The Direct Radiative Forcing Impact of Agriculture-emitted Black Carbon Associated with India’s Green Revolution

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Key Points:

- Agricultural emission in India is an important sector contributing to the local and regional black carbon contamination and climate forcing
- Estimated regional black carbon direct radiative forcing in India showed a fourfold increase during the operation of the Green Revolution
- The contribution of India’s intensive agriculture associated with Green Revolution to global black carbon climate forcing grew significantly

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Abstract

Biomass burning contributes considerably to black carbon (BC) emissions in South Asia, but such emissions have not been linked with the Green Revolution (GR) which has enabled substantial crop production growth in South Asian countries, India in particular. Here, we use an earth system model to quantify climate change through the direct radiative forcing (DRF) by agriculture-emitted BC associated with the GR in India. We show that the BC DRF in India has increased significantly since the GR, especially during the post-GR period. The estimated BC DRF in India rose from +0.197 W/m² in 1961 to +0.805 W/m² in 2011; this represents a fourfold increase in DRF since the onset of the GR. The contribution of BC DRF by India’s intensive agriculture to the global BC forcing also increased from 2.6% to 4.4% during the GR. Our results reveal that increasing BC emissions associated with the GR raises the importance of emission mitigation from agriculture source.

Plain Language Summary

Black carbon originated from incomplete combustion can endanger human health and contaminate the environment. The light-absorbing nature of black carbon is of vital importance to regional and global climate. Emissions from agriculture sources consist of large portion of black carbon particles, especially in India with intensive agriculture. The Green Revolution aiming at improving agriculture development in India has accomplished great success since the 1960s, but its side effects on long-term climate change have not been assessed. In the present study, we quantify black carbon contamination and direct radiative forcing induced by agriculture activities including crop residue burning from 1961 to 2011 during which the Green Revolution has been operated. Our results reveal that agricultural emission in India is an important sector contributing to the local and regional climate forcing. Such contribution could extend to the global climate. We propose that considerable and continuous efforts need to be made to control agriculture emissions in India to achieve a sustainable Green Revolution, in the meanwhile, mitigate the climate change.

1 Introduction

Green Revolution (GR) is featured by the application of high yielding crop varieties in Latin America and Asia from the mid-1960s, which has greatly altered India’s sustainable social and economic development ever since (Stevenson et al., 2013). Evenson and Gollin extended GR from 1960 to 2000 (Evenson & Gollin, 2003). Pingali has distinguished the first GR period of 1966 through 1985 and the post-GR period as the next two decades (Pingali, 2012). As one of the largest agricultural countries in the world, the agriculture sector accounted for approximately half of the total economic output in India during its first Five-Year Plan that began in 1951 (Amundson, 1964; S. Singh, 2020); however, the first Five-Year Plan did not markedly promote economic and population growth until the mid-1960s, when the GR came to the country. The GR has accelerated crop yields in India from the late 1960s to the end of the 20st century thanks to the development of new high-yielding varieties (Eliazer Nelson et al., 2019; Stevenson et al., 2013). And the post-GR (from
2001 to 2011 as defined in this study) has further promoted the food production through intensified use of inorganic fertilizers (Eliazer Nelson et al., 2019). However, concerns have been raised that climate warming might hamper crop yields; this has inspired extensive investigation into the responses and sensitivities of crop yields to climate change (Kukal & Irmak, 2018; Lobell & Field, 2007; Ray et al., 2015; Zhao et al., 2016). Accordingly, the effect of anthropogenic agricultural activities on climate has also been a focus of the scientific community. It has been revealed that agricultural advances could increase the amplitude of seasonal atmospheric CO₂, which helps to explain the seasonal variations in CO₂ uptake by terrestrial vegetation (Zeng et al., 2014). Land use and land cover change associated with agricultural activities have been shown to impact regional air temperature (Ge, 2010; Roy et al., 2007).

Aerosols, including black carbon (BC) released by crop residue biomass burning, have been considered as an important driver that contributes to climate forcing (Bikkina et al., 2019; Chung & Seinfeld, 2002; Jacobson, 2004; Ramanathan & Carmichael, 2008; Shen et al., 2019). BC is a major light-absorbing aerosol that originates from incomplete combustion (Bikkina et al., 2019; Chung & Seinfeld, 2002). The optical properties, microphysics, morphology, climate effects, and long-range transport of BC have been extensively studied in recent decades (Chung & Seinfeld, 2002; Ding et al., 2019; Feichter & Stier, 2012; He, 2019; Liu et al., 2011, 2020; Lund et al., 2018; Sharma et al., 2013; Wang et al., 2017; Zhang et al., 2018). To date, BC radiative forcing is still a serious concern due to large knowledge gaps in the understanding of its climate effects, such as its mixing state (Feichter & Stier, 2012; He, 2019; Liu et al., 2011; Matsui et al., 2018; Zhang et al., 2018). The global redistribution and transfer of BC from mid-latitude industrial regions to remote Arctic regions has been partly responsible for the occurrence of Arctic haze and alters climate globally (Qi et al., 2017; Ramanathan & Carmichael, 2008; Ren et al., 2020; Schmale et al., 2021; Zhou et al., 2012; Zhu et al., 2020). Typically, the regional impact of BC on climate forcing can be remarkable where regional BC emissions are high, even though the global mean radiative forcing is low (Chung & Seinfeld, 2005). Among the major BC sources across the globe, agricultural activities in India emit large amounts of BC into the atmosphere. It has been estimated that the mass of postharvest crop residues in India is even higher than the mass of crop yields, which indicates that the BC emissions induced by crop residue burning could also be very high during the postharvest season (Jethva et al., 2019). In addition to crop residue burning in open fields, many rural residents in India rely on crop residues as fuels for cooking and heating; this practice has adverse effects on both air quality and human health (Apte & Pant, 2019; Arif et al., 2018). Important as agricultural BC is, previous investigations have not linked long-term climate forcing with the burning of agricultural crop residues associated with the GR. Given that the post-GR, or second GR, began in the early 2000s and is currently underway in less developed countries under the umbrella of the United Nations (Otsuka & Larson, 2013), where the ecosystem and the environment are fragile in response to climate warming (Kishore et al., 2018), it is crucial to assess the GR-induced climate forcing. Such assessment
would shed light on sustainable GR development by taking into account appropriate mitigation strategies for reducing BC emissions and regulating the indoor and outdoor crop residue burning.

2 Methods

2.1. Community Earth System Model

We use Community Earth System Model version 2 (CESM2) scientifically validated component set FHIST to assess temporal and spatial distribution of BC. The model is run at a time step of 30 minutes, and grid resolution is 0.9°×1.25° latitude by longitude with 32 layers in the vertical direction. The atmosphere component uses Community Atmosphere Model 6 (CAM6), with Modal Aerosol Mode with 4 modes (MAM4) (Emmons et al., 2020; Liu et al., 2012, 2016; Sartelet et al., 2006; Y. Wang et al., 2018). Community Land Model version 5.0 (CLM5) is also coupled within the model.

In MAM4, BC is emitted into primary carbon mode and gradually aged by coating monolayers of sulfate and other secondary organic aerosols (SOA) with high hygroscopicity thus transferring from primary carbon mode into accumulation mode. The aerosol particle sizes increase via condensation and coagulation and the BC aging rate is proportional to condensation and coagulation rates (Liu et al., 2012, 2016; Y. Wang et al., 2018). Monolayer number of sulfate and SOA, of which criterion is 8 for MAM4, is a main parameter to control the aging processes of BC (Liu et al., 2016; Y. Wang et al., 2018). When monolayer number is larger, it takes more time for BC to be aged, therefore reducing its wet removal rate. The BC lifetime is often estimated by atmospheric burden divided by its emission rate (Cape et al., 2012; Koch et al., 2009; Y. Wang et al., 2018).

There are two wet scavenging processes for aerosols in CAM6, namely the in-cloud and below-cloud scavenging (Wang et al., 2021). Stratiform cloud-borne aerosols can only be removed by in-cloud scavenging. And the below-cloud scavenging through impaction, interception, and Brownian diffusion can wash out BC in both primary carbon and accumulation modes. Aerosol dry deposition velocities are calculated based on a multiple-resistance approach developed by Wesley (Wesely, 1989), which has also been applied in Model for Ozone and Related Chemical Tracers version 4 (MOZART-4) for online dry deposition calculation (Emmons et al., 2010). Dry deposition velocities over land, ocean, and ice/snow are combined to determine the grid-averaged dry deposition velocities, which are weighted by the fraction of land, ocean, and snow/ice at each model grid. The specializations of some deposited species like peroxy acetyl nitrate (PAN) and CO are also defined in dry deposition module. Dry deposition velocity of BC is specified to be 0.1 cm/s (Cooke et al., 1999; Lamarque et al., 2012).

RRTMG (Rapid Radiative Transfer Model for general circulation models) which has been implemented in various models such as GEOS-chem is also applied in CAM6 (Feldman et al., 2014; X. Wang et al., 2018). Constituents of radiatively active
gases and aerosols are defined for four different modes to calculate total radiation fluxes. By modifying mode definition and radiative diagnostic definition, the radiation fluxes of BC can be calculated (Y. Wang et al., 2018).

Table 1. Model scenario description.

| Model scenario | Simulation year | Emission Year | Emission source |
|----------------|-----------------|--------------|-----------------|
| B1961          | 1961            | 1961         | Agriculture     |
| B1971          | 1971            | 1971         | Agriculture     |
| B1981          | 1981            | 1981         | Agriculture     |
| B1991          | 1991            | 1991         | Agriculture     |
| B2001          | 2001            | 2001         | Agriculture     |
| B2011          | 2011            | 2011         | Agriculture     |
| C1971          | 1971            | 1961         | Agriculture     |
| C1981          | 1981            | 1961         | Agriculture     |
| C1991          | 1991            | 1961         | Agriculture     |
| C2001          | 2001            | 1961         | Agriculture     |
| C2011          | 2011            | 1961         | Agriculture     |
| T2011          | 2011            | 2011         | Total           |

We design different modeling scenarios including six baseline (B) simulations, five control (C) simulations, and one total-emission (T) simulation. Each scenario runs 14 months with first two months as spin-up time. In the baseline model run, the input BC emissions vary with time. In the control model run, agricultural BC emissions in 1961 are used for all control cases to fix the emissions at the pre-GR level. In the total-emission model run, the input BC emissions from both agriculture and non-agriculture sectors are implemented to represent the actual emission situation. In the present study, we adopted Evenson and Gollin’s definition by considering the agriculture development in India through the period from the mid 1960s to 2000 to be at the mercy of the GR (Evenson & Gollin, 2003). We take 1961 as the pre-GR scenario, 1971–1991 the GR scenario, and 2001 and 2011 the post-GR scenario. Detailed model scenario description can be found in Table 1.

2.2. Emission Inventory

We employ PKU-BC-v2 inventory (accessible from http://inventory.pku.edu.cn/), 0.1° by 0.1° latitude/longitude resolution, spanning 1960 to 2014, for input BC emission in the present study. PKU-BC-v2 is based on the method developed by Bond et al. who combined fuel consumption data and BC emission factors (EF_{BC}) for different activities to determine BC emissions (Bond et al., 2004; Wang, Tao, Shen, et al., 2014). Detailed technology divisions for different sectors (industry, transportation, residential, agriculture, etc.) and fuel types (firewood, diesel, crop residue, etc.) were taken into consideration during the inventory development (Wang, Tao, Shen, et al., 2014). The uncertainties of BC emission EF_{BC} can be significant since EF_{BC} depends on combustion conditions, fuel characteristics, technological treatment, and so on (Saud et al., 2012; Wang, Tao, Shen, et al., 2014).
The PKU-BC inventory has been verified extensively in estimating BC concentration and radiative forcing in various studies (Shen et al., 2019; Shi et al., 2020; Wang, Tao, Balkanski, et al., 2014; Yi et al., 2019). In this study, gas/diesel emission from agriculture, agriculture waste burning (outdoor crop residue burning), and indoor crop residue burning were integrated to obtain the final BC agriculture emissions. Gas/diesel consumption data in agriculture sector were obtained from the International Energy Agency (IEA) (Wang, Tao, Shen, et al., 2014). Crop residue open burning was calculated from crop production collected from Food and Agriculture Organization of the United Nations (FAO), the ratio of production to residue, and the percentage of residue burned in open fields (Wang et al., 2013; Wang, Tao, Shen, et al., 2014). Residential crop residue consumption was adopted from the difference between residential solid biomass data from IEA and residential firewood data from FAO (Wang, Tao, Shen, et al., 2014). The agriculture waste burning emission only accounts for the outdoor burning of crop residue. The indoor crop residue burning has been classified into residential sector in its original classification. However, given the significance of the emission of crop residue burning, the contribution from its indoor use as fuel is nonnegligible. Since promotion of crop production during agricultural development goes hand in hand with the rise in crop residue (Jethva et al., 2019), both indoor and outdoor crop residue are originated from crop harvest activities. Hence, it is reasonable to include residential emissions of crop residue into the agriculture-related BC emissions.

2.3 Model evaluation

To validate CESM2, we compare the aircraft observations of accumulation mode BC concentration with CESM2 outputs. Grid model results that are closest to aircraft flight zone and flight time span are averaged to obtain real time BC concentrations. As shown in Figure S1, CESM2 modeled BC concentrations fall in the range of the flight observations and show the best estimate of BC concentrations in the mid troposphere. But the model tends to underestimate BC concentrations near the surface and overestimate concentrations in the upper troposphere. Overall, the difference between measured and simulated BC concentrations is within the error range of less than one order of magnitude.

Also, we compare the modeled BC concentration with previous observation data as shown in Table 2. BC concentrations vary with season and location significantly and are usually the lowest during the monsoon season and the highest in winter and pre-monsoon season. The BC concentration level in the IGP region is always ranked at the top across India. Annual mean BC concentration in India calculated in total-emission run is about 1.0 μg/m$^3$ and annual mean BC concentration in the IGP is about 1.2 μg/m$^3$. Measured BC concentrations at a background station of India range from 0.5 to 1.8 μg/m$^3$ from 2006 to 2009, and from 4.1 to 9.5 μg/m$^3$ near New Delhi during 2008 and 2009 (Hyvärinen et al., 2011), where the background results generally agree with our estimate. Observed outdoor BC concentration in rural areas across the IGP in 2016 ranges from 8 to 24 μg/m$^3$ (Arif et al., 2018), approximately an order of magnitude higher than our model results in 2011. Measured
equivalent BC concentration during the period of 2016 to 2018 at fifteen sampling stations indicates that the heaviest BC pollution occurred in New Delhi with annual mean BC concentration exceeding 12 μg/m$^3$, while the lowest mean BC concentration (about 2 μg/m$^3$) is reported in Ranichauri (Kumar et al., 2020). Long-term observations in southern India reveal that intra-seasonal mean BC concentration is within the range of 1.2 to 3.6 μg/m$^3$ (Kalluri et al., 2020), a little higher than our estimate in 2011. Basically, our modeling results agree reasonably well with these observations.

Table 2. Comparison between observational data and modeling results.

| Period  | Region                        | Concentration (μg/m$^3$) | Reference                  |
|---------|-------------------------------|--------------------------|----------------------------|
| 2006-2009 | Mukteshwar (background station) | 0.8–1.8 (Seasonal average) | Hyvärinen et al., 2011     |
| 2008-2009 | Gual Pahari (near New Delhi)   | 4.1–9.5 (Seasonal average) | Hyvärinen et al., 2011     |
| 2016     | Rural areas across IGP        | 8–24 (Seasonal average)   | Arif et al., 2018          |
| 2016-2018 | India                         | 2–14 (Annual average)     | Kumar et al., 2020         |
| 2008-2017 | Southern India                | 1.2–3.6 (Seasonal average) | Kalluri et al., 2020       |
| 2011     | IGP                           | 1.2 (Annual average)      | Total emission scenario in this study |
| 2011     | India                         | 1.0 (Annual average)      | Total emission scenario in this study |

BC DRF from literatures is further compared with our modeling results. There have been extensive investigations in the regional climate change and BC climate forcing in India. Menon et al. estimates the radiative forcing at +6 W/m$^2$ over India using a climate model (Menon et al., 2002). Diurnal clear sky radiative forcing in Kanpur, a city in northern India, is predicted to be +9 W/m$^2$ during December 2004 (Tripathi et al., 2005). Annual mean radiative forcing at the top of the atmosphere in Visakhapatnam over eastern India is about +4 W/m$^2$ in 2006 (Sreekanth et al., 2007). These studies predict BC radiative forcing by taking total BC emissions from all sectors into account, which is comparable to our estimate of about +3 W/m$^2$ BC DRF in the total emission scenario and about an order of magnitude higher than the BC DRF computed in baseline simulations. Yi et al. find that BC DRF from agriculture sectoral emissions in India result in less than +0.04 W/m$^2$ over Himalayas and Tibetan Plateau in 2011 (Yi et al., 2019), which is lower than our prediction of about +0.8 W/m$^2$ because Himalayas and Tibetan Plateau are much less affected by India’s domestic agriculture BC emissions. Overall, the estimated BC DRF in the present study conform to previous studies.
2.4. Uncertainty Analysis

First-order error propagation is employed in this study to integrate uncertainties from multiple processes in the model (Huang et al., 2020). The uncertainty of model estimation mainly derives from emission inventories, chemical schemes, and physical parameterizations (Liu et al., 2011; Y. Wang et al., 2018). The chemically-inert nature of BC makes it unnecessary to consider the chemical transformation during its transportation. In addition, other factors such as coating material and wet removal are not further explored. In this study, three major processes concerning dry deposition, BC emission, and aging are analyzed to estimate their separate impacts on model estimations.

Sensitivity $S$ is frequently used to evaluate the response of model predicted variables to different parameters, defined as the ratio of relative change in input parameters ($I$) to relative change in output parameters ($O$).

$$S = \frac{\Delta O/O}{\Delta I/I}$$

(1)

Here, in sensitivity tests, BC agriculture emission and dry deposition velocity near the surface for model input are lowered 10% respectively to assess the response from output BC DRF. In the evaluation of the BC aging effect on modeling results, monolayer number is edited to 7. Table S2 summarizes calculated sensitivities. The decrease of the dry deposition velocity and aging rate results in the increase in BC DRF over India by prolonging the retention time of BC in the atmosphere. The reduction of BC emission has a negative effect on BC DRF owing to the decrease in ambient BC concentration. Differing from some previous results, accelerating BC aging rate causes rising BC DRF in India, which may be related to aerosol cloud interaction in this region (Bjordal et al., 2020). The absolute value of $S$ indicates that emission is a more important parameter to constrain BC climate effects in India. On a global scale, BC DRF is more sensitive to agriculture BC emission, whereas the impact of dry deposition process to global BC DRF is not significant. According to Wang et al., editing monolayers from 3 to 8 leads to a 26% increase in global BC DRF (Y. Wang et al., 2018), which is comparable to our result.

The method of first-order error propagation to calculate uncertainties of modeling results requires sensitivities and corresponding confidence factors of input parameters, as defined by equation (2). All input parameters in equation (2) need to be log-normally transferred around medians. $C_{f_{\text{out}}}$ and $C_{f_{i}}$ represent confidence factors of output and input parameters that are within the range of 95% confidence interval.

$$C_{f_{\text{out}}} = \exp \left( \sum_i (\ln C_{f_i})^2 \times S_i^2 \right)$$

(2)

Due to the lack of dry deposition measurements, it is not straightforward to constraint BC deposition velocity in a climate model (Emerson et al., 2018; Liu et al., 2011). The dry particle deposition velocity depends largely on its size and surface type, etc. Cooke et al. (Cooke et al., 1999) have identified that the hydrophilic BC deposition velocity on wet surfaces is 0.02 cm/s, while 0.025 cm/s is assumed for hydrophobic BC and hydrophilic BC on dry surfaces. The dry deposition velocity of
BC over ice/snow is mostly in the order of $O(10^{-2})$ cm/s (Yasunari et al., 2013), and a minimal value of 0.01 cm/s deposition velocity is adopted to estimate BC deposition and its climate impacts over Himalayan glaciers (Yasunari et al., 2010). A global average dry deposition velocity of 0.1 cm/s is suggested by Huang et al. to capture the seasonality of BC near the surface in the Arctic, which is also the most commonly used aerosol bulk dry deposition velocity in various models (Chung & Seinfeld, 2005; Huang et al., 2010; Sharma et al., 2013). Sharma et al. pointed out that dry deposition velocity at 0.05 cm/s could be more appropriate to estimate BC in the Arctic compared to 0.1 cm/s (Sharma et al., 2013). A dry deposition velocity of 0.08 cm/s is estimated for BC using boundary layer information in southern Scotland (Cape et al., 2012). According to these studies, we select 2 to represent the confidence factor of BC dry deposition velocity.

The uncertainties in the PKU-BC-v2 emission inventory are mainly resulted from the estimation of $E_{BC}$ (Wang, Tao, Balkanski, et al., 2014), activity data, and technology splits (Bond et al., 2007). The range between the first and third quartile of BC emission in India is 0.39–1.02 Tg/yr with a median of 0.63 Tg/yr, and it ranges from 5.56 to 14.5 Tg/yr for the global emission with a median of 8.99 Tg/yr (Wang, Tao, Balkanski, et al., 2014). Accordingly, for logarithmic normal distributed BC emission, the confidence factor is calculated to be 4 at the confidence level of 95% for both India and the world. This confidence factor was used here for agriculture BC emission in the light of the confidence factor of total emission.

The number of monolayers in the model controls the aging rate of BC and affects its fate in the atmosphere. Wang et al. indicate that CAM5-MAM4 performs better at a criterion of 3 monolayers for estimating BC in Beijing and Huston (Y. Wang et al., 2018). When simulating BC concentration near polar regions, a larger monolayer number of 8 could better conform observations compared to monolayer number of 1, 2 and 4 (Liu et al., 2016). Based on these studies, we take 3 as the confidence factor of monolayer number in the present study.

With the sensitivities and the confidence factors of input parameters, integrated confidence factors of BC DRF for India and the world are calculated to be 3.5 and 5.5 respectively. This result suggests that the uncertainty of modeled BC radiative forcing in India is smaller than the uncertainty in the world.
3 Results and Discussion

3.1. Agricultural BC Emissions and Crop Production

Figure 1. Annual food grain production, yield, and BC emissions in India. Food grains refer to rice, wheat, coarse cereals (barley, maize, millet and sorghum), and pulses (beans, chickpeas, lentils, peas, and pigeon peas). Food yield and production data can be accessed through http://www.fao.org/faostat/en/#data/QC.

The ever-growing problem of agricultural BC pollution is driven, to a large extent, by increasing food demand. BC emissions from the burning of indoor and outdoor crop residues account for a large portion of total agricultural emissions (Figure S2). According to FAO data, the total production (measured by mass) of food grains increased quickly after the beginning of the GR (Figure 1). The harvest area of India did not change significantly from 1961 to 2011 (Figure S3). Therefore, the temporal trend of food grain yield (defined as production per unit area) is similar to that of food grain production. The Pearson correlation coefficient between food production and agricultural BC emissions reaches 0.91, which suggests that agricultural BC emissions are mainly attributable to food production. However, while food production has grown monotonically during the past half century, there has been a sudden rise in agricultural BC emissions during the post-GR period. The normalized food grain production and agricultural BC emissions data in the post-GR period deviate the most from the 1:1 reference line, as shown in Figure 1d. The change in agricultural BC emissions during the post-GR period is primarily attributed to a strong perturbation in residential solid waste energy consumption (Figure S4), which is employed in the construction of the PKU-BC inventory (Wang, Tao, Shen, et al., 2014). In fact, increases in mechanized harvesting practices promote the generation of
crop residues (Kishore et al., 2018; Sarkar et al., 2018), and the use of crop residues as residential fuels has been increasing in India, especially in rural areas, to meet the fuel demand of the growing population (Arif et al., 2018).

Data reported by the Government of India indicate that nationwide food grain yields (Figure S5) share a similar spatial distribution to agricultural BC emissions (Figure S6). The northwestern states of India had the largest yields in 2011, during which time the agricultural emissions were also high. Likewise, the low food grain yields in central India correspond to relatively low agricultural BC emissions in this region. However, there are some differences between the distributions of BC emissions and food grain yields. For example, in the northeastern part of India, BC emissions are fairly high even though food grain yields are not significantly high. Because the ratio of crop residue to crop production is dependent on the crop type and many other factors, the ratio is not constant in each state (Jethva et al., 2019; Sahai et al., 2007; T. Singh et al., 2020); instead, the fraction of residues burned in open fields varies from place to place (Chawala & Sandhu, 2020; Jain et al., 2014; Lasko et al., 2017; Lohan et al., 2018). Above all, the energy supply structure between Indian households can be quite different, largely because of variation in household wealth (Arif et al., 2018).

To further explore BC emitted from agricultural operations, MODIS 8-day fire mask (MOD14A2) and land cover type (MCD12Q1) data are collected to estimate open fire across croplands in India. Because Terra (1999) was launched earlier than Aqua (2002) and we intend to know the relative change in fire mask number between 2001 (the start of post-GR) and 2011, MOD14A2 data from Terra were also used in this study. It is noted that Global Fire Emissions Database version 4 with small fires (GFED4s) which consists of open fires on all kinds of land cover (such as cropland and savanna) have been recently updated (van Marle et al., 2017; van der Werf et al., 2017). As we only focus on crop residue burning, we adopt MODIS data instead of GFED4s. For a fire mask marked in MOD14A2 file, if the land cover type at a grid of the latitude and longitude coordinate in MCD12Q1 file is cropland, we anticipate that the fire mask is caused by crop residue burning.

Figure 2a shows the change in the number of fire masks between 2001 and 2011. In both 2001 and 2011, the number of fire masks reaches its first peak in May and its second peak in October; this corresponds well with the two postharvest crop residue burning periods during the spring and autumn seasons, known as the rice-wheat cropping seasons, respectively, when massive agricultural residues are burned (Kumar et al., 2020; Shyamsundar et al., 2019). The largest number of fire masks occur in Punjab, Haryana, and Uttar Pradesh, in line with other studies (Jethva et al., 2019; Lohan et al., 2018). The total annual number of fire masks in 2011 is approximately 1.4 times higher than the number of fire masks in 2001, which indicates that the intensity of agricultural waste burning in open fields increased during the post-GR decade (Jethva et al., 2019). Compared to 2001, the first harvest season in 2011 was somewhat earlier, followed by an extended burning period. Accordingly, the second harvest in 2011 was delayed by approximately two weeks,
and the intensity of crop residue burning was enhanced. The fire mask number from Aqua in 2003 and 2011 are given in Figure S7. It shows that total number in 2011 is significantly higher than that in 2003, confirming the result from Jethva et al., which suggests an increasing trend of fire mask number in northwestern India (Jethva et al., 2019). Different from the result of Terra data, the maximum fire mask number occurred in October rather than in May, and the total fire number detected by Aqua was nearly twice of that detected by Terra due to the different transit time.

Figure 2. MODIS-measured 8-day fire masks (MOD14A2) at three confidence levels (low, nominal, and high) on croplands. a. Datum for day 169 is missing for 2001; therefore, the total number of fire masks indicated here may be less than the actual number of fire masks. The legend in the upper right corner represents the total number of fire masks during 2001 and 2011. The MODIS fire mask and land type products
used here can be accessed through https://ladsweb.modaps.eosdis.nasa.gov/search/. b–c. Red dots represent fire masks.

In Figures 2b and 2c, cropland fires are mainly detected in northern India, where agricultural BC emissions are also high, implying that crop residue burning is a more serious problem in the Indo-Gangetic Plain (IGP), a region also known as the “breadbasket”, a mostly cultivated region across India where nearly two-thirds of the country’s food grains are produced (Jethva et al., 2019). Postharvest fires over the croplands in central India increased from 2001 to 2011, which indicates that more crop residues in this region are burned in open fields.

3.2. Change in BC Concentrations from 1961 to 2011.

The annual average agricultural BC concentrations near the surface, hereafter referred to as BC concentrations, are depicted in Figure 3 for each of the six baseline simulations every 10 years from 1961 to 2011. The IGP region has long been recognized as the predominant source area in India (Arif et al., 2018; Kumar et al., 2020), and higher BC atmospheric levels across the IGP can also be observed in this study, which indicates that the intensity of agricultural activities is positively related to agricultural BC emissions. In the IGP, a large amount of BC has been released into the atmosphere since the GR began (Figure S6). Agricultural BC emissions have increased noticeably since 1961, with higher emissions recorded in the dry season and lower emissions recorded in the wet season. A large proportion of agricultural BC emissions come from the residential use of crop residues as biofuel (Figure S2), which contributes significantly to ambient air pollution. Due to the high level of agricultural emissions, the BC concentrations in the northern grain belt and the southern seaboard of India were relatively higher than in other regions of India, even prior to the GR. Since the GR began, the region with high BC concentrations extended from northern India to the south. In 2011, these two regions with high levels of BC concentrations merged, with BC concentrations exceeding 100 ng/kg throughout the country. From 1961 to 2011, the nationwide BC concentrations increased nearly fourfold. With overall increasing BC concentrations, we can identify an accelerating increase in BC concentrations during the post-GR period compared to the GR period. This rapid rise in the BC concentration is in line with the rapid increase in agricultural BC emissions recorded during this period. The BC concentrations in the IGP are significantly higher than the average BC concentration across India throughout the simulation period, which suggests that the IGP accounts for a large portion of BC concentrations in the country. While BC contamination data during the GR is scarce in previous investigations, the mean BC surface concentrations in India averaged over 2000 to 2017 was the highest over the IGP region (Rana et al., 2019), confirming our modeling results. Higher BC levels in this region have been also reported by other studies (Bikkina et al., 2019; Conibear et al., 2018). One-half and two-thirds of two black carbon subfractions in this region have been attributed to biomass combustion (Gustafsson et al., 2009), of which post-harvest agricultural crop residue burning emissions have been revealed as a major source of BC in the IGP during January–June and September–October (Rana et al., 2019). Extensive use of biofuel (or wood)
combustion for domestic household cooking purposes was also considered as a major BC source (Budhavant et al., 2015), which has been viewed by Rehman et al. as the dominant source of ambient BC over the IGP region based on their simultaneous indoor and outdoor BC sampling result (Rehman et al., 2011).

Figure 3. Annual BC concentrations from six baseline (B) simulations every 10 years from 1961 to 2011. a–f. Annual BC concentration distribution. g. Mean BC concentration across India. h. Mean BC concentration across the IGP.

The locations with higher BC column burdens match those regions with higher BC concentrations near the surface (Figure S8). Because BC concentrations generally decrease with height (Figure S9) (Talukdar et al., 2019), BC concentrations at low atmospheric levels overwhelm the distribution of the BC column burden. During summer, however, BC concentrations in the upper troposphere may increase with
height (Figure S9). This inversion of the BC vertical distribution could be attributed to special meteorological changes in the summertime. The vertical velocity variance in the upper troposphere is significantly larger in warm seasons than in cold seasons (Figure S10), which indicates that the vertical movement of aerosol particles is more active during the summertime so that more BC particles can be lifted to the upper troposphere. In addition, the fraction of low clouds is higher in summer than in other seasons (Figure S11), implying that BC in the low and mid troposphere can be more easily scavenged, leading to an increase in BC concentrations with height in the upper troposphere.

To discern the regions with the fastest-growing BC concentrations after the launch of the GR, we illustrate the ratio of the monthly BC concentration in 2011 ($C_{BC2011}$) to the monthly BC concentration in 1961 ($C_{BC1961}$), expressed as $C_{BC2011}/C_{BC1961}$. The results show that the BC concentrations overall exhibit an approximately fourfold increase in India during this time period (Figure S12). The western seaboard and mid-east of India experienced the largest growth in BC concentrations, recording ratios higher than 10. It should be noted that the regions with high BC concentrations do not overlap with the high ratio regions. This suggests that the variations in BC concentrations recorded in regions with low BC levels were likely affected by neighboring regions with high BC concentrations. In addition, there is a clear difference in the ratio distribution among different months, which may be largely due to the Indian monsoon as indicated by previous studies (Arif et al., 2018; Hyvärinen et al., 2011; Kalluri et al., 2020; Kumar et al., 2020). For the IGP region, the monthly mean ratio of the BC concentration is always less than the national mean value, which is particularly evident during the summertime (Figure S13). When the monthly mean vector winds are superimposed over the monthly BC ratio maps (Figure S12), it is observed that winds blowing from inland India during the dry season can drive BC to the southwest coast, notably enhancing the BC concentrations over the Arabian Sea while reducing the BC concentrations in the IGP. During the wet season, the southwest monsoon stops BC from diffusing outward from land regions towards the oceans, which enables the accumulation of BC in downwind coastal regions, especially along the western and eastern seaboard.

While BC emissions sources play an important role in determining the ambient BC concentration, concerns have been raised regarding the influences of climate on the spatiotemporal changes in BC concentrations. We approached this concern by performing control (C) simulations using fixed agricultural BC emissions in 1961, thereby excluding the effects of BC emissions but highlighting the climate influence. Figure S14 illustrates the ratios of the annual BC surface concentrations at 10-year intervals from 1971 to 2011 from five control runs to the baseline simulation in 1961. Remarkably, the most significant increase in BC concentrations occurs primarily in Northwest India, where agricultural BC emissions are particularly high, which indicates that the areas with extensive agricultural activities are probably more vulnerable and more sensitive to the climate. The estimated mean BC concentration ratios in India show a minor temporal variation, with a dip during the first few decades followed by a slight upswing afterwards, implying that the climate is shifting
in a slightly unfavorable way for pollution control. This suggests that, in addition to India’s growing emissions, climate change will likely exacerbate the increasing trend of BC concentrations across the country, which could lead to additional difficulties in mitigating pollution.

![Figure 4](image)

**Figure 4.** BC concentrations under different emission scenarios in 2011. a. The distribution of BC concentrations under the total-emission (T) simulation. b. BC concentrations in India and in the IGP under three simulation scenarios in 2011.

The BC concentrations under the total-emission (agriculture plus nonagricultural sector) scenario are shown in Figure 4a. The distribution of the total BC concentration is similar to that of the agricultural BC concentration, showing higher BC levels in the IGP region where both industry and agriculture are well developed. The calculated BC concentration in the IGP region is approximately 1.2 times higher than the national average. According to Figure 4b, approximately 24% of BC in the ambient air is attributed to agricultural sources, while in the IGP, that percentage of the contribution from agricultural emissions reaches 26%. The increase in agricultural emissions associated with the GR contributed approximately 17% to the total ambient BC concentration in 2011, indicating that the GR has greatly impacted air quality in India. From the comparison of BC concentrations under different emission scenarios, we deduce that the distribution of BC in India is highly correlated with the emission levels from local sources, especially agricultural sources, with some disturbances attributable to climate.
3.3. BC Direct Radiative Forcing

Instantaneous radiative forcing at the top of the atmosphere (TOA) and the tropopause are frequently used to estimate aerosol radiative forcing (Chung & Seinfeld, 2002, 2005; Jacobson, 2004; Y. Wang et al., 2018). To examine the climate forcing of BC induced by the GR in India, the differences in the net short- and longwave radiation fluxes at the TOA with and without BC are calculated and termed the BC DRF in this study. Figure 5a shows the modeled BC DRF across India from six baseline runs (BC DRF\textsubscript{B}) from 1961 to 2011 every 10 years and five control runs (BC DRF\textsubscript{C}) from 1971 to 2011 every 10 years. Overall, the increase and southward extension of the BC DRF\textsubscript{B} (Figure S15) over India during this half century are in agreement with the BC concentrations shown in Figure 3 and the agricultural BC emissions in Figure S6. The results from the baseline simulations reveal that the strength of BC DRF\textsubscript{B} increased from 1961 to 2011, with the maximum DRF in northeastern India growing from about +0.4 W/m\textsuperscript{2} in 1961 to more than +1 W/m\textsuperscript{2} in 2011. In 1961, we can identify only a small area in northeastern India with BC DRF exceeding +0.4 W/m\textsuperscript{2}. However, the +0.4 W/m\textsuperscript{2} DRF contour line extends to the southern edge of India by 2011. On the other hand, the BC DRF\textsubscript{C} from the control run does not exhibit a significant increase, and the maximum BC DRF\textsubscript{C} is approximately +0.4 W/m\textsuperscript{2} in northeastern India throughout the period from 1971 to 2011 (Figure S16). The significant differences in the BC DRF between the baseline and control simulations manifest again that the GR-induced agricultural BC emissions contribute remarkably to climate forcing in India. On a national scale, the rise in the regional BC DRF\textsubscript{B} in the IGP is more significant than in other regions. In particular, the increase in the BC DRF\textsubscript{B} in India has accelerated since 1981, with the fastest growth rate of the post-GR period recorded after 2001 (Figure 5a). Since the fixed agricultural BC emissions in 1961 were used in the five control simulations, the differences in the BC DRF\textsubscript{C} among five control runs were primarily driven by meteorological fields. The change in the BC DRF\textsubscript{C} implies inherent climate change signals, showing a southward extension trend of the BC DRF\textsubscript{C} from 1971 to 2011 and a weak increase in the BC DRF\textsubscript{C} in India during the same period (Figure S16). This weak increasing trend of the BC DRF\textsubscript{C} in India induced by climate change appears to overlap with the increasing trend of the BC DRF\textsubscript{B} induced by agricultural emissions. However, compared with the baseline simulations, the BC DRF\textsubscript{B} induced by agricultural emissions associated with the GR entirely overwhelms the climate-induced rise in BC DRF\textsubscript{C}.

Figure 5b compares the modeled mean annual BC DRF\textsubscript{B} averaged over India (brown bars) and the global BC DRF\textsubscript{B} with and without the contribution of BC DRF\textsubscript{B} in India (wheat hatched and light-wheat bars) every 10 years from 1961 to 2011, with the corresponding BC DRF\textsubscript{B} values presented in Table S1. The fractions of the increment in the global BC DRF\textsubscript{B} with and without India included (blue solid line) and the ratio of the BC DRF\textsubscript{B} in India to the global BC DRF\textsubscript{B} (red solid line) are presented as well. As shown, the BC DRF\textsubscript{B} values in India are approximately 5-8 times greater than the global values, and a sudden increase in the BC DRF\textsubscript{B} in India occurs after 2001. The considerably higher BC DRF\textsubscript{B} in India than the global average suggests that India contributes markedly to the global agricultural BC emission-
induced DRF. This contribution increased more significantly after 2001, characterized by the large ratio and fraction in 2011, which agrees with the growing BC emissions under the GR in India. The mean BC DRF$_B$ associated with agricultural BC emissions in India in 2011 increased more than fourfold over the past half century from +0.197 to +0.805 W/m$^2$, although straw crop yields grew merely 2 times and production amplified 3 times during the same period (Figure 1). The fraction of change in the global BC DRF$_B$ with and without taking the BC DRF$_B$ in India into consideration could represent the contribution of agricultural emissions in India to the global BC DRF$_B$. During the GR, the enhancement of the BC DRF$_B$ induced by India’s agricultural practices was highly intensified, with the fraction growing from 2.6% to 4.4%. This result shows that India has been increasingly contributing to the global BC DRF$_B$ in the past half century despite accounting for only 0.6% of the global surface area. Such an increasing contribution indicates the aggravation of agricultural emissions in India, which have a nonnegligible impact on the global climate. It is worth noting that although the global BC DRF$_B$ is considerably weaker than the BC DRF$_B$ of India during the same period, we also observe a 2.5-fold increase from 1961 to 2011 driven by BC agricultural emissions worldwide. However, the global total food grain (rice, wheat, and maize) production increased 3.6 times from 1961 to 2011 according to FAO crop production data.

![Figure 5](image_url) **Figure 5.** BC DRF in different simulation scenarios. a. The temporal evolution of BC DRF from six baseline simulations (blue line) and five control simulations (red line). b–c. Mean BC DRF in India, the global BC DRF with and without India included, the fraction of the increment in the global BC DRF with and without India included, and the ratio of the BC DRF in India to that of the global BC DRF. The colors of the y-axis labels correspond to the colors of the bars and lines in the graph.

For comparison, the BC DRF values in 2011 under three different emission scenarios are given in Figure 5c. The fraction of the change in the global BC DRF with and without taking the BC DRF in India into consideration, as well as the ratio of the BC DRF in India to the global BC DRF, is the lowest in the total-emission simulation case and the highest in the baseline simulation case. This highlights the enhanced contribution to the global climate radiative forcing induced by GR-related agricultural activities compared to meteorological and nonagricultural factors. The fractions in all five control simulations are significantly larger than the fraction in the total-emission simulation (Table S1), which suggests that emissions induced by the
agriculture sector outweigh the nonagricultural sector, even during the pre-GR period. Notably, the uptick of the fraction in the control simulations from 1971 to 2001 is even more obvious than that in the baseline simulations. However, the fraction in the baseline case soared in 2011 and was much higher than the fraction in the control case. It can be inferred that the portion of the agricultural BC DRF in India averaged on a global scale is relatively low before post-GR and significantly enhanced thereafter.

The BC DRF under the total emission scenario, represented as the BC DRF_T, is illustrated in Figure S17. The mean BC DRF_T in India is approximately +3 W/m^2. The IGP in India is the region most affected by BC emissions, recording a regional BC DRF_T that prominently exceeds the national average. The agricultural BC DRF_B calculated in the baseline simulation accounts for 26.5% of the total BC DRF_T under the total-emission simulation, which is comparable to the percentage of agricultural BC concentrations in the total BC concentrations driven by both agricultural and nonagricultural emissions. However, the ratio of the mean BC DRF_T in India to the BC DRF_T worldwide in the total-emission case is only half of that in the baseline case, as shown in Table S1. This suggests that the emission level of agricultural activities in India is significantly higher than the global average. As a result, agriculture-induced regional climate change is more significant in India than in the rest of the world. As seen in Table S1, the estimated regional BC DRF_B from BC agricultural emissions (+0.805 W/m^2) in India in 2011 is even higher than the global BC DRF_T from BC total emissions (+0.738 W/m^2) in the same year. This finding raises a serious concern about regional climate change in India forced by agricultural BC emissions associated with the GR. BC concentrations and BC DRF are dominated by the distribution of BC emissions in all scenarios; this suggests that emissions mitigation is the most efficient way to clean the air and slow the pace of climate change. For India, the regulation of agricultural activities could be the most beneficial measure to reduce the total BC emissions, alleviate environmental pollution in the country, and mitigate climate change regionally and globally.

4 Conclusions and Implications

Fueled by agricultural technology developments and the seed revolution, global food grain yields have experienced a giant leap since the 1970s, especially in China, India, and many other countries (Otsuka & Larson, 2013; Pingali, 2012; Stevenson et al., 2013). It is a priority to develop agriculture and promote food production in India because it has the second largest population in the world. The Green Revolution has played a crucial role in social and economic development by meeting the increased food demand for India’s growing population over the past half century. The great success of the GR notwithstanding, concerns have also been raised in the last two decades regarding the side effects of the GR. These side effects are mostly identified as issues of environmental degradation induced by increased use of water resources, deforestation, conversion of land cover to cropland, and the increased application of pesticides and fertilizers, which can cause ecosystem deterioration and adverse human health effects (Evenson & Gollin, 2003; Pingali, 2012; Rahman,
Besides, large consumption of fossil fuel in agriculture sector has been witnessed during the worldwide GR (Pellegrini & Fernández, 2018), which could result in increasing BC emissions. However, little is known about the GR’s effect on climate. It is recognized that there is a great mitigation potential in the agricultural sector to reduce GHG emissions (Ouyang et al., 2013). One such measure is to increase the production of agricultural biofuel from crops (Koizumi, 2014). In the case of India, climate forcing by BC associated with the GR poses a new challenge for the mitigation of climate warming, a problem that seems to have previously been overlooked. Our results reveal positive BC direct radiative forcing at the TOA, which suggests a warming effect attributable to crop residue biomass burning under intensive agricultural practices in India that entirely overwhelms the weak warming trend induced by meteorological and other nonagricultural factors (Figure 5 and Table S1). By 2011, the agricultural emission-yielded BC DRF had exceeded 3.4 times the contribution from meteorological factors. The BC emissions induced by the GR also significantly altered the climate on both the regional and the global scales, especially during the post-GR period (Figure 5). Comparing the BC DRF from agricultural activities in the pre-GR period with that in the post-GR period, a fourfold increase in the BC DRF is observed in India. This surpasses the relative growth rate of the global BC DRF, which indicates the large contribution of agricultural BC emissions in India to the world (Table S1). It also indicates that if BC emissions from crop residue biomass burning were reduced or eliminated, India could significantly and promptly abate its climate warming trend and contribute to the reduction of global BC DRF.

India, especially the IGP region, suffers remarkably from both indoor and outdoor crop residue burning (Arif et al., 2018; Sarkar et al., 2018; T. Singh et al., 2020). Actions have already been taken in India to mitigate and reduce the practice of crop residue biomass burning (Bhattacharyya & Barman, 2018; Lohan et al., 2018; Shyamsundar et al., 2019), including investing in economically viable no-burn alternatives and subsidizing farmers to reduce field crop residue burning. However, despite the mitigation efforts already taken, data from the IEA indicate that BC agricultural emissions, mostly from indoor crop residue burning, seem to have bounced back since the early 2000s (Figure S4). Continuous efforts need to be made to mitigate agricultural BC emissions in India through air quality control policy and clean energy transition to achieve a sustainable GR (Tibrewal & Venkataraman, 2020). India’s mitigation efforts could also provide reference and guidance to other less developed countries undergoing the new phase of the Green Revolution (GR II), such as those in Sub-Saharan Africa, to improve sustainable social and economic development (Armanda et al., 2019; Otsuka & Larson, 2013; Tyagi, 2016). It is worth noting that some regions experiencing GR benefits in India could also see associated changes in its economic conditions, food consumption patterns, individual behavior, and exposure to other sources of BC emissions. This suggests that the India’s GR is likely to exert broader influences on its climate, in addition to its intensive agriculture emitted BC.

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References

Amundson, R. H. (1964). India’s Third Five Year Plan—1961–1966. Review of Social Economy, 22(2), 87–103. https://doi.org/10.1080/00346766400000026

Apte, J. S., & Pant, P. (2019). Toward cleaner air for a billion Indians. Proceedings of the National Academy of Sciences of the United States of America, 166(22), 10614–10616. https://doi.org/10.1073/pnas.1905458116

Arif, M., Kumar, R., Kumar, R., Zusman, E., Singh, R. P., & Gupta, A. (2018). Assessment of Indoor & Outdoor Black Carbon emissions in rural areas of Indo-Gangetic Plain: seasonal characteristics, source apportionment and radiative forcing. Atmospheric Environment, 191(July), 227–240. https://doi.org/10.1016/j.atmosenv.2018.07.057

Armanda, D. T., Guinée, J. B., & Tukker, A. (2019). The second green revolution: Innovative urban agriculture’s contribution to food security and sustainability – A review. Global Food Security, 22(August), 13–24. https://doi.org/10.1016/j.gfs.2019.08.002

Bhattacharyya, P., & Barman, D. (2018). Crop Residue Management and Greenhouse Gases Emissions in Tropical Rice Lands. Soil Management and Climate Change: Effects on Organic Carbon, Nitrogen Dynamics, and Greenhouse Gas Emissions. Elsevier Inc. https://doi.org/10.1016/B978-0-12-812128-3.00021-5

Bikkina, S., Andersson, A., Kirillova, E. N., Holmstrand, H., Tiwari, S., Srivastava, A. K., et al. (2019). Air quality in megacity Delhi affected by countryside biomass burning. Nature Sustainability, 2(3), 200–205.
Bjordal, J., Storelvmo, T., Alterskjær, K., & Carlsen, T. (2020). Equilibrium climate sensitivity above 5 °C plausible due to state-dependent cloud feedback. *Nature Geoscience, 13*(11), 718–721. https://doi.org/10.1038/s41561-020-00649-1

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J. H., & Klimont, Z. (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research: Atmospheres, 109*(14), 1–43. https://doi.org/10.1029/2003JD003697

Bond, T. C., Bhardwaj, E., Dong, R., Jogani, R., Jung, S., Roden, C., et al. (2007). Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850-2000. *Global Biogeochemical Cycles, 21*(2), 1–16. https://doi.org/10.1029/2006GB002840

Budhavant, K., Andersson, A., Bosch, C., Kruså, M., Kirillova, E. N., Sheesley, R. J., et al. (2015). Radiocarbon-based source apportionment of elemental carbon aerosols at two South Asian receptor observatories over a full annual cycle. *Environmental Research Letters, 10*(6). https://doi.org/10.1088/1748-9326/10/6/064004

Cape, J. N., Coyle, M., & Dumitoreanu, P. (2012). The atmospheric lifetime of black carbon. *Atmospheric Environment, 59*, 256–263. https://doi.org/10.1016/j.atmosenv.2012.05.030

Chawala, P., & Sandhu, H. A. S. (2020). Stubble burn area estimation and its impact on ambient air quality of Patiala & Ludhiana district, Punjab, India. *Heliyon, 6*(1), e03095. https://doi.org/10.1016/j.heliyon.2019.e03095

Chung, S. H., & Seinfeld, J. H. (2002). Global distribution and climate forcing of carbonaceous aerosols. *Journal of Geophysical Research Atmospheres, 107*(19), AAC 14-1-AAC 14-33. https://doi.org/10.1029/2001JD001397

Chung, S. H., & Seinfeld, J. H. (2005). Climate response of direct radiative forcing of anthropogenic black carbon. *Journal of Geophysical Research D: Atmospheres, 110*(11), 1–25. https://doi.org/10.1029/2004JD005441

Conibear, L., Butt, E. W., Knote, C., Arnold, S. R., & Spracklen, D. V. (2018). Residential energy use emissions dominate health impacts from exposure to ambient particulate matter in India. *Nature Communications, 9*(1), 1–9. https://doi.org/10.1038/s41467-018-02986-7

Cooke, W. F., Lioussse, C., Cachier, H., & Radioactivit, F. (1999). for carbonaceous aerosol and implementation radiative impact in the ECHAM4 model found using bulk aerosol emission factors , while global black carbon emissions carbon emissions m -2 were Because of secondary carbon aerosol be doubled m -2 . The resultant, 104.

Ding, S., Zhao, D., He, C., Huang, M., He, H., Tian, P., et al. (2019). Observed Interactions Between Black Carbon and Hydrometeor During Wet Scavenging in
Mixed-Phase Clouds. *Geophysical Research Letters*, 46(14), 8453–8463. https://doi.org/10.1029/2019GL083171

Eliazer Nelson, A. R. L., Ravichandran, K., & Antony, U. (2019). The impact of the Green Revolution on indigenous crops of India. *Journal of Ethnic Foods*, 6(1), 1–10. https://doi.org/10.1186/s42779-019-0011-9

Emerson, E. W., Katich, J. M., Schwarz, J. P., McMeeking, G. R., & Farmer, D. K. (2018). Direct Measurements of Dry and Wet Deposition of Black Carbon Over a Grassland. *Journal of Geophysical Research: Atmospheres*, 123(21), 12,277-12,290. https://doi.org/10.1029/2018JD028954

Emmons, L. K., Walters, S., Hess, P. G., Lamarque, J. F., Pfister, G. G., Fillmore, D., et al. (2010). Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4). *Geoscientific Model Development*, 3(1), 43–67. https://doi.org/10.5194/gmd-3-43-2010

Emmons, L. K., Schwantes, R. H., Orlando, J. J., Tyndall, G., Kinnison, D., Lamarque, J. F., et al. (2020). The Chemistry Mechanism in the Community Earth System Model Version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, 12(4), 1–21. https://doi.org/10.1029/2019MS001882

Evenson, R. E., & Gollin, D. (2003). Assessing the impact of the Green Revolution, 1960 to 2000. *Science*, 300(5620), 758–762. https://doi.org/10.1126/science.1078710

Feichter, J., & Stier, P. (2012). Assessment of black carbon radiative effects in climate models. *Wiley Interdisciplinary Reviews: Climate Change*, 3(4), 359–370. https://doi.org/10.1002/wcc.180

Feldman, D. R., Collins, W. D., Pincus, R., Huang, X., & Chen, X. (2014). Far-infrared surface emissivity and climate. *Proceedings of the National Academy of Sciences of the United States of America*, 111(46), 16297–162302. https://doi.org/10.1073/pnas.1413640111

Ge, J. (2010). MODIS observed impacts of intensive agriculture on surface temperature in the southern Great Plains. *International Journal of Climatology*, 30(13), 1994–2003. https://doi.org/10.1002/joc.2093

Gustafsson, Ö., Kruså, M., Zencak, Z., Sheesley, R. J., Granat, L., Engström, E., et al. (2009). Brown clouds over South Asia: Biomass or fossil fuel combustion? *Science*, 323(5913), 495–498. https://doi.org/10.1126/science.1164857

He, C. (2019). *Radiative Properties of Atmospheric Black Carbon (Soot) Particles with Complex Structures*. Springer International Publishing. https://doi.org/10.1007/978-3-030-20587-4_5

Huang, L., Gong, S. L., Jia, C. Q., & Lavoué, D. (2010). Importance of deposition processes in simulating the seasonality of the Arctic black carbon aerosol. *Journal of Geophysical Research Atmospheres*, 115(17), 1–15. https://doi.org/10.1029/2009JD013478

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Huang, T., Ling, Z., Ma, J., Macdonald, R. W., Gao, H., Tao, S., et al. (2020). Human exposure to polychlorinated biphenyls embodied in global fish trade. *Nature Food, 1*(5), 292–300. https://doi.org/10.1038/s43016-020-0066-1

Hyvärinen, A. P., Raatikainen, T., Brus, D., Komppula, M., Panwar, T. S., Hooda, R. K., et al. (2011). Effect of the summer monsoon on aerosols at two measurement stations in Northern India-Part 1: PM and BC concentrations. *Atmospheric Chemistry and Physics, 11*(16), 8271–8282. https://doi.org/10.5194/acp-11-8271-2011

Jacobson, M. Z. (2004). The short-term cooling but long-term global warming due to biomass burning. *Journal of Climate, 17*(15), 2909–2926. https://doi.org/10.1175/1520-0442(2004)017<2909:TSCBLG>2.0.CO;2

Jain, N., Bhatia, A., & Pathak, H. (2014). Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research, 14*(1), 422–430. https://doi.org/10.4209/aaqr.2013.01.0031

Jethva, H., Torres, O., Field, R. D., Lyapustin, A., Gautam, R., & Kayetha, V. (2019). Connecting Crop Productivity, Residue Fires, and Air Quality over Northern India. *Scientific Reports, 9*(1), 1–11. https://doi.org/10.1038/s41598-019-52799-x

Kalluri, R. O. R., Gugamsetty, B., Kotalo, R. G., Thotli, L. R., Tandule, C. R., & Akkiraju, B. (2020). Long-term (2008–2017) analysis of atmospheric composite aerosol and black carbon radiative forcing over a semi-arid region in southern India: Model results and ground measurement. *Atmospheric Environment, 240*(August). https://doi.org/10.1016/j.atmosenv.2020.117840

Kishore, A., Pal, B. D., Joshi, K., & Aggarwal, P. (2018). Unfolding government policies towards the development of climate smart agriculture in India. *Agricultural Economics Research Review, 31*(conf), 123. https://doi.org/10.5958/0974-0279.2018.00028.9

Koch, D., Schulz, M., Kinne, S., McNaughton, C., Spackman, J. R., Balkanski, Y., et al. (2009). Evaluation of black carbon estimations in global aerosol models. *Atmospheric Chemistry and Physics, 9*(22), 9001–9026. https://doi.org/10.5194/acp-9-9001-2009

Koizumi, T. (2014). Biofuels and food security: Biofuel impact on food security in Brazil, Asia and major producing countries. In *SpringerBriefs in Applied Sciences and Technology* (pp. 50–51). https://doi.org/10.1007/978-3-319-05645-6

Kukal, M. S., & Irmak, S. (2018). Climate-Driven Crop Yield and Yield Variability and Climate Change Impacts on the U.S. Great Plains Agricultural Production. *Scientific Reports, 8*(1), 1–18. https://doi.org/10.1038/s41598-018-21848-2

Kumar, R. R., Soni, V. K., & Jain, M. K. (2020). Evaluation of spatial and temporal heterogeneity of black carbon aerosol mass concentration over India using three
year measurements from IMD BC observation network. Science of the Total Environment, 723, 138060. https://doi.org/10.1016/j.scitotenv.2020.138060

Lamarque, J. F., Emmons, L. K., Hess, P. G., Kinnison, D. E., Tilmes, S., Vitt, F., et al. (2012). CAM-chem: Description and evaluation of interactive atmospheric chemistry in the Community Earth System Model. Geoscientific Model Development, 5(2), 369–411. https://doi.org/10.5194/gmd-5-369-2012

Lasko, K., Vadrevu, K. P., Tran, V. T., Ellicott, E., Nguyen, T. T. N., Bui, H. Q., & Justice, C. (2017). Satellites may underestimate rice residue and associated burning emissions in Vietnam. Environmental Research Letters, 12(8). https://doi.org/10.1088/1748-9326/aa751d

Liu, D., He, C., Schwarz, J. P., & Wang, X. (2020). Lifecycle of light-absorbing carbonaceous aerosols in the atmosphere. Npj Climate and Atmospheric Science, 3(1). https://doi.org/10.1038/s41612-020-00145-8

Liu, J., Fan, S., Horowitz, L. W., & Levy, H. (2011). Evaluation of factors controlling long-range transport of black carbon to the Arctic. Journal of Geophysical Research Atmospheres, 116(4). https://doi.org/10.1029/2010JD015145

Liu, X., Easter, R. C., Ghan, S. J., Zaveri, R., Rasch, P., Shi, X., et al. (2012). Toward a minimal representation of aerosols in climate models: Description and evaluation in the Community Atmosphere Model CAM5. Geoscientific Model Development, 5(3), 709–739. https://doi.org/10.5194/gmd-5-709-2012

Liu, X., Ma, P. L., Wang, H., Tilmes, S., Singh, B., Easter, R. C., et al. (2016). Description and evaluation of a new four-mode version of the Modal Aerosol Module (MAM4) within version 5.3 of the Community Atmosphere Model. Geoscientific Model Development, 9(2), 505–522. https://doi.org/10.5194/gmd-9-505-2016

Lobell, D. B., & Field, C. B. (2007). Global scale climate-crop yield relationships and the impacts of recent warming. Environmental Research Letters, 2(1). https://doi.org/10.1088/1748-9326/2/1/014002

Lohan, S. K., Jat, H. S., Yadav, A. K., Sidhu, H. S., Jat, M. L., Choudhary, M., et al. (2018). Burning issues of paddy residue management in north-west states of India. Renewable and Sustainable Energy Reviews, 81(August), 693–706. https://doi.org/10.1016/j.rser.2017.08.057

Lund, M. T., Samset, B. H., Skeie, R. B., Watson-Parris, D., Katich, J. M., Schwarz, J. P., & Weinzierl, B. (2018). Short Black Carbon lifetime inferred from a global set of aircraft observations. Npj Climate and Atmospheric Science, 1(1), 1–8. https://doi.org/10.1038/s41612-018-0040-x

van Marle, M. J. E., Kloster, S., Magi, B. I., Marlon, J. R., Daniau, A. L., Field, R. D., et al. (2017). Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750-2015). Geoscientific Model Development, 10(9), 3329–3357.
Matsui, H., Hamilton, D. S., & Mahowald, N. M. (2018). Black carbon radiative effects highly sensitive to emitted particle size when resolving mixing-state diversity. *Nature Communications*, 9(1), 1–11. https://doi.org/10.1038/s41467-018-05635-1

Menon, S., Hansen, J., Nazarenko, L., & Luo, Y. (2002). Climate effects of black carbon aerosols in China and India. *Science*, 297(5590), 2250–2253. https://doi.org/10.1126/science.1075159

Otsuka, K., & Larson, D. F. (2013). *An African Green Revolution*. An African Green Revolution. https://doi.org/10.1007/978-94-007-5760-8

Ouyang, W., Qi, S., Hao, F., Wang, X., Shan, Y., & Chen, S. (2013). Impact of crop patterns and cultivation on carbon sequestration and global warming potential in an agricultural freeze zone. *Ecological Modelling*, 252(1), 228–237. https://doi.org/10.1016/j.ecolmodel.2012.05.009

Pellegrini, P., & Fernández, R. J. (2018). Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. *Proceedings of the National Academy of Sciences of the United States of America*, 115(10), 2335–2340. https://doi.org/10.1073/pnas.1717072115

Pingali, P. L. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences of the United States of America*, 109(31), 12302–12308. https://doi.org/10.1073/pnas.0912953109

Qi, L., Li, Q., Henze, D. K., Tseng, H.-L., & He, C. (2017). Sources of Springtime Surface Black Carbon in the Arctic: An Adjoint Analysis. *Atmospheric Chemistry and Physics Discussions*, 1–32. https://doi.org/10.5194/acp-2016-1112

Rahman, S. (2015). Green revolution in India: Environmental degradation and impact on livestock. *Asian Journal of Water, Environment and Pollution*, 12, 75–80.

Ramanathan, V., & Carmichael, G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience*, 1(4), 221–227. https://doi.org/10.1038/ngeo156

Rana, A., Jia, S., & Sarkar, S. (2019). Black carbon aerosol in India: A comprehensive review of current status and future prospects. *Atmospheric Research*, 218(111), 207–230. https://doi.org/10.1016/j.atmosres.2018.12.002

Ray, D. K., Gerber, J. S., Macdonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature Communications*, 6, 1–9. https://doi.org/10.1038/ncomms6989

Rehman, I. H., Ahmed, T., Praveen, P. S., Kar, A., & Ramanathan, V. (2011). Black carbon emissions from biomass and fossil fuels in rural India. *Atmospheric Chemistry and Physics*, 11(14), 7289–7299. https://doi.org/10.5194/acp-11-7289-2011
Ren, L., Yang, Y., Wang, H., Zhang, R., Wang, P., & Liao, H. (2020). Source attribution of Arctic black carbon and sulfate aerosols and associated Arctic surface warming during 1980-2018. *Atmospheric Chemistry and Physics*, 20(14), 9067–9085. https://doi.org/10.5194/acp-20-9067-2020

Roy, S. Sen, Mahmood, R., Niyogi, D., Lei, M., Foster, S. A., Hubbard, K. G., et al. (2007). Impacts of the agricultural Green Revolution-induced land use changes on air temperatures in India. *Journal of Geophysical Research Atmospheres*, 112(21). https://doi.org/10.1029/2007JD008834

Sahai, S., Sharma, C., Singh, D. P., Dixit, C. K., Singh, N., Sharma, P., et al. (2007). A study for development of emission factors for trace gases and carbonaceous particulate species from in situ burning of wheat straw in agricultural fields in India. *Atmospheric Environment*, 41(39), 9173–9186. https://doi.org/10.1016/j.atmosenv.2007.07.054

Sarkar, S., Singh, R. P., & Chauhan, A. (2018). Crop Residue Burning in Northern India: Increasing Threat to Greater India. *Journal of Geophysical Research: Atmospheres*, 123(13), 6920–6934. https://doi.org/10.1002/2018JD028428

Sartelet, K. N., Hayami, H., Albriet, B., & Sportisse, B. (2006). Development and preliminary validation of a modal aerosol model for tropospheric chemistry: MAM. *Aerosol Science and Technology*, 40(2), 118–127. https://doi.org/10.1080/02786820500485948

Saud, T., Gautam, R., Mandal, T. K., Gadi, R., Singh, D. P., Sharma, S. K., et al. (2012). Emission estimates of organic and elemental carbon from household biomass fuel used over the Indo-Gangetic Plain (IGP), India. *Atmospheric Environment*, 61, 212–220. https://doi.org/10.1016/j.atmosenv.2012.07.030

Schmale, J., Zieger, P., & Ekman, A. M. L. (2021). Aerosols in current and future Arctic climate. *Nature Climate Change*, 11(2), 95–105. https://doi.org/10.1038/s41558-020-00969-5

Sharma, S., Ishizawa, M., Chan, D., Lavoué, D., Andrews, E., Eleftheriadis, K., & Maksyutov, S. (2013). 16-year simulation of arctic black carbon: Transport, source contribution, and sensitivity analysis on deposition. *Journal of Geophysical Research Atmospheres*, 118(2), 943–964. https://doi.org/10.1029/2012JD017774

Shen, G., Ru, M., Du, W., Zhu, X., Zhong, Q., Chen, Y., et al. (2019). Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. *Nature Communications*, 10(1), 1–8. https://doi.org/10.1038/s41467-019-11453-w

Shi, T., Pu, W., Zhou, Y., Cui, J., Zhang, D., & Wang, X. (2020). Albedo of Black Carbon-Contaminated Snow Across Northwestern China and the Validation With Model Simulation. *Journal of Geophysical Research: Atmospheres*, 125(9). https://doi.org/10.1029/2019JD032065

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Shyamsundar, P., Springer, N. P., Tallis, H., Polasky, S., Jat, M. L., Sidhu, H. S., et al. (2019). Fields on fire: Alternatives to crop residue burning in India. *Science, 365*(6453), 536–538. https://doi.org/10.1126/science.aaw4085

Singh, S. (2020). Agriculture Development in India: A State Level Analysis. *South Asian Journal of Social Studies and Economics*, (April), 17–34. https://doi.org/10.9734/sajasse/2020/v6i230162

Singh, T., Biswal, A., Mor, S., Ravindra, K., Singh, V., & Mor, S. (2020). A high-resolution emission inventory of air pollutants from primary crop residue burning over Northern India based on VIIRS thermal anomalies. *Environmental Pollution, 266*, 115132. https://doi.org/10.1016/j.envpol.2020.115132

Sreekanth, V., Niranjan, K., & Madhavan, B. L. (2007). Radiative forcing of black carbon over eastern India Radiative forcing of black carbon over eastern India, (September). https://doi.org/10.1029/2007GL030377

Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T., & Maredia, M. (2013). Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. *Proceedings of the National Academy of Sciences of the United States of America, 110*(21), 8363–8368. https://doi.org/10.1073/pnas.1208065110

Talukdar, S., Venkat Ratnam, M., Ravikiran, V., & Chakraborty, R. (2019). Influence of Black Carbon Aerosol on the Atmospheric Instability. *Journal of Geophysical Research: Atmospheres, 124*(10), 5539–5554. https://doi.org/10.1029/2018JD029611

Tibrewal, K., & Venkataraman, C. (2020). Climate co-benefits of air quality and clean energy policy in India. *Nature Sustainability*, (3). https://doi.org/10.1038/s41893-020-00666-3

Tripathi, S. N., Dey, S., & Tare, V. (2005). Aerosol black carbon radiative forcing at an industrial city in northern India, 32. https://doi.org/10.1029/2005GL022515

Tyagi, A. C. (2016). Towards a Second Green Revolution. *Irrigation and Drainage, 65*(4), 388–389. https://doi.org/10.1002/ird.2076

Wang, R., Tao, S., Ciais, P., Shen, H. Z., Huang, Y., Chen, H., et al. (2013). High-resolution mapping of combustion processes and implications for CO2 emissions. *Atmospheric Chemistry and Physics, 13*(10), 5189–5203. https://doi.org/10.5194/acp-13-5189-2013

Wang, Rong, Tao, S., Balkanski, Y., Ciais, P., Boucher, O., Liu, J., et al. (2014). Exposure to ambient black carbon derived from a unique inventory and high-resolution model. *Proceedings of the National Academy of Sciences of the United States of America, 111*(7), 2459–2463. https://doi.org/10.1073/pnas.1318763111

Wang, Rong, Tao, S., Shen, H., Huang, Y., Chen, H., Balkanski, Y., et al. (2014). Trend in global black carbon emissions from 1960 to 2007. *Environmental Science and Technology, 48*(12), 6780–6787. https://doi.org/10.1021/es5021422
Wang, X., Heald, C. L., Liu, J., Weber, R. J., Campuzano-Jost, P., Jimenez, J. L., et al. (2018). Exploring the observational constraints on the simulation of brown carbon. *Atmospheric Chemistry and Physics, 18*(2), 635–653. https://doi.org/10.5194/acp-18-635-2018

Wang, Yong, Xia, W., Liu, X., Xie, S., Lin, W., Tang, Q., et al. (2021). Disproportionate control on aerosol burden by light rain. *Nature Geoscience, 14*(2), 72–76. https://doi.org/10.1038/s41561-020-00675-z

Wang, Yuan, Ma, P. L., Peng, J., Zhang, R., Jiang, J. H., Easter, R. C., & Yung, Y. L. (2018). Constraining Aging Processes of Black Carbon in the Community Atmosphere Model Using Environmental Chamber Measurements. *Journal of Advances in Modeling Earth Systems, 10*(10), 2514–2526. https://doi.org/10.1029/2018MS001387

Wang, Yuanyuan, Liu, F., He, C., Bi, L., Cheng, T., Wang, Z., et al. (2017). Fractal Dimensions and Mixing Structures of Soot Particles during Atmospheric Processing. *Environmental Science and Technology Letters, 4*(11), 487–493. https://doi.org/10.1021/acs.estlett.7b00418

van der Werf, G. R., Randerson, J. T., Giglio, L., Van Leeuwen, T. T., Chen, Y., Rogers, B. M., et al. (2017). Global fire emissions estimates during 1997-2016. *Earth System Science Data, 9*(2), 697–720. https://doi.org/10.5194/essd-9-697-2017

Wesely, M. L. (1989). Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models. *Atmospheric Environment (1967), 23*(6), 1293–1304. https://doi.org/10.1016/0004-6981(89)90153-4

Yasunari, T. J., Bonasoni, P., Laj, P., Fujita, K., Vuillermoz, E., Marinoni, A., et al. (2010). Estimated impact of black carbon deposition during pre-monsoon season from Nepal Climate Observatory - Pyramid data and snow albedo changes over Himalayan glaciers. *Atmospheric Chemistry and Physics, 10*(14), 6603–6615. https://doi.org/10.5194/acp-10-6603-2010

Yasunari, Teppei J., Tan, Q., Lau, K. M., Bonasoni, P., Marinoni, A., Laj, P., et al. (2013). Estimated range of black carbon dry deposition and the related snow albedo reduction over Himalayan glaciers during dry pre-monsoon periods. *Atmospheric Environment, 78*, 259–267. https://doi.org/10.1016/j.atmosenv.2012.03.031

Yi, K., Meng, J., Yang, H., He, C., Henze, D. K., Liu, J., et al. (2019). The cascade of global trade to large climate forcing over the Tibetan Plateau glaciers. *Nature Communications, 10*(1). https://doi.org/10.1038/s41467-019-10876-9

Zeng, N., Zhao, F., Collatz, G. J., Kalnay, E., Salawitch, R. J., West, T. O., & Guanter, L. (2014). Agricultural Green Revolution as a driver of increasing atmospheric CO2 seasonal amplitude. *Nature, 515*(7527), 394–397. https://doi.org/10.1038/nature13893

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Zhang, Y., Favez, O., Canonaco, F., Liu, D., Močnik, G., Amodeo, T., et al. (2018). Evidence of major secondary organic aerosol contribution to lensing effect black carbon absorption enhancement. *Npj Climate and Atmospheric Science, 1*(1). https://doi.org/10.1038/s41612-018-0056-2

Zhao, C., Piao, S., Wang, X., Huang, Y., Ciais, P., Elliott, J., et al. (2016). Plausible rice yield losses under future climate warming. *Nature Plants, 3*(December), 1–5. https://doi.org/10.1038/nplants.2016.202

Zhou, C., Penner, J. E., Flanner, M. G., Bisiaux, M. M., Edwards, R., & McConnell, J. R. (2012). Transport of black carbon to polar regions: Sensitivity and forcing by black carbon. *Geophysical Research Letters, 39*(22), 1–6. https://doi.org/10.1029/2012GL053388

Zhu, C., Kanaya, Y., Takigawa, M., Ikeda, K., Tanimoto, H., Taketani, F., et al. (2020). FLEXPART v10.1 simulation of source contributions to Arctic black carbon. *Atmospheric Chemistry and Physics, 20*(3), 1641–1656. https://doi.org/10.5194/acp-20-1641-2020