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Black carbon cookstove emissions: A field assessment of 19 stove/fuel combinations

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HIGHLIGHTS

- Results of optical black carbon (BC) measurements of 19 cookstoves is presented.
- An attenuation cross-section was determined for BC analysis using transmissometry.
- BC emission factors and BC/PM is presented for five stove classes.
- Potential relative climate impacts were estimated using CO_2-equivalents.

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ABSTRACT

Black carbon (BC) emissions from household cookstoves consuming solid fuel produce approximately 25 percent of total anthropogenic BC emissions. The short atmospheric lifetime of BC means that reducing BC emissions would result in a faster climate response than mitigating CO_2 and other long-lived greenhouse gases. This study presents the results of optical BC measurements of two new cookstove emissions field assessments and 17 archived cookstove datasets. BC was determined from attenuation of 880 nm light, which is strongly absorbed by BC, and linearly related between 1 and 125 attenuation units. A relationship was experimentally determined correlating BC mass deposition on quartz filters determined via thermal optical analysis (TOA) and on PTFE and quartz filters using transmissometry, yielding an attenuation cross-section (σ_{ATN}) for both filter media types. σ_{ATN} relates TOA measurements to optical measurements on PTFE and quartz ($\sigma_{ATN(PTFE)} = 13.7$ cm^{-2} μg, $R^2 = 0.87$, $\sigma_{ATN(Quartz)} = 15.6$ cm^{-2} μg, $R^2 = 0.87$). These filter-specific σ_{ATN}, optical measurements of archived filters were used to determine BC emission factors and the fraction of particulate matter (PM) in the form of black carbon (BC/PM). The 19 stoves measured fell into five stove classes; simple wood, rocket, advanced biomass, simple charcoal, and advanced charcoal. Advanced biomass stoves include forced- and natural-draft gasifiers which use wood or biomass pellets as fuel. Of these classes, the simple wood and rocket stoves demonstrated the highest median BC emission factors, ranging from 0.051 to 0.14 g MJ^{-1}. The lowest BC emission factors were seen in charcoal stoves, which corresponds to the generally low PM emission factors observed during charcoal combustion, ranging from 0.0084 to 0.014 g MJ^{-1}. The advanced biomass stoves generally showed an improvement in BC emissions factors compared to simple wood and rocket stoves, ranging from 0.0031 to 0.071 g MJ^{-1}. BC/PM ratios were highest for the advanced and rocket stoves. Potential relative climate impacts were estimated by converting aerosol emissions to CO_2-equivalent, and suggest that some advanced stove/fuel combinations could provide substantial climate benefits.

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1. Introduction

Approximately 41% of the world's households, or about 2.8 billion people globally, depend on solid fuels for meeting daily cooking needs (Bonjour et al., 2013). Use of these fuels for cooking and heating results in the emissions of climate forcing pollutants such as methane and black carbon (BC) (Jetter and Kariher, 2009; MacCarty et al., 2008; Preble et al., 2014). Introduction of cleaner-burning stoves and fuels has been proposed and pursued as a means to reduce household pollutant emissions that influence global and regional climate. BC emissions from cookstoves are of particular interest, as BC is estimated to be second only to CO_2 in its warming impact (Ramanathan and Carmichael, 2008) and solid fuel burning for cooking of heating in homes produces approximately 25 percent of total anthropogenic BC emissions (Bond et al., 2013). Since the atmospheric lifetime of BC is only a few days, reducing BC emissions can produce near-term climate change mitigation, whereas benefits due to reductions in CO_2 and other long-lived greenhouse gases accrue over decades to centuries (Bond and Sun, 2005).

Quantifying emissions of short-term climate pollutants is important for both climate modeling as well as understanding the implications of promoting different stove/fuel interventions. Ideally, this information can be used to incentivize household energy programs and cooking technology developers to produce and promote solutions which maximize benefits. Frameworks which incentivize household energy programs to provide reductions in long-term climate benefits by quantifying and trading carbon offsets have been in place for several years, and now relatively new methodologies have been developed which provide a similar mechanism trading short-term climate benefits (The Gold Standard Foundation, 2015). Importantly, quantifying these short-term benefits requires a careful assessment of their aerosol emissions. Particulate matter (PM) emissions include both BC and organic carbon (OC). While BC has a strong warming impact, OC has a cooling effect, as it tends to scatter light rather than absorb it (Bond et al., 2013). Thus, characterization of the BC and OC aerosol emissions is fundamental to understanding and quantifying the climate benefits posed by household energy interventions.

To date, while there have been a handful of field studies which have reported on real-world black and organic carbon emissions from cookstoves (Johnson et al., 2008; Johnson et al., 2011a; Roden et al., 2006), there is still relatively little information on how various classes of stove/fuel intervention technologies may impact these emissions. Specifically, very little data is available on newer and more advanced types of technologies, such as forced-draft and pellet stoves, which may have the greatest potential for reducing emissions from solid fuels. Additional comparisons with data from controlled laboratory testing are also needed to help us better characterize the differences which have been observed between laboratory and field performance (Johnson et al., 2010; Roden et al., 2009). Finally, emissions sampling is relatively intensive and costly compared to other types of stove performance testing in homes, and thus the data sets are comprised of stove fuel combinations (e.g. 1–5 fuel/stove combinations) and/or small sample sizes (e.g. 5–20 homes or events). Complimenting and augmenting these studies with larger data sets is needed to provide a more definitive characterization of aerosol emissions from household energy technologies.

To address these needs, here we present black and organic carbon emissions estimates from 19 stove/fuel combinations being used in Asia and Africa. All testing was conducted in homes during uncontrolled cooking events to provide real-world estimates of emissions performance.

2. Methods

2.1. Field campaigns

A combination of archived filters (N = 453) and newly collected filters (N = 44) were analyzed for this study, which is outlined in Table 1. Field campaigns occurred at seven locations in Asia and Africa. Brief descriptions of the stove and fuel types, sample sizes, and study locations for the field campaigns can be found in Table 1. Additional details and maps are provided in the supporting information.

2.2. Emissions sampling

All samples were collected following the same fundamental protocol. Emissions sampling was conducted during uncontrolled cooking events in participants' homes, for which the cook was instructed to prepare a meal as they normally would, without altering stove operation, cooking techniques, or fuel type. An example of the measurement scheme is shown in Fig. 1. The emissions species measured included carbon dioxide (CO_2), carbon monoxide (CO), particulate matter $\leq$ 2.5 μm in aerodynamic diameter ($PM_{2.5}$), and black carbon (BC). Additional measurements of elemental carbon (EC) and organic carbon (OC) were made in India and Cambodia.

Before and after each cooking event, all fuels were weighed separately. Ash and char were immediately removed from the stove, separated using an ash screen, and weighed. Scale type varied, but all scales were calibrated using NIST standard weights before use and were checked daily for drift throughout the field campaigns. Fuel moisture content was determined using either a two-pin resistance style moisture meter (Extech M0210) or a moisture analyzer balance (Precisa, Model - XM 60-HR). Fuel mass was converted to equivalent energy using energy densities determined via bomb calorimetry (C200, IKA Works Inc., USA) or default values provided by the Water Boling Test protocol version 4.2.4 (WBT Technical Committee, 2013).

Emissions were collected using the partial capture method and emissions factors were determined using the carbon balance approach. Details of partial capture and carbon balance methods have been described in previous publications (Johnson et al., 2011a; Roden et al., 2006; Smith et al., 2000), as well as the Water Boling Test protocol version 4.2.3 (WBT Technical Committee, 2013). Briefly, real-time concentrations of CO and CO_2 were measured using a TSI IAQ-CALC 7545 (TSI Inc., USA), and gravimetric measurements were taken to quantify $PM_{2.5}$ and BC. When Measuring EC and OC, two sample streams were drawn by constant-flow SKC sampling pumps (SKC Inc., USA), splitting after the sample exited a BGI Triplex cyclone (BGI, USA) at 0.75 L per minute (LPM) (1.5 LPM total through cyclone) from each line to remove particles larger than 2.5 μm in diameter. One sample line drew air through a PTFE filter to determine $PM_{2.5}$ mass deposition followed by a quartz filter (Advantec) to collect gas phase OC when measured. The other sample line passed air through only a quartz filter and collected both particle and gas phase OC and EC. Mass deposition was determined gravimetrically by weighing the Teflon filters before and after sampling in a constant humidity and temperature room on an electronic microbalance with 0.1 μg resolution (Mettler Toledo, USA).

Emissions factors were determined using the carbon balance approach, as has been done in previous studies of stove emissions and is described in the WBT 4.2.3 protocol (Johnson et al., 2011b; Roden et al., 2006; Smith et al., 2000; WBT Technical Committee, 2013). Flow rates and sample volumes were adjusted for temperature and pressure, which were recorded before and after each event.