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Household Light Makes Global Heat: High Black Carbon Emissions From Kerosene Wick Lamps

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Abstract

Kerosene-fueled wick lamps used in millions of developing-country households are a significant but overlooked source of black carbon (BC) emissions. We present new laboratory and field measurements showing that 7–9% of kerosene consumed by widely used simple wick lamps is converted to carbonaceous particulate matter that is nearly pure BC. These high emission factors increase previous BC emission estimates from kerosene by 20-fold, to 270 Gg/year (90% uncertainty bounds: 110, 590 Gg/year). Aerosol climate forcing on atmosphere and snow from this source is estimated at 22 mW/m² (8, 48 mW/m²), or 7% of BC forcing by all other energy-related sources. Kerosene lamps have affordable alternatives that pose few clear adoption barriers and would provide immediate benefit to user welfare. The net effect on climate is definitively positive forcing as co-emitted organic carbon is low. No other major BC source has such readily available alternatives, definitive climate forcing effects, and co-benefits. Replacement of kerosene-fueled wick lamps deserves strong consideration for programs that target short-lived climate forcers.

Introduction

One-fifth of the global population lacked access to electricity in 2009,¹ and many more had only intermittent access. Lack of clean energy provisions for basic household needs leads to use of appliances and fuels with high pollutant emissions. Products of incomplete combustion from biomass and coal used in cookstoves affect not only household environments and human health² but also outdoor air pollution and climate.³ Lighting is another component of this household energy challenge, with millions of households still relying on simple liquid-fueled lamps, but little is known of the associated environmental and health impacts.

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SUPPORTING INFORMATION AVAILABLE

Field and laboratory sampling system descriptions and schematics, measurement QA/QC, disaggregated emission factors and aerosol properties, real time emissions, kerosene consumption for lighting, regional and global BC emission rates, forcing from direct BC forcing and from deposition on snow by global region. This information is available free of charge via the Internet at <http://pubs.acs.org/>

One environmental issue that has been linked with emissions from household-solid fuel burning is that of black carbon (BC) and climate change.⁴ BC is a product of incomplete combustion and one of the few components of atmospheric aerosol that absorbs light and heats the atmosphere, thereby contributing to climate warming.⁵ The most common measure of climate impact, termed radiative forcing, describes the change in Earth's net energy balance imposed by a single constituent or set of constituents at the top of the atmosphere. Positive forcing is associated with average warming. During its short atmospheric lifetime, one kg of BC produces as much positive forcing as 700 kg of carbon dioxide (CO₂) does during 100 years.⁶ Some have proposed that reducing BC emissions could rapidly reduce this warming and prevent Earth's temperature from reaching dangerous levels,^{7–9} while simultaneously improving human health.¹⁰ Most sources of BC, however, also emit aerosol organic carbon (OC), which cools the Earth by reflecting sunlight¹¹ and increasing cloud brightness.^{12, 13} The net effect (warming or cooling) of particles from any source depends on how much of the emitted total aerosol carbon (TC) is BC.¹⁴ Thus, mitigating many BC sources may not actually reduce warming if their OC emissions are substantial.

Kerosene (paraffin) is the most common lamp fuel in developing countries because it is easily transported, stored, and affordable, due principally to government subsidies. It has been estimated that houses without electricity consume 77 billion liters of liquid fuels (mostly kerosene) to meet lighting requirements, corresponding to 190 million metric tonnes of CO₂ per year.¹⁵ Despite the existence of clean and efficient lamp designs, households often burn kerosene in locally constructed simple wick lamps, which consist of a rope or cloth wick extending from a metal or glass container. Also common is the commercially manufactured, glass-shrouded "hurricane" wick lamp. These lighting devices emit particulate matter (PM)^{16, 17} that remains in the atmosphere for several days due to its small size.^{17, 18}

The contribution of kerosene lighting devices to global BC emissions has not been investigated in depth. Particulate emissions from hurricane-style kerosene lamps were reported as mostly BC (about 80%), but in that study the lamps were deliberately operated at conditions unrepresentative of typical household usage.^{19, 20} Here we present field and laboratory measurements of BC and particulate emission factors from kerosene wick lamps. We then develop new estimates of fuel usage for lighting and combine them with measured emission factors to infer a global emission rate, and finally we estimate the effect of these particles on Earth's radiative energy budget.

Materials and Methods

Emission measurement

In-field emissions were measured from simple wick lamps purchased and prepared by local residents in Southwestern Uganda. Field conditions ensure that the devices tested and their fuels are representative of actual practice, but measurements are made under challenging conditions without electricity, so that less controlled measurements are possible relative to laboratory testing. Therefore, to ensure that the results were robust, repeated tests of simple wick lamps from Uganda and Peru, and sensitivity studies, were also performed in a laboratory setting at the University of Illinois at Urbana-Champaign.

For laboratory tests, a baseline lamp operating condition, based on field observations, consisted of a cloth wick at a height of 1–1.5 mm ("low"). Unless stated otherwise, laboratory tests were conducted using kerosene purchased in the USA (grade 1-K) and tested in triplicate. Sensitivity tests included replacing the cloth wick with a rope-style wick (also used in kerosene stoves), increasing the wick height to 3–4 mm ("high"), and burning kerosene imported from Uganda. Sensitivity tests in the lab were conducted in triplicate on

one of the three simple wick lamps used for baseline testing. A hurricane lamp was also tested in the laboratory.

Emissions measured in real-time were carbon monoxide (CO), carbon dioxide (CO₂), and particle optical properties—light absorption and scattering. These real-time measurements were recorded every four seconds during tests lasting approximately one hour. In the field, a modified Portable Emission Monitoring System (PEMS, Aprovecho Research Center, Cottage Grove, OR) measured CO (SS1128, Senko) and CO₂ (Telaire T6004, GE) using electrochemical and non-dispersive infrared (NDIR) sensors, respectively. The real-time particle scattering coefficient was measured with the PEMS PM sensor at a red wavelength (660nm). A Particle Soot Absorption Photometer (PSAP, Radiance Research, Shoreline, WA) measured absorption at three wavelengths of 467, 530 and 660 nm. For laboratory tests, CO₂ and CO concentrations were measured in real-time with a Li-COR 6252 (Li-COR Biosciences, Lincoln, NE) and Horiba AIA-220 (Horiba, Kyoto, Japan) non-dispersive infrared (NDIR) analyzer, respectively. Particle scattering was measured with an integrating nephelometer (M903, Radiance Research, Shoreline, WA) at a wavelength of 530 nm, and absorption was also measured with the PSAP. Measured scattering and absorption was used to calculate climate relevant characteristics of aerosols, including the single scattering albedo (SSA), mass scattering cross section (MSC), and mass absorption cross section of black carbon (MAC_{BC}). An enhancement in the laboratory system, which has been described and evaluated elsewhere,²¹ was an additional sample dilution using dry particle-free air (dilution ratio of about 3:1 for simple-wick lamps) to accommodate high particle concentrations and provide more accurate optical measurements. All real-time measurements (CO, CO₂, particle absorption and scattering coefficient) were converted to standard conditions (1 atm and 20 °C). Background CO and CO₂ concentrations, and particle scattering and absorption, were subtracted. A more detailed description of the sampling system and procedures, including schematics, photographs of lamps tested, and instrument settings and calibration is provided in the Supporting Information (Section S1).

Samples for PM_{2.5} or PM_{TSP} mass and elemental (EC) and organic (OC) carbon analysis were captured on filter membranes integrated over the entire test. For laboratory tests, sample flow was passed through a micro-centrifuge (URG-2000-30EN, URG Corp, Chapel Hill, NC) with an aerodynamic cut-off diameter of 2.5 μm; no aerodynamic cutoff was applied in field measurements. Negligible PM was found in the centrifuge collector used in the laboratory; that is, all emitted PM had diameters smaller than 2.5 μm. Two filter holders (URG-2000-30RAF, URG Corp, Chapel Hill, NC) were used to collect filter samples for test-integrated mass measurements of PM, OC and EC. One filter holder contained a pre-baked 47mm quartz fiber filter (TISSUQUARTZ 2500QAT-UP, Pall). The other holder contained a 47mm Teflon filter (1.0 μm pore size, Fluoropore™ Membrane Filters, FALP04700, Millipore) upstream of another pre-baked quartz fiber filter. The Teflon filter was weighed before and after sampling to obtain PM mass using a microbalance (Cahn C-31, Thermo Electron Corp.) in a temperature and humidity controlled room after 24 hours of conditioning. Elemental carbon (EC), presented here as an equivalent to BC, and OC were measured on the quartz filters with a Sunset Laboratory OC/EC Analyzer (Sunset Laboratory, Tigard, OR) using the thermal-optical-transmittance method (TOT).²² In the TOT method, filter transmittance is monitored during the whole procedure and used to correct for OC charring (pyrolysis). When such charring occurs, it is known to introduce uncertainties into the determination of EC. However, as shown in the results, little OC was present that could char. Under these circumstances, the division between elemental and organic carbon has little artifact, and the EC so determined is nearly equivalent to BC. The quartz filter downstream of the Teflon filter was used to account for organic vapor adsorption.^{23, 24} Field blanks were collected during field sampling and apparent mass was an average of six times lower than sampled filters (p < 0.05).

Emission factor calculation

Emission factors for PM, BC and OC (EF_{PM} , EF_{OC} or EF_{BC}) are expressed in units of g PM (OC or BC) per kg of kerosene burnt and determined with the carbon balance method (CBM). This method assumes that all gaseous and particulate carbon present in a volume of sampled air came from the fuel that also produced the pollutants in that volume, so that emission factors can be calculated with a ratio between the two concentrations. One advantage of the CBM is the ability to obtain emission rates with low sampling flows and, hence, low power. Another advantage is the ability to sample sources for which containment within a hood would degrade the quantity, realism, or operation. This method has been used for measuring emissions from cookstoves,²¹ biomass burning,²⁵ and vehicles.²⁶ One limitation of the method is the need to obtain a representative sample across the exhaust plume, which we accomplish by using a sampling probe with 16 equal-flow ports. A potential inaccuracy compared with constant-volume sampling occurs if dilution or flow rates through the combustion device vary during the sampling period, but lamp combustion was quite stable. Further description of the carbon balance calculations is given in SI (Section S1.4).

Global BC emissions

Emissions (EM) from a single type of lighting device (e.g. simple wick, hurricane) were calculated as the product of five factors:

$$EM = KERO \times f_{light} \times f_{device} \times EF_{device} \times f_{outdoor}$$

where $KERO$ is regional kerosene use in the residential sector in year 2005 from the International Energy Agency (IEA),^{27, 28} f_{light} is the fraction of residential kerosene consumption attributable to lighting demands (described below), f_{device} is the fraction of kerosene lighting accomplished with a particular lighting device, EF_{device} is the device-specific pollutant emission factor (e.g. EF_{BC}), and $f_{outdoor}$ is the fraction that escapes outdoors. Emissions are calculated separately for simple wick lamps and hurricane lamps and then added to obtain total emissions from lighting. Lamps are assumed to be either simple wick or hurricane style, so that f_{device} for the two types sums to unity. Uncertainties for each factor in Equation 1 were implemented in a Monte Carlo analysis assuming that they were independent. Values of f_{light} were based on observations as described below. For regions where f_{light} is greater than zero, it ranges from 0.01 in Southern Africa to 0.6 in Northern Africa. Values of f_{device} for simple-wick lamps range from 0.25 in the Middle East to 0.8 in most of Asia. EF_{device} comes from the measurements presented here, and $f_{outdoor}$ was 0.89 with a 90% uncertainty range of 0.60 to 0.97. The Supporting Information contains regionally dependent values of f_{light} and f_{device} , their uncertainties, and support for the calculation of $f_{outdoor}$ (Section S2.1).

Residential kerosene consumption for lighting

Kerosene consumed in the residential sector may be used for lighting, cooking, or heating. To estimate the fraction of residential kerosene used for lighting (f_{light} in Equation 1), we first estimated the annual consumption of kerosene for lighting with “bottom-up” estimates in countries where the number of houses using kerosene for light is reported, or can be inferred with knowledge about households that lack access to electricity. Such data were available for several nations, including India, one of the largest residential kerosene users, nineteen countries in Africa, four in South East Asia, and ten in Latin America. Finally, the bottom-up estimates for each available country within a region was divided by the corresponding residential kerosene consumption reported by IEA^{27, 28} to obtain a value of f_{light} . In turn, these values were extrapolated to the entire region. Data supporting this

analysis, including a summary of country-level statistics on kerosene lighting, are given in the Supporting Information (Section S2.1). We also applied additional data to constrain the consumption for lighting in India based on nationally representative household-level surveys.

Radiative forcing

Kerosene lighting occurs in different regions than most fossil-fuel BC emissions, and this spatial distribution could affect the magnitude of radiative forcing. To estimate global climate forcing caused by kerosene lighting, we applied maps of forcing per emission⁶ specific to each region of emission and location of impact. As described by Bond et al.,⁶ forcing in all regions was first scaled equally so that the global median forcing matched the median forcing from 16 global models, and then the regional forcing was scaled, when possible, according to regional forcing values from other studies. Use of these “ensemble adjustments” reflects the most current knowledge of the community.

Results

Emission factors

The EF_{PM} for a simple wick lamp operated at baseline settings in laboratory tests was 81 ± 15 g/kg kerosene, while device-specific EF_{PM} ranged from 71–87 g/kg kerosene; in other words, 7–9% of the fuel is converted to particulate matter (Table 1). The majority of PM mass was BC, with measured BC/TC ratios ranging from 0.88–1.00 and an EF_{BC} of 76 ± 15 g/kg kerosene. Variation in EF_{BC} was 9–23% for tests of a single lamp and about 20% for similar tests on different lamps. EF_{OC} ranged from 4–6 g/kg kerosene, so the ratio between OC and BC was 0.06 ± 0.05 . EF_{BC} from a hurricane lamp was 9 ± 1 g/kg kerosene, or 8–10 times lower than the average simple wick device, but the majority of PM mass was still BC (BC/TC = 0.95 ± 0.03). EF_{CO} for the simple wick and hurricane lamps were 16 ± 1 g/kg kerosene and 3 ± 1 g/kg kerosene, respectively. Further description of results, including tables of disaggregated emission factors, aerosol properties, and real-time emission profiles are available in the SI (Section S3.1 and S3.2)

Much of the variability in EF_{BC} is associated with variation in the rate of kerosene consumption (“burn rate” or X_{BR}). Figure 1 summarizes all field measurements and sensitivity tests, showing that EF_{BC} and X_{BR} have an approximately linear relationship ($EF_{BC} = 240X_{BR} + 54$, $R^2 = 0.52$). This relationship changes by less than 2% after adjusting for unbalanced repeated measurements by aggregating by lamp or applying mixed effects models. Combining this relationship with our central value of fuel burn rate (0.12 g min^{-1}) gives an EF_{BC} for a simple wick lamp of 83 g/kg kerosene, with 90% uncertainty bounds of (63, 109). The average values of EF_{BC} and EF_{PM} collected in Western Uganda from simple wick lamps were higher than those measured under laboratory conditions by 14 g/kg kerosene (18%) and 12 g/kg kerosene (12%), respectively. Much of the discrepancy between laboratory and field-based emissions can be explained by differences in fuel burn rates.

EF_{PM} measured in the lab for a hurricane lamp is consistent with the EF_{PM} reported by Fan and Zhang¹⁷ for a hurricane lamp operated at high wick setting ($EF_{PM} = 9.0 \pm 4.0$ g/kg), and three times higher than their emission at a normal flame height ($EF_{PM} = 3.3 \pm 2.8$ g/kg). Higher EF_{BC} values have been measured when hurricane lamps generated soot for research purposes,^{19, 20} but these conditions would cause the lamp glass to quickly cover in soot, reducing useful light.

The average EF_{BC} for a simple wick lamp of 76 ± 15 g/kg kerosene, and the BC/TC ratio of 0.95 ± 0.05 , are much higher than other sources of BC (Figure 2).²⁹ In contrast, EF_{CO} (not shown in figures) was lower than that from other BC sources at 16 ± 1 g/kg. BC emission

factors from simple wick lamps are two orders of magnitude higher than those from kerosene-fueled cookstoves. Cooking uses the heat produced when fuel is converted to carbon dioxide and water, and it is most efficient when combustion is complete. In contrast, BC within a flame is the agent of illumination, a fact known since Faraday lectured that “all things that burn and produce solid particles... give us this glorious and beautiful light.”³⁰ Simple lighting devices therefore must produce BC. Then, rapid cooling of combustion effluents prevents further oxidation, resulting in high BC emissions.

Sensitivity of emission factors to operating conditions

Heightening the wick of a simple lamp to increase illumination is common in households. At high wick settings, the fuel burn rate increased, and the average EF_{BC} increased by 28 g/kg (38%), with a smaller 5 g/kg (30%) increase in average CO and no change in EF_{OC} .

Several other modifications to baseline lamp settings could alter emissions. The simple wick of a liquid-fuel lamp is fashioned from cloth or rope. Fuel is transported by capillary action and the rate of transport might be influenced by material. When rope was used in place of cloth, no significant difference in emissions or fuel burn rate was observed. Burning Ugandan kerosene in place of fuel produced in the United States (1-K) increased average EF_{PM} by 42%, but had no significant effect on EF_{BC} , EF_{OC} , or EF_{CO} . The greater PM from imported Ugandan fuel might be explained by its approximately doubled sulfur content (0.08 Wt%), or 13% increase in aromatic content (18 Vol%), based on fuel analysis.

Aerosol optical properties

Three climate relevant characteristics of aerosols are single-scattering albedo (SSA), which is the fraction of extinction caused by scattering rather than absorption; mass absorption cross-section (MAC_{BC}), which is the absorption cross-section per BC mass; and the mass scattering cross-section (MSC), which is the scattering cross-section per PM mass. Particles from lamps had SSA of 0.25–0.30, mass scattering cross-section of 1.9–3.1 m²/g, and mass absorption cross-section of 6.4–7.8 m²/g (530 nm) (Table 1). These values are similar to those of freshly generated, pure BC particles (SSA = 0.2–0.3; $MAC = 7.5 \pm 1.2$ m²/g at 550 nm).³¹ Therefore, particles emitted from simple wick lamps have both the chemical and optical properties of nearly pure BC.

Global kerosene consumption for lighting

In the year 2005, residential use of kerosene fuel was only 0.5% of global energy consumption.^{27, 28} The most recent emission inventories, lacking measured values for BC and OC emitted from lighting, used emission factors from cooking stoves for all uses of kerosene.^{29, 32} Because the two emission factors are so different, improving emission inventories first requires an estimate of the amount of kerosene used for lighting.

As discussed in the Methods section, we estimated the fraction of kerosene used for lighting based on survey data. Combining available information on kerosene lighting prevalence and usage patterns led to an estimate of global kerosene consumption for residential lighting of 5,000 Gg/year, with 53% attributable to simple wick lamps. This constitutes 25% of the reported residential kerosene consumption in South Asia and 29% in African countries. These estimates are restricted to household consumption and do not consider usage in other sectors (e.g. public or small scale business lighting).

We further constrained consumption estimates in India, one of the largest consumers of residential kerosene, using information from a large consumer expenditure survey on the household consumption of goods and services. This survey, conducted by the National Sample Survey Organization (NSSO), includes per-capita kerosene consumption for

combined lighting and cooking and reports values separately for the rural and urban population in each state.^{33, 34} Using NSSO survey results and the number households in each state, but applying separate consumption rates for lighting and cooking, led to estimates of consumption for lighting of 2500 Gg/year for 2005. The central estimate for kerosene cooking was 6700 Gg/year for 2005. For comparison, the estimate of combined consumption of 9200 Gg, is in agreement with that estimated from reported per-capita consumption data given by NSSO surveys (8550 Gg), and the value reported by IEA (9377 Gg) for total residential applications.²⁷ Thus, lighting accounts for approximately one quarter of the annually reported residential kerosene consumption in India, while cooking, which consumes fuel at a significantly faster rate^{35, 36} and diversion of government subsidized kerosene to non-residential sectors may account for the remainder. Additional information supporting this analysis for India, including further description of data sources, is available in the SI (Section S2.2).

BC emission rates

Emission factors for simple wick lamps were based on the central estimate of fuel burn rate, as stated previously. A value of EF_{BC} for hurricane lamps was estimated as 2.2 g BC/kg kerosene (1.3, 5.0) using EF_{PM} values reported by Fan and Zhang¹⁷ along with the BC/TC ratio measured in this study for a hurricane lamp (0.95 ± 0.03).

Applying these emission factors to fuel consumption estimates, the central value of atmospheric emission rate from residential kerosene lighting is 270 Gg BC/year. A Monte Carlo analysis considering uncertainties in the parameters gives (110, 590) Gg BC/year as 90% uncertainty bounds. BC emission rates by global region are presented in the SI (S3.3).

Previous estimates that assumed only cooking emission factors for residential kerosene use resulted in negligible estimates of emissions: 12 Gg BC and 34 Gg OC per year for all kerosene uses. For comparison with other BC sources, a total of 890 Gg BC and 280 Gg OC are estimated from diesel engines, or 1900 Gg BC and 7700 Gg OC from cooking and heating with solid fuels (biomass and coal).²⁹ The BC emissions from lamps alone are 20–25% of the global BC emissions from diesel engines and 10–15% of BC from residential use of solid fuel.²⁹ While BC emissions from kerosene lamps are smaller in absolute terms than other major source categories, their contribution is notable because the fuel consumed is much lower, and because they have been formerly assumed to be so small.

Modeled atmospheric concentrations based on current emission inventories, which do not include kerosene-based lighting sources, predict absorbing aerosols reasonably well in most world regions, with South Asian and African regions being exceptions.³⁷ Surface³⁸ and aircraft³⁹ measurements report unexpectedly high concentrations of BC in South Asia, where particles are much more absorbing than in other world regions.⁴⁰ These observations are consistent with large unquantified sources of very dark aerosol that may be explained in part by the use of kerosene lighting in both regions. This formerly “missing” source of black carbon may explain why estimates of aerosol impacts indicate much greater atmospheric absorption in Asia when observational constraints are applied.⁴¹

The emission estimates presented here may be low for several reasons. The annual estimate of kerosene consumption for residential lighting is less than one-tenth of that given by Mills (65,000 Gg kerosene/year).¹⁵ A comparison of the methods provides two major differences between study estimates: this study applied information from national household surveys to arrive at a more constrained number of households reliant on kerosene, and applied a fuel burn rate based on laboratory and field measurements of simple wick lamps that is roughly four times lower. Fuel impurities are also known to decrease combustion efficiency and kerosene used in lab measurements is likely representative of the cleanest consumer

kerosene. Finally, we did not estimate emissions from lighting in non-household settings, such as schools, restaurants, and street vendors and, except for India, in households with intermittent access to electricity.

Climate forcing

The most common measure of climate impact, termed radiative forcing, describes the change in Earth's net energy balance imposed by a single constituent at the top of the atmosphere. Positive forcing is associated with average warming. Spatially distributed direct forcing by emissions from kerosene lamps (Figure 3) was estimated by applying maps of forcing per emission specific to each of 17 regions.⁶ Latitudinal breakdowns of forcing for regional emissions are provided in the SI (Table S6a and S6b). Local direct forcing can be as high as +0.6 W/m² and diluted effects extend to the upper latitudes. Globally averaged forcing is 20 mW/m² (90% uncertainty: 8, 48 mW/m²) and 1.5 mW/m² on snow, or about 7% of global BC forcing from all energy-related emissions. For comparison, net climate impact by short-lived climate forcers (without snow forcing) has been estimated as 60 mW/m² for household biomass fuel and 85 mW/m² for on-road diesel engines.⁴² Negative forcing by co-emitted organic carbon from lamps offsets less than 0.5% of the positive forcing by BC.

Increased aerosol concentrations can increase the brightness of liquid clouds, imposing negative forcing that counteracts positive direct forcing. However, models that estimate the cloud effects of BC with negligible OC - rather than BC emitted along with large quantities of OC - have found very small negative forcing or even positive forcing.^{13, 43}

The addition of a short-lived climate forcer to the atmosphere causes a rapid change in the energy flow to the Earth system. This energy addition is known as the forcing by a particular constituent. This energy flow is not kept in the Earth system, but has to be re-radiated to achieve equilibrium, resulting in a higher Earth temperature after adjustment. Bond et al.⁶ used the notion of the Specific Forcing Pulse (SFP) to describe this energy addition:

$$P_j = \sum_i SFP_{i,j} \cdot Em_i$$

where Em_i is the emission rate in region i (g/sec) and $SFP_{i,j}$ is the Specific Forcing Pulse (GJ/g) that represents forcing at location j caused by emissions in region i .

Figure 4 summarizes energy flows into each of four latitude bands due to emissions from kerosene lamps (Latitudinal values of SFP for each region are given in S3.3.2). The total 10 TW energy flow resulting from absorption of solar radiation by BC and other aerosols emitted from kerosene lamps is three orders of magnitude greater than the heat released by burning the fuel (6.6 GW) and about six orders of magnitude greater than the energy that produces useful light.

Caution is warranted in comparing the effects of short-lived climate forcing agents with those of long-lived greenhouse gases. Nevertheless, dividing the energy added to the Earth system by short-lived climate forcers by the integrated forcing of CO₂ yields an approximate estimate of equivalence.⁶ The direct forcing (without snow) by one year's BC and OC emissions from kerosene lamps is equivalent to the forcing that 230 Tg (Mtonne) of CO₂ exerts over 100 years after emission. This emission level is equivalent to about four percent of the United States' CO₂ emissions in 2008.

Implications for mitigation of short-lived climate forcers

Reductions in emissions of BC and other short-lived climate forcers have been proposed to play an important role in limiting temperature increases over the next 50 years.¹⁰ The previous lack of information about kerosene lighting emissions, however, means that this BC source has been excluded from such discussions. Replacements for kerosene lighting do exist. Providing reliable and affordable electricity to households is an ideal alternative, but other options are available while the required infrastructure is built. For example, low cost light-emitting diode lamps are now designed for developing-country markets, charged by photovoltaic cells or electricity during non-peak hours. Even kerosene-fueled hurricane lamps or pressurized mantle lamps may decrease emissions.

From a climate standpoint, ideal targets for BC mitigation co-emit little OC, so that there is confidence that reduction of PM emissions reduces climate warming. For economic effectiveness, alternatives capable of eliminating significant emissions at low cost are needed. For equity considerations, end-users should obtain significant benefits from the replacement, in efficiency, quality of life, and health. Table 2 provides a basic comparison of the contributions of major BC sources, as well as current mitigation opportunities. Replacement of simple wick lamps scores highly in terms of low co-emissions and economy.^{44, 45} Growing evidence confirms that benefits to household air quality and human exposure are also high.¹⁸ Unlike many other major sources of BC, many kerosene lamps are used indoors and in close proximity to users, which means that more of their emissions are inhaled, increasing the risk of several adverse health outcomes, including respiratory diseases such as tuberculosis, currently a leading cause of early mortality in developing countries.^{46, 47} Considering these characteristics, replacing simple kerosene lamps should be considered one of the most attractive first steps to reduce warming by short-lived climate forcers.

The national lighting program in India (labl.teriin.org) and efforts in several African countries (www.lightingafrica.org) are currently developing and deploying low-cost LED lamps in populations that currently rely on kerosene and other fuel-based lighting sources due to limited or non-existent access to electricity. When these programs are successful, developing countries will have made a substantial contribution to reducing global warming and improving human welfare.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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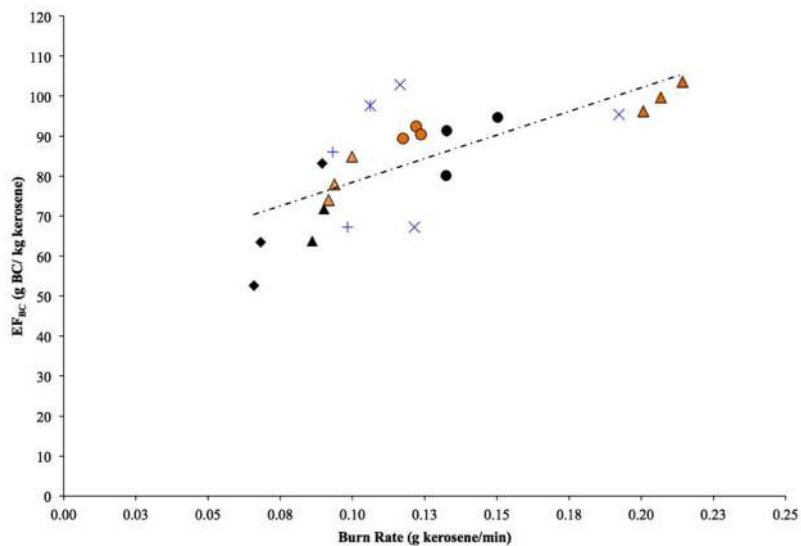


Figure 1.

EF_{BC} versus kerosene burn rate from laboratory (black and orange) and field (blue) emission measurements. Marker shapes represent individual simple wick devices. Black markers represent simple wick lamps operated at baseline conditions. Orange markers represent altered lamp settings: high wick (triangles on far right of figure), rope wick (triangles on left), and Ugandan kerosene (circles). The dotted line is the line of best fit ($R^2 = 0.52$).

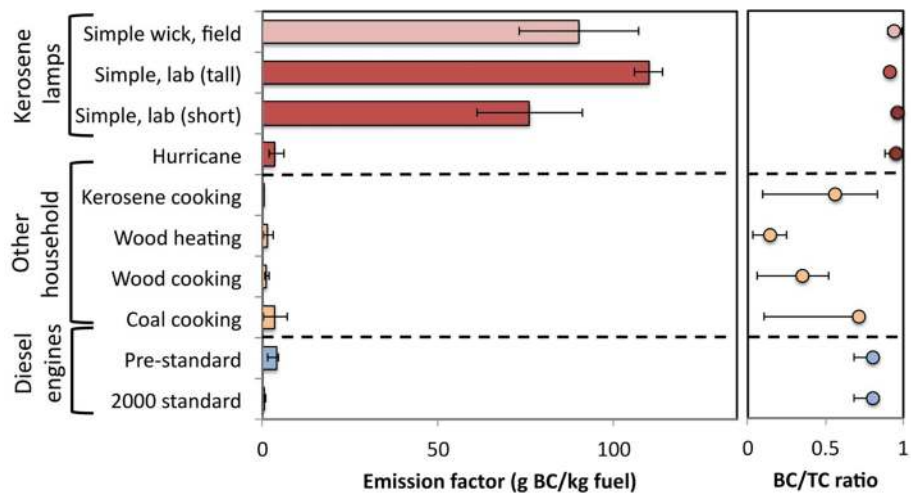


Figure 2. Comparison of emission factors for black carbon (EF_{BC}) and black carbon fraction of total aerosol carbon (BC/TC) for kerosene lamps, other household uses, and diesel engines. Error bars represent 90% uncertainty bounds.

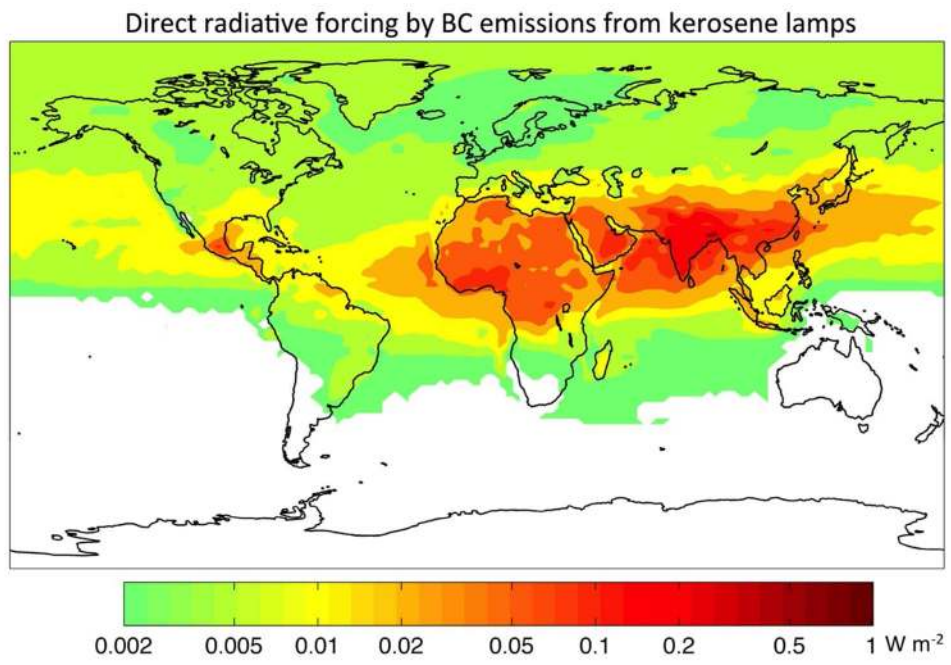


Figure 3.
Direct BC radiative forcing from residential kerosene lighting (W/m²)

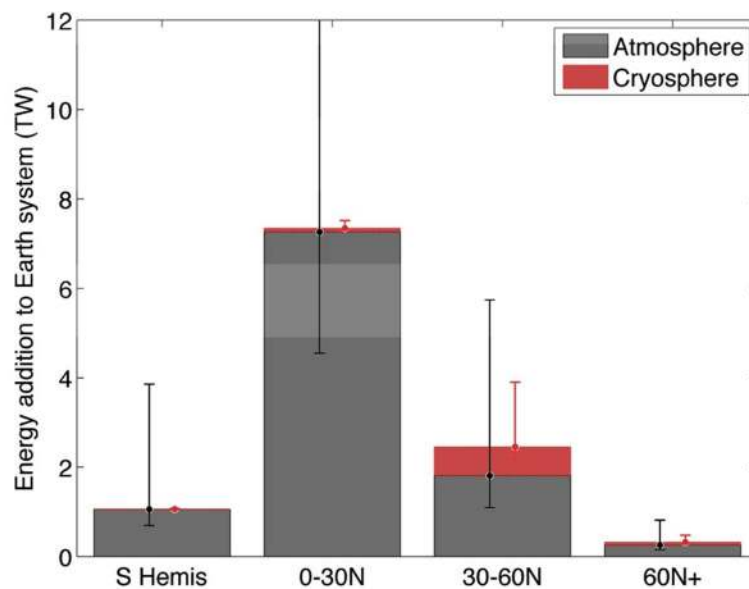


Figure 4. Contribution to energy flows into the Earth system by black carbon emissions from household kerosene lamps. The distribution of aerosol forcing depends on the region of emission, so regional averages are used to convey the location of forcing impact. Energy values can be summed and divided by the area of the Earth to obtain the traditional measure of forcing given in W/m^2 . Negative forcing by organic carbon is not shown, but offsets less than 0.5% of the positive forcing by BC.

Table 1

Laboratory and field-based BC, OC, PM_{2.5}, CO emission factors, and particle optical characteristics for simple wick kerosene lamps

Sample		Emission Factors				Optical Properties [‡]			Burn Rate	
N	n	g/kg-fuel	g/kg-fuel	g/kg-fuel	PM _{2.5} [‡]	CO	MAC	MSC	SSA	g-fuel/hour
		BC	OC							
Lab										
Low Wick (Baseline)	3	9	76 (15)	5 (4)	81 (15)	16 (1)	7.0 (0.6)	2.5 (0.5)	0.27 (0.01)	6 (2)*
High Wick	1	3	100 (4)	3 (3)	95 (12)	21 (1)	7.1 (0.1)	3.1 (0.4)	0.29 (<0.01)	12 (0.4)
Rope Wick	1	3	79 (6)	3 (4)	70 (8)	16 (1)	7.0 (0.2)	3.0 (0.5)	0.27 (<0.01)	6 (0.3)
Uganda Kerosene	1	3	91 (2)	2 (1)	124 (7)	16 (1)	7.1 (0.2)	2.1 (0.1)	0.29 (<0.01)	7 (0.2)
Field										
Typical	3	7	90 (17)	0.4 (0.8)	93 (23)	11(2)	11.1 (1.6)	1.9 (0.6)	0.17 (0.01)	7 (2)*

Numbers in parentheses represent one standard deviation

N= devices tested, n = measurement events,

Baseline settings are low wick (1–1.5mm), 1-K USA kerosene, and cloth (cotton) wick

* n = 8 (Lab), n = 6 (Field)

[‡]Field results represent total suspended particles (TSP)

[‡]MAC – mass absorption cross section (530 nm), MSC- mass scattering cross section, SSA – single scattering albedo, MSC and SSA were calculated at 530nm for laboratory tests and 660nm for field tests.

Table 2

Characteristics of major BC sources and associated mitigation opportunities

Source category	Fraction of global BC emissions ¹	Annual BC emissions (Gg) ¹	Major co-emissions ²	Potential Interventions ³
Kerosene lamps	3%	270 (110, 590)	None	LED or more efficient fuel- based lamps (e.g. pressure, hurricane)
Diesel engines	17%	1320 (530, 2400)	NO _x (-)	Particle traps, retrofit, standard introduction
Residential solid fuel	24%	1880 (480, 5300)	OM (-)	Efficient stoves, improved combustion, fuel switching
Industrial coal	12%	740 (160, 2800)	SO ₂ (-)	Process modernization
Open biomass burning	40%	2750 (980, 12000)	OM(-)	Suppression, controlled burning with capture

¹Values in parentheses represents 90% uncertainty bounds

²Symbols in parentheses represents the direction of forcing (+/-) for co-emissions

³Only the possibilities with greatest mitigation potential are listed here

BC annual emissions and uncertainty bounds obtained from procedures in Bond et al. (2004), with updates as described in Lamarque et al. (2011).⁴⁸ The exception is kerosene lamps, which are based on results from this study