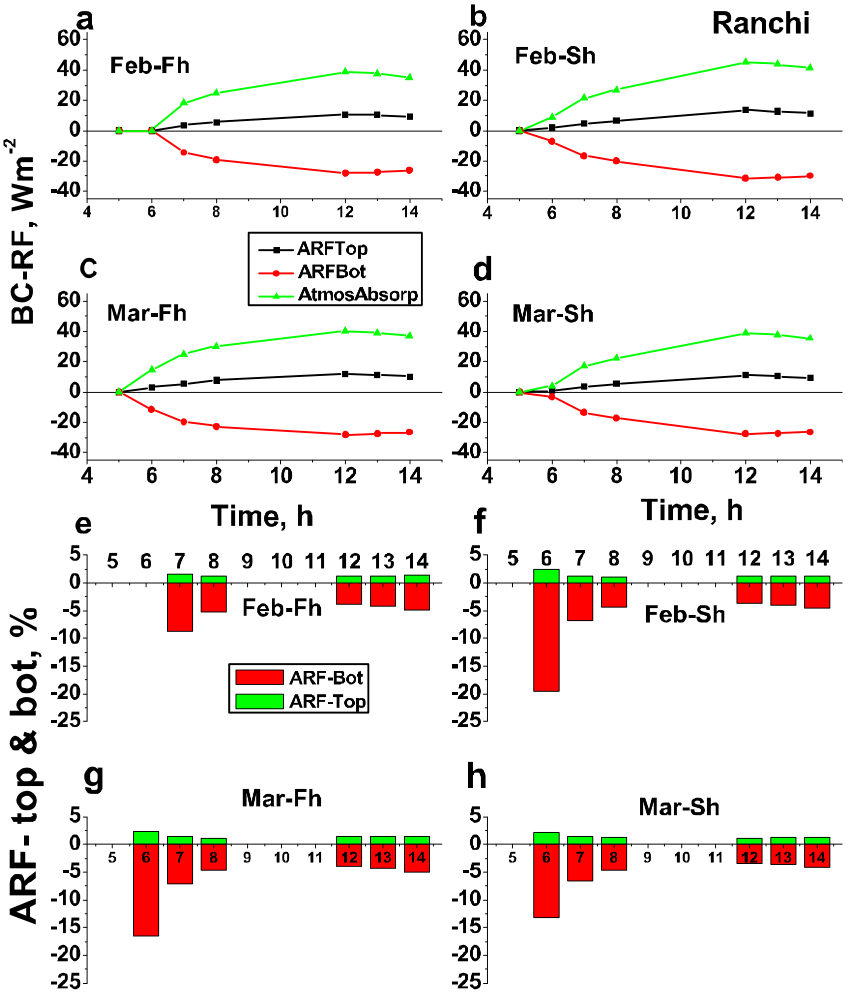

Fig. 6. ARF-BC (Aerosol Radiative Forcing -BC) at bottom, top and atmospheric absorption at Ranchi for a) Feb-Fh b) Feb-Sh (second half), c) Mar- Fh and d) Mar-Sh; ARF-BC percentage with respect to the radiation for aerosol-free atmosphere at bottom and top for d) Feb-FH, e) Feb-SH, f) Mar-FH and e) Mar-Sh at Ranchi.

agricultural production is not easily decipherable to the farmer. Earlier observations over Cassava canopy during solar eclipse have indicated reduction of solar radiation below a minimum threshold could stop photosynthesis completely and re-establish it as radiation increases beyond the threshold limit (Latha and Murthy, 2012). Loomis and Amthor (1996) have shown that PAR_A (photosynthetically active absorbed radiation) can be calculated from the fraction of solar radiation at the top of the canopy, which is transmitted to the ground (I/I_0), such that: $PAR_A = R_S \times 0.5 \times 0.9 \times (1 - I/I_0)$ where R_S refers to the total solar radiation (MJ m^{-2} d^{-1}); the factor 0.5 refers to the fraction of total solar energy, which is photosynthetically active; $(1 - I/I_0)$ is the fraction of total solar radiation flux, which is intercepted by the crop; and $0.9 \times (1 - I/I_0)$ is the fraction of radiation absorbed by the crop allowing for a 6 percent albedo and for inactive radiation absorption. Hence it is obvious that the reduction in radiation affects possible yield through reduction in photosynthesis, especially in winter with low radiation levels.

The Case of Winter/Rabi Wheat

As per India Government website of Department of Agriculture and Co-operation (www.agricoop.nic.in), wheat and peas are two of the major crops during rabi/winter-spring season for Varanasi and Ranchi districts. Wheat is sown generally from October to November end; with a period of about 150 days from sowing to cultivation, with the major stages as germination to anthesis (~115 days) and antheis to harvesting (~40 days). The first stage prefers a cold environment and the second stage needs longer days for maximizing the yield. For a crop, sown around October 15–31, there is a need of colder optimum temperature within 12–21°C (Acevedo *et al*., 2002). Cold winter temperatures prevailing till about February 15, over IGB region, would satisfy the requirement of 'Vernalisation (minimum cold temperatures in 0–7°C)' of the crop. Evans (1987), states that this necessity can be fulfilled with short days with temperature range 16–21°C. 'Antheis or floral induction' is faster as the day length increases (Evans *et al*., 1975; Major and Kinry, 1991). Major (1980) and Boyd (1986) found that reproductive phase ahead of floral induction is also photoperiod sensitive, shorter days leading to longer duration of this phase. However, Stefany (1993), observed that though shorter days prolong the days from 'double ridge to

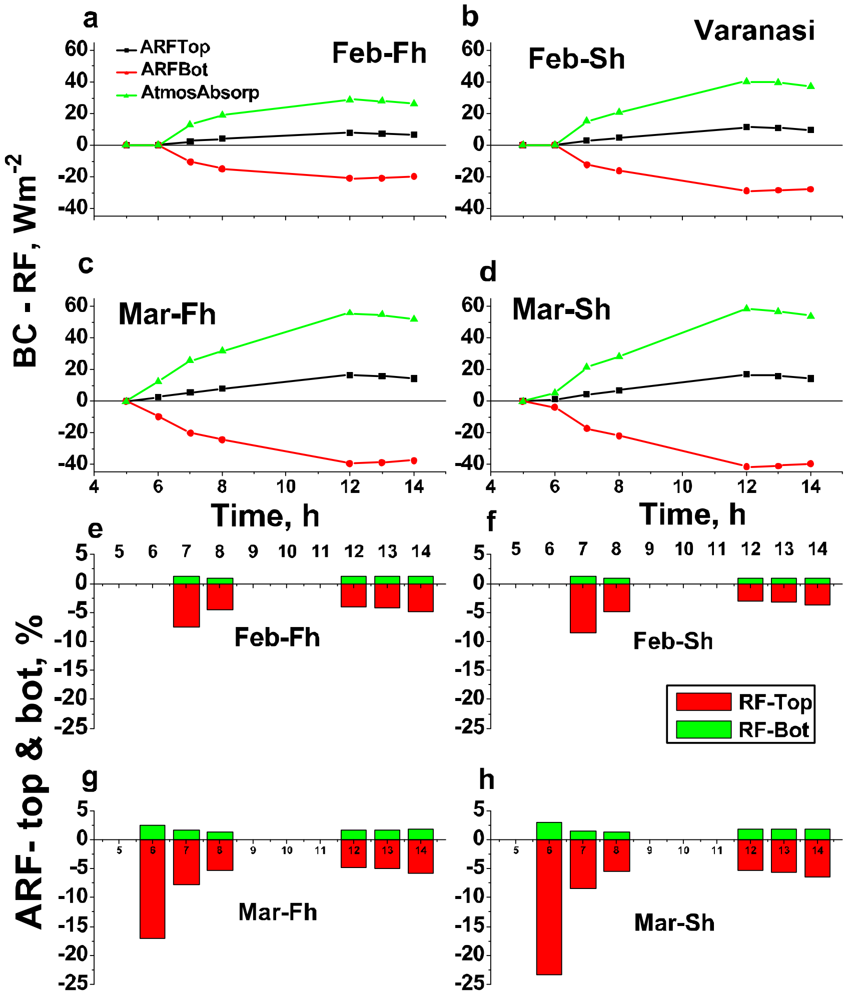

Fig. 7. Same as Fig. 6 but for Varanasi.

terminal spikelet', it may be help increase the number of spikelet per spike.

Since in the present study we are concentrating on the late start of the day and reduction in solar radiation during the day, we look for direct radiation effect rather than modification of temperature on winter wheat. Villegas *et al.* (2016) find that in northern latitudes, less than 1.8 kJ per kernel per day has limited kernel weight and became a constraint to achieve potential yield. As explained in section 4.1, PAR_A is much less than 50% of the incoming radiation. Evrendilek *et al.* (2008) during their study in Turkey, find that the saturation PAR for wheat is about 1800 J mol m^{-2} sec^{-1} which requires 1000 Wm^{-2} of incoming solar radiation. Observations over Ranchi (eastern IGB) show that winter peak radiation is only about 500 Wm^{-2}. This implies that the mean incoming radiation is not enough to lead wheat to its photosynthetic saturation levels of PAR and with aerosols reducing radiation further, it may be possible that this limit is applicable to the winter wheat as well. Moreover, Fischer (1985) suggests that there is a significant correlation between incoming solar radiation and spikelets per unit area and that the available radiation decides photosynthates availability for the spikelet growth. Mexican experiments of Abbate *et al.* (1995) reiterate that a positive linear relation exists between intercepted PAR and the mean growth rate and grain number during spike growth period. Experiments in Turkey by Evrendilek *et al.* (2008) demonstrate the threshold radiation input for wheat to start photosynthesis, after which there is a steep increase in photosynthesis rate, which stabilizes to almost constant value, in spite of increase in PAR, that is similar to our observations over Cassava plantation (Latha and Murthy, 2012). Delayed start of the day and early end due to aerosol induced radiation reduction effect, especially during winter, would reduce the period when the photosynthesis could have a maximum light use efficiency due to large solar zenith angle.

A fully operative crop model may not be suitable to quantify the effect of radiative forcing on crop yield, since our study is limited only to two months; the most photosensitive periods to winter wheat, but not the entire 'Rabi season'. Hence, to quantify the possible effect of BC aerosol induced-radiation reduction, we use the following equations presented in Ahmed and Hassan (2009) in their study at Pakistan for solar radiation effect on wheat crop dividing the duration as anthesis (SR1) and maturity (SR2) with the assumption that all other components like water and nutrient availability, disease free conditions assured. They developed two regression equations as follows:

$$GM = -19542.51 + 29.53(SR1),\quad GW = -0.15 + 0.0005(SR1),\quad Y = -1516.47 + 3.9549\,(SR1) \tag{4}$$

$$GM = -21272.63 + 19.90(SR2),\quad GW = -0.1551 + 0.0003(SR2),\quad Y = -1575.8369 + 2.57(SR2) \tag{5}$$

where GM- grain number per sq. meter, GW- spikelet grain weight, Y- yield in kg per hectare, SR1- radiation at anthesis and SR2- radiation at maturity. To quantify the loss due to radiation change, the term (indicating a yield reduction per unit reduction in radiation) associated with SR1 and SR2 is multiplied with respective ARF-BC in February (anthesis period) and March (maturity period) at both places. Details of yield reduction estimated using the above equations are detailed in Table 2. During anthesis period, reduction in radiation is more effective (higher coefficient) in reducing the yield, whereas during maturity the effect is not to that extent. Both in Ranchi and Varanasi, ARF-BC is increasing from February to March; at Ranchi about 1.5 Wm^{-2} and at Varanasi 7.5 Wm^{-2}. This change in reduction causes a loss in February, 79 kg per hectare, close to that in March at 70 kg per hectare at Varanasi while at Ranchi February loss estimate is a high 83 kg per hectare but it is much less in March at about 58 kg per hectare due only to a small increase in radiation cut off at maturity. Cumulatively, the respective reductions are capable of reducing the terminal yield by about 149 and 141kg per hectare for winter wheat crop at Varanasi and Ranchi respectively, albeit anthropogenic.

Similar could be the case of many other crops during this period like peas, etc. particularly the photosensitive ones. Present climate change perturbations such as western disturbances induced early hailstorms and increasing temperatures; an early harvesting may be favorable for the farmers to save their yield. Elevated aerosol content, especially of the absorbing nature needs to be eliminated for the timely daybreak and to receive most optimal radiation. Estimates from the current study are the possible values, based solely on the effect of absorbing aerosols alone, the composite aerosols may worsen or complicate the results as the scattering aerosols could convert direct radiation to diffuse radiation and thus allow more leaves to partake in the photosynthesis process, in turn adding some more photosynthates and hence slightly more yield. Moreover, these aerosols can also affect the crop yield through their indirect effects, modification of cloud microphysical properties; these details are not parameterized by the current equation and hence the estimate.

SUMMARY AND CONCLUSIONS

Observed relatively higher BC concentration in Varanasi as compared to that in Ranchi during February and March (moderately well mixed boundary layer) suggests the dominance of anthropogenic activity of biomass burning in Varanasi that overrides the combined effect of coal mining, open transport of coal and other local sources in Ranchi.

Biomass burning constantly controls the BC absorption at Varanasi; while it dominates at Ranchi only when used as a means to fight cold. The afternoon BC concentrations are less than 50% of that of early morning or late evening in Varanasi while this variation is not much marked over Ranchi. Both the stations show an increasing trend in BC from February to March that could be the result of inflow from NE with maximum fire counts during this period. The back-trajectories in the March 4th week show this inflow in Ranchi. AAE remains close to 1.2 over both stations, with maximum 1.52 during evenings in Varanasi indicating BC aerosols of mixed nature but size information is unclear. OC(UV) (370 nm)/BC (880 nm) ratios over Ranchi, being almost unity (= 1.0) except in the evenings and in Varanasi during February noon, also supports this fact. Organic carbon influence exists throughout March in Varanasi as indicated by the spectral curve.

Varanasi reports a steady increase of ARF-BC from February to March i.e., from –30 Wm^{-2} to –55 Wm^{-2}, due to an increase in BC concentration as well as mixed layer height. Over Ranchi, though there is some increase in BC, maximum ARF-BC that occurs around noon remains about –30 Wm^{-2} in both months for similar BC concentration. Relatively higher humidity at Ranchi restricts the mixed layer height to increase significantly.

An approximate estimate of crop yield, using an empirical formulae developed from observations, taking February as anthesis and March, as maturity stage and considering that in these areas the winter wheat is generally sown in November and harvested in April, indicates a probable cumulative loss of 149 kg per hectare (at Varanasi) and 141 kg per hectare (at Ranchi) for winter wheat due to radiation cut off induced by black carbon aerosols alone during anthesis and maturity.

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