Supporting Information

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

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S1. Materials and Methods: Emission Testing

S1.1 Photographs of Lamps Tested Under Laboratory Conditions

Fig. S1a. Simple wick lamps

Fig. S1b. Hurricane wick lamp

S1.2 Emission Sampling System and Procedures

S1.2.1 Laboratory Measurement System

Figure S2 provides an overview of the sampling system used to measure emissions from lamps. A multipoint dilution sampling probe[1] was used to extract the lamp emissions at a flow rate of 5 LPM. The probe sets include a 1.5 ft probe, four 6 in and four 2 in probes with decreasing hole size closer to the center. Dry, particle-free air was used as the diluent at a ratio of 2-3:1. After, the dilution CO_2 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) analyzers, respectively. Gas analyzers were calibrated with standard span gas (S.J. Smith Co., Decatur, IL) under sampling conditions. A second dilution step with dry particle-free air at a dilution ratio of 3:1 was required to prevent the overloading of the scattering coefficient signal of the integrating nephelometer (M903, Radiance Research, Shoreline, WA) operating at a wavelength of 530 nm. This instrument was calibrated before and after the experiment with dry particle free air (ZERO) and Coleman-grade CO_2 (SPAN). Parallel to the nephelometer a particle soot absorption photometer (PSAP, Radiance Research, Shoreline, WA) was operated at a flow rate of 0.2 LPM to measure the absorption coefficient at three wavelengths of 467, 530 and 660 nm. Flow rates through filter holders varied from 0.2-0.6 L/min. Laboratory tests were conducted at the University if Illinois at Urbana-Champaign.

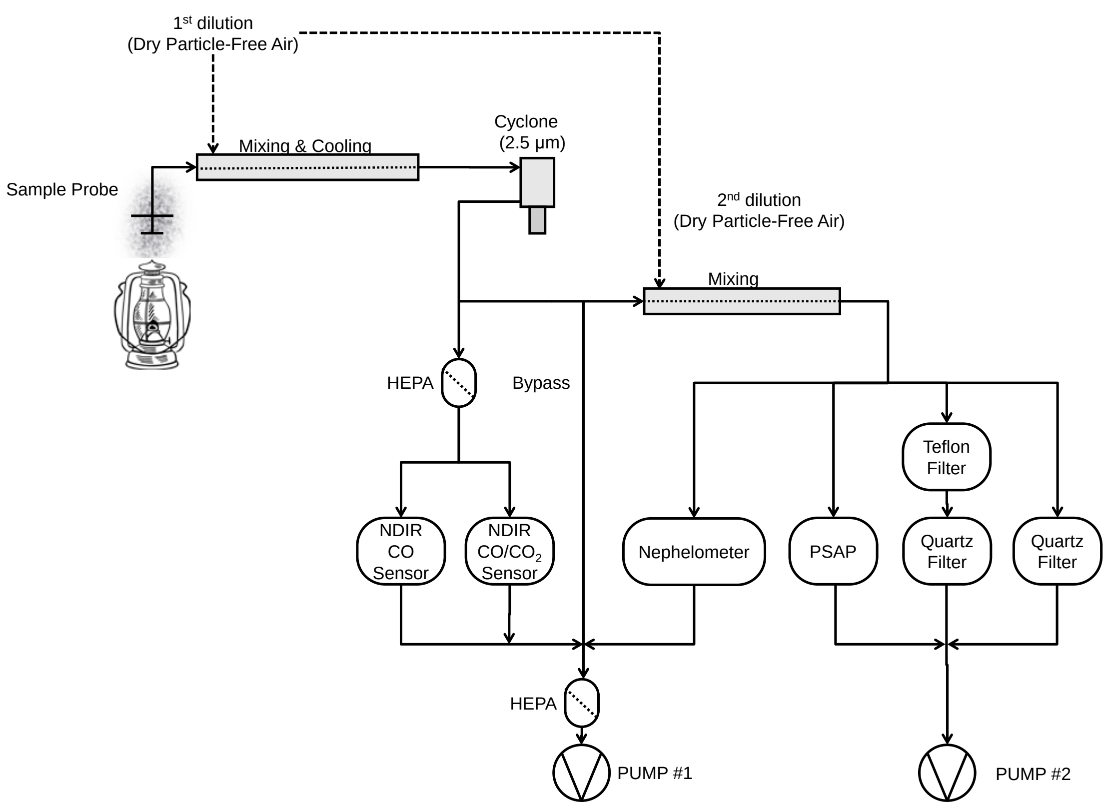

Fig. S2. Laboratory emission sampling system schematic

S1.2.2 Field Measurement System

Figure S3 is a schematic of the sampling system used to measure emissions from lamps under field conditions. Samples were taken on an outdoor patio with lamps placed on the ground. A multipoint sampling probe was used to extract emissions at a flow rate of ~2 L/min. Real-time data were recorded every second.

CO and CO_2 sensors were calibrated with zero and span gases. The raw scattering signal from the PM sensor was calibrated with an integrating nephelometer (3563, TSI Inc., Shoreview, MN) to provide a particle scattering coefficient at red wavelength (660 nm). All calibrations were performed in the laboratory before the field campaign. Ambient temperature, pressure and relative humidity were recorded for each test, and were used to correct measured concentrations to standard conditions.

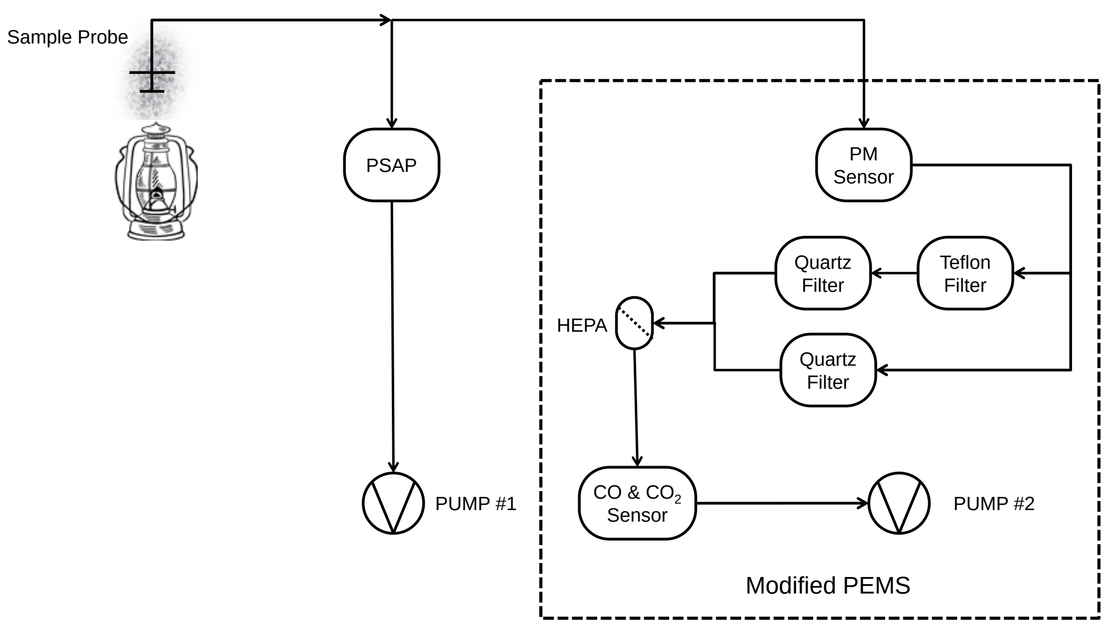

Fig. S3. Field emission sampling system schematic

S1.3 Analytical Procedures

S1.3.1 Instrument Corrections: PSAP, Nephelometer

We performed further corrections of the absorption coefficient (b_{ap}) due to flow rate, filter size (spot size), particle scattering effect and instrument precision as suggested by Bond et al.[2] The truncation correction of the nephelometer was set to be 4% according to

Anderson and Ogren.[3] All the measured results were corrected to standard conditions (1 atm and 20 °C).

S1.3.2 Thermal Optical Transmittance Method: OC/EC Analysis

In the NIOSH TOT method,[4] OC and carbonate carbon in the sample are first volatized in a pure helium atmosphere as the temperature is stepped to 890°C. The temperature is then reduced and oxygen-helium carrier gas is introduced. The temperature is then raised to 860°C in steps, when elemental carbon (here used as equivalent to black carbon) is evolved. Temperature profiles are shown in Fig. S4 and Fig. S5. All carbon evolving from the filter is reduced to methane, and measured with a flame ionization detector. Figure S5 shows a typical thermogram to which has been added the differentiation of the laser transmission curve, divided by an assumed absorption cross-section.[5] That curve approximately represents the formation (negative values) or loss (positive values) of charred OC. Formation and loss of char at all points in the analysis are small relative to BC.

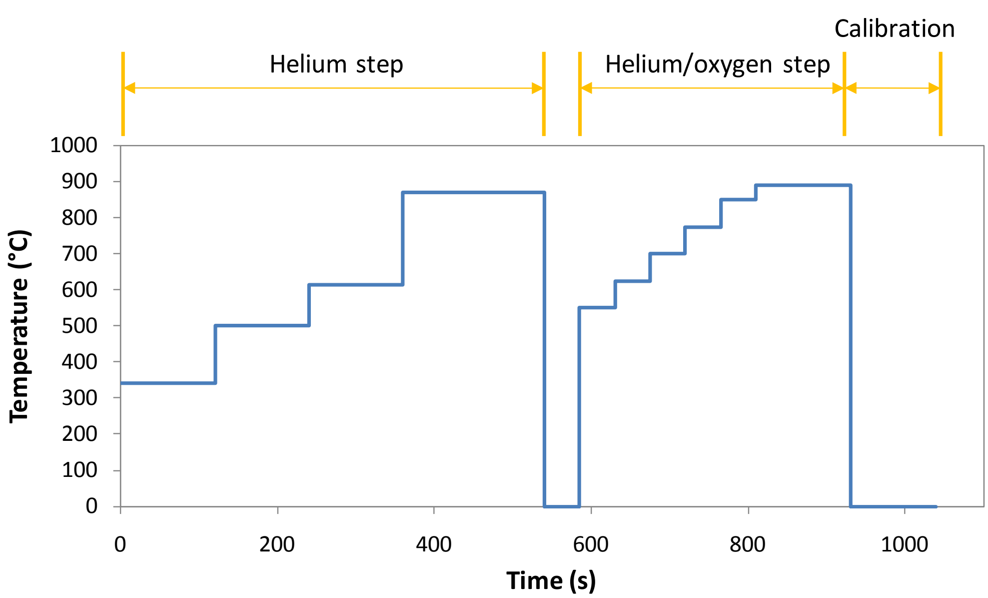

Fig. S4. Temperature profile of NIOSH TOT method on the Sunset OC/EC analyzer

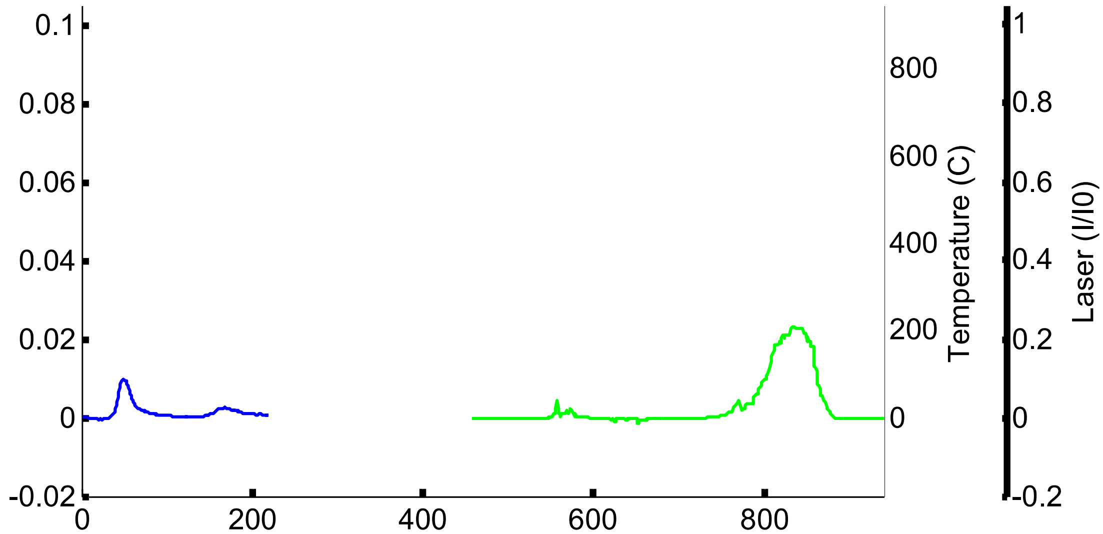

Fig. S5. Thermogram of a typical sampled filter from laboratory tests of kerosene lamps

S1.4 Data Processing

S1.4.1 Calculation of Emission Factors

Before calculating emission properties, real-time measured concentrations (CO, CO_2, particle absorption and scattering coefficient) were converted to standard conditions (1 atm and 20 °C). Background CO and CO_2 concentrations and scattering, absorption, were subtracted.

Emission factors for PM, OC and EC (EF_{PM}, EF_{OC} or EF_{EC}) are expressed in units of g PM (OC or EC)/kg kerosene burnt and determined with the following equation with EF_{PM} as an example.

$$EF_{PM}(g/kg\ kerosene) = \frac{C_{PM}(g/m^3\ air)}{Fuel\ (kg/m^3\ air)} = \frac{M_{PM}/(Q_{PM} \cdot T)(g/m^3 air)}{Fuel\ (kg/m^3\ air)}$$

Where, M_{PM} is the mass of PM on the filter as determined by the methods described previously, Q_{PM} is the flow rate through the filter, and T is the length of the sampling period. Emission factors of CO and CO_2 were determined in a similar way but used the test averaged CO or CO_2 concentration instead of C_{PM}. *Fuel* has the unit of kg kerosene consumed per cubic meter of air sampled (kg/m^3) and determined using the "carbon balance method", which uses the total gaseous and particulate carbon ($CO + CO_2 + EC + OC$) emissions as a proxy for total fuel burnt. Carbon content of kerosene is approximately 85%.[6] *Fuel* is calculated with the following equation:

$$Fuel\ (kg/m^3air) = gas_{carb}\frac{m^3}{m^3air}\cdot\left(0.499\frac{kgC}{m^3gas_{carb}}\right)\Big/0.85\frac{kgC}{kg\ kerosene}$$

S1.4.2 Calculation of SSA, MSC and MAC$_{BC}$

Data obtained from real-time measurements, sometimes combined with filter results, can be used to calculate test-averaged properties such as single scattering albedo (SSA), mass scattering cross section (MSC) and mass absorption cross section (MAC_{BC}).

$$SSA_{lab} = \frac{b_{sp,avg}}{b_{sp,avg} + b_{ap530,avg}}$$

$$SSA_{field} = \frac{b_{sp,avg}}{b_{sp,avg} + b_{ap660,avg}}$$

$$MSC = \frac{b_{sp,avg}}{C_{PM}}$$

$$MAC_{BC} = \frac{b_{ap530,avg}}{C_{BC}}$$

Where $b_{sp,avg}$ is the test-averaged scattering coefficient (530nm for the laboratory tests and 660nm for field tests, Mm^{-1}), $b_{ap530,avg}$ is the : test-averaged absorption coefficient (530nm, Mm^{-1}), $b_{ap660,avg}$ is the test-averaged absorption coefficient (660nm, Mm^{-1}), C_{PM} is the filter-integrated PM concentration for a test (g/m^3), and C_{BC} is the filter-integrated BC concentration for a test (g/m^3).

S1.5 Fuel Analysis

Testing of kerosene fuel composition was performed on kerosene purchased and produced in the USA and Uganda by Intertek Labs (Chicago, Illinois, USA). Tested samples were taken from the same fuel stocks burned in lamps tested in the lab. Ugandan kerosene had approximately twice the sulfur content and six times the particulate contamination (Table S1). Aromatic content was also slightly higher as were some trace elements, including calcium, silicon, sodium, and zinc.

Table S1. Kerosene fuel composition

ASTM Method		Uganda	USA	Units
ASTM D4294	**Sulfur Content**	0.082	0.015	Wt %
ASTM D1319	**Aromatics**	18.8	16.1	Vol %
ASTM D482	**Ash**	<0.001	0.002	Wt %
ASTM D7111	**Trace Elements**			
	Calcium	0.12	< 0.10	mg/kg
	Silicon	1.40	0.1	mg/kg
	Sodium	0.50	0.41	mg/kg
	Zinc	2.00	< 0.10	mg/kg
ASTM D5452	**Particulate Contamination**	6.80	1.11	mg/L

S2. Materials and Methods: Kerosene Consumption and BC Emissions

S2.1 Kerosene Consumption

For each country-level bottom-up estimate of kerosene consumption for lighting, $KERO_{est}$, five factors were multiplied:

$$KERO_{est} = N_{house} \times f_{kero} \times N_{lamp} \times t \times BR \times 365$$

1. N_{house} - Number of households in the country
2. f_{kero} - Fraction of households reported or estimated to rely on kerosene for lighting.
3. N_{lamp} - Number of lamps in each household
4. t - Duration of time the lamp is used per day
5. *BR* – Fuel burn rate of each device

The product of the five factors was multiplied by 365 days to arrive at an annual kerosene consumption rate. These bottom-up values were then divided by the country specific residential kerosene consumption reported by IEA, as described in the Methods of the text, to arrive at an estimate of the fraction of residential kerosene used for lighting (f_{light}).

Censuses or national household surveys provided the number of households (Factor 1). Factors 2-4 were taken from previous publications, nationally representative surveys performed by statistics bureaus, international survey institutions (e.g. DHS), and publicly available lighting market research. In some cases, the fraction of households relying on kerosene for lighting (Factor 2) was estimated using data on household access to electricity (S2.1.1), which is more commonly measured as part of household surveys. Table S2 shows the list of countries used to derive regional estimates. In total, this list comprises the majority of the population in regions assumed to have non-zero lighting consumption: Central America (78%), South America (72%), African regions (73%), South Asia (72%), and Southeast Asia (71%). The kerosene lighting fraction was assumed to be zero for several regions considered most developed, including the USA, Canada, Japan, and the former USSR. The same was assumed for East Asia, with the exception of China where a previous analysis of rural energy consumption found that residential oil, including kerosene, is used primarily for lighting in areas without access to grid-based electricity.[7] One survey containing lighting information was found for the Middle East so we instead estimated the fraction of kerosene lighting for the region using the data on household access to electricity in 2009, reported by IEA in 2011.[8]

The number of lamps (Factor 3) was estimated at 2 per house and a triangular distribution bounded at (1, 3), with the exception of Africa where several detailed surveys were available (S2.1.3). Use was estimated at 3 hours per day with a triangular distribution bounded at (2, 4). The selection of a fuel burn rate (Factor 5) was guided by measurements reported in this study, with a central value of 0.12 g/min and 90% uncertainty bounds (0.05, 0.20) and a normal distribution. We apply the burn rate from simple wick lamps to all kerosene lighting devices, including hurricane lamps, so our estimate of kerosene consumption for lighting is likely conservative as simple wick lamps have the lowest burn rate of the lighting devices commonly used in households.[9] However, in estimating the fraction of kerosene burned in simple wick lamps, we also do not consider differences in burn rates. Thus, our final estimate of consumption in simple wick lamps is unbiased by the neglect of higher consumption rates in other lighting devices represented primarily by hurricane lamps.

Table S2. Percent of households using kerosene for lighting by country and region

Region	Country	Year	% Households Using Kerosene as Primary Lighting	Source
Eastern Africa	Ethiopia	2008	74%	Lighting Africa [10]
Eastern Africa	Kenya	2008	87%	Lighting Africa [11]
Eastern Africa	Madagascar*	2008	73%	DHS [12]
Eastern Africa	Rwanda	2002	68%	IPUMS [13]
Eastern Africa	Sudan	2008	40%	Ismail and Khlafala (2009) [14]
Eastern Africa	Uganda	2009	80%	Uganda Bureau of Statistics [15]
Eastern Africa	Zambia	2008	13%	Lighting Africa [16]
Northern Africa	Egypt*	2008	36%	DHS [12]
Northern Africa	Morocco*	2008	20%	DHS [12]
Southern Africa	Angola*	2007	55%	DHS [12]
Southern Africa	South Africa	2010	3%	Statistics South Africa [17]
Southern Africa	Swaziland*	2009	50%	CSO Swaziland [18]
Southern Africa	Tanzania	2008	67%	Lighting Africa [19]
Western Africa	Cameroon*	2004	47%	DHS [12]
Western Africa	Congo*	2008	75%	DHS [12]
Western Africa	Ghana	2007	66%	Lighting Africa [20]
Western Africa	Nigeria	2006	75%	NBS Nigeria [21]
Western Africa	Senegal	2002	19%	IPUMS [13]
Western Africa	Sierra Leone	2003	79%	SLIHS [22]
Central America	El Salvador	2007	6%	DIGESTYC [23]
Central America	Guatemala	2000	21%	IPUMS [13]
Central America	Honduras	2010	9%	INE Honduras [24]
Central America	Nicaragua	2005	21%	INIDE Nicaragua [25]
Central America	Panama	2010	8%	INE Panama [26]
Middle East	Jordan	2004	1%	IPUMS [13]
South America	Bolivia*	2008	18%	DHS [12]
South America	Brazil*	2009	2%	ECLAC [27]
South America	Colombia*	2005	3%	DANE [28]
South America	Jamaica	2001	9%	IPUMS [13]
South America	Peru*	2010	11%	INEI Peru [29]
South Asia	Bangladesh	2004	56%	BIDS/ESMAP [30]
South Asia	India	2007	34%	NSSO [31, 32]
South Asia	Nepal	2001	53%	IPUMS [13]
South East Asia	Cambodia	2008	38%	IPUMS [13]
South East Asia	Indonesia	2007	5%	Statistik Indonesia [33]
South East Asia	Philippines	2000	27%	IPUMS [13]
South East Asia	Vietnam	2009	4%	IPUMS [13]

* Estimated from data on household access to electricity (S2.1.1), $f_{kero} = 0.87 * f_{no\text{-}electricity} + 0.01$

S2.1.1 Estimating f_{kero} From Household Electricity Access

The percent of households using kerosene for lighting is not collected as part of all household surveys or censuses and was estimated for several countries using the fraction of houses without electricity. Figure S6 shows a regression of the percent of households reporting kerosene as a primary lighting fuel (f_{kero}) and the percent of households without access to electricity ($f_{no\text{-}elec}$) for 24 countries for which data were available. Information on electricity access prevalence was obtained primarily from Demographic and Health Surveys[12] to minimize uncertainty due to differences in the definition of electricity access. The resulting relationship between kerosene lighting and household access to electricity is approximately linear ($f_{kero} = 0.78 * f_{no\text{-}electricity} + 0.03$) with a strong correlation ($R^2 = 0.65$) that increases substantially, while altering the linear estimates very little, when one outlier (Zambia) is excluded ($f_{kero} = 0.87 * f_{no\text{-}electricity} + 0.01$, $R^2 = 0.79$; applied in Table S2). Zambia is unique among other countries represented in the dataset, as the majority of households are without electricity (82%), however lighting is performed almost entirely with candles.[16] Overall, these results provide supporting evidence that kerosene is still the primary source of household lighting fuel in areas without access to electricity.

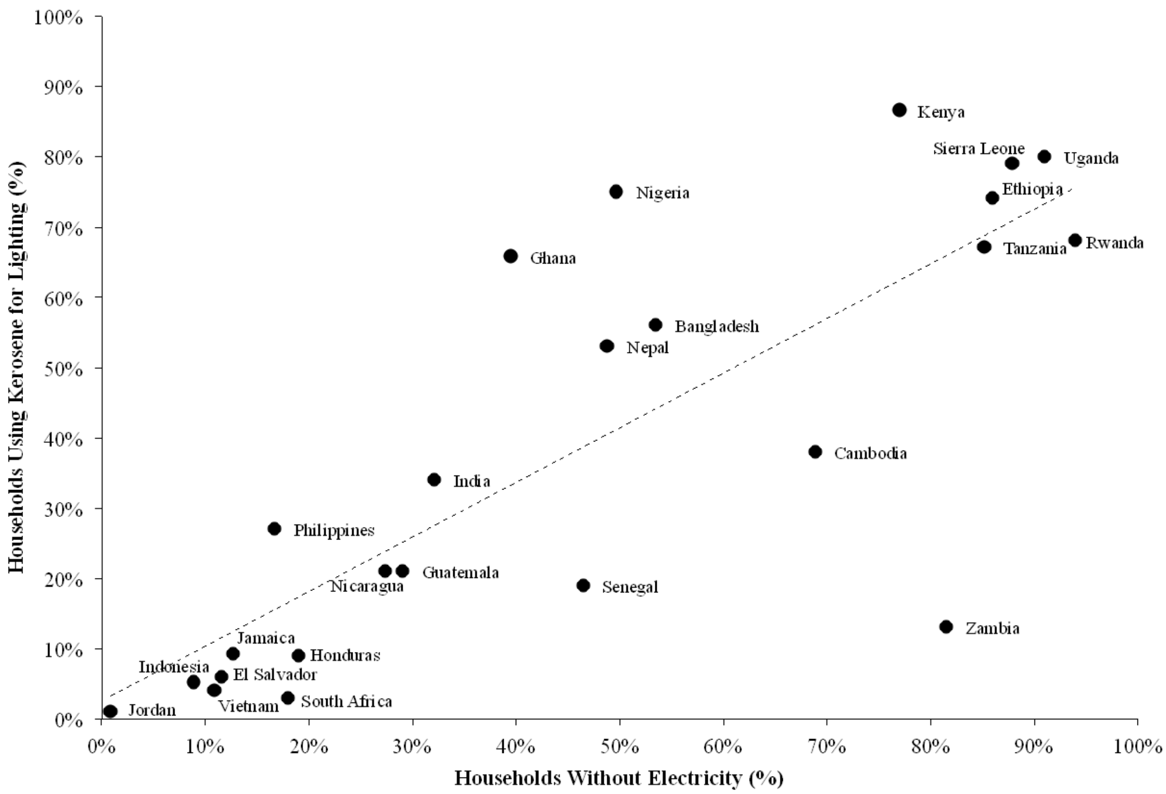

Fig. S6. Percent of households reporting kerosene as a primary source of lighting (f_{kero}) versus the percent of households without access to electricity ($f_{no\text{-}elec}$) (N = 24). The dashed line represents the best-fit line using all available data (All Data, R^2 = 0.65; without Zambia, R^2 = 0.79)

S2.1.2 Lighting in South Asia (Excluding India)

Kerosene lighting is prevalent in several South Asian countries outside of India. Household lighting information for Bangladesh (~5% South Asian population) was available from rural energy surveys collected by the Bangladesh Institute of Development Studies in 2004, and summarized recently by the Energy Management Assistance Program.[30] These surveys indicate that approximately 71% of rural households rely on kerosene devices (simple wick or hurricane) as primary lighting sources (average 1.8 simple wicks, and 0.89 hurricanes per house). Assuming the urban sector has minimal usage of kerosene for lighting and considering the urban/rural population fraction provided in the same report (~80% rural), 71% of rural households corresponds to approximately 56% of all households. Results from the 2001 census in Nepal indicate that 53% of households relied on kerosene fuel as a primary lighting source,[13] however this number may be slightly lower now, given the age of the dataset.

S2.1.3 Lighting in African Regions

National household survey data confirm anecdotal accounts of kerosene fuel being a primary and dominant source of lighting fuel in African households. In East Africa several in-depth and nationally representative evaluations of household lighting by Lighting Africa, and statistics bureaus (e.g. Uganda and Rwanda) have been performed. Several sources provide data on the number of lighting devices used per house, estimated hours of daily usage, and the prevalence of lighting devices (e.g. simple wick, hurricane, electric bulb, candles etc.). Based on these sources we use a central estimate of 1.3 simple wick lamps per household. Usage hours and burn rate were the same as those used for all other regions and described previously. We used data from the following countries in this analysis:

Region	**Countries**
Eastern Africa	Ethiopia 2007/2008 [10], Kenya 2007/2008 [11], Zambia 2007/2008 [16]
Northern Africa	Sudan 2008 [14], Egypt 2006 [a] [13], Morocco 2003 [a] [12]
Western Africa	Ghana 2007/2008 [20], Nigeria 2006 [21]
Southern Africa	South Africa 2010 [17], Tanzania 2007/2008 [19]

[a] had much greater fuel use relative to Sudan

While some information from other countries was available (Uganda, Madagascar, Sierra Leone, Rwanda, Senegal), it was not used to develop estimates of f_{light} because IEA does not report disaggregated fuel statistics for these countries.

Several surveys (e.g. Lighting Africa Market Reports, Ugandan Household Survey, Sudanese Census) provide detailed information on the primary type of lighting device used.[15] A population-weighted average for all reporting countries indicates that 62% of kerosene lighting devices used in houses are of the simple wick type, while the remainder is primarily hurricane wick lamps.

S2.2 *Kerosene Consumption in India*

Kerosene consumption for lighting was estimated for each state using survey results on state-level fractions of households using kerosene lighting and number of households (mean household size of 5 persons). Lamp usage assumptions, central estimates and uncertainty bounds, were 2 (1, 4) kerosene lamps per household, 4 (3, 5) hours of use per day,[34] and a burn rate guided by results from this study of 0.12 g/min (0.05, 0.20), and the same distributions discussed previously (S2.1). The prevalence of kerosene devices are not collected as part of National Sample Survey Organization (NSSO) surveys, however, several sources indicate that simple wicks are the dominant device used in households without access to electricity.[35, 36] As with all global estimates, these estimates do not consider the use of lighting for small-scale businesses (e.g. retail stalls, fishing).

In India, household kerosene use is typically limited to cooking and lighting (no heating). NSSO surveys also provide information on cooking fuels used in households. Based on household consumption surveys reported by NSSO, rural use of kerosene for lighting reduced from 103 to 72 households per thousand, between 2000 and 2005.[31] There was no reduction, however, in per capita rural kerosene use in the same period.[32] This implies that larger amounts of kerosene use for lighting and cooking may occur. Kerosene would replace electricity for lighting. Daily electricity outages (or load shedding), especially during the evening peak-load period, occur for 2.5-4 hrs and 11-12 hrs in urban and rural consumer segments, respectively.[37] Assuming a central frequency at which kerosene substitutes for electric lighting of 25% (rural) and 10% (urban), adds to the fraction of households using kerosene lighting. Kerosene use for daily household cooking was based on an average household requirement of 11 MJ of delivered energy.[38] This can be converted to an equivalent kerosene consumption rate using the energy density of kerosene (42.6 MJ/kg kerosene) and the average efficiency of the kerosene cooking stove.[38] The use of kerosene as a secondary cooking fuel is common, but secondary uses are not measured as part of NSSO or other assessments and therefore not included in the fraction of households reported as cooking with kerosene. Based on local correspondence and best approximations, we assume that kerosene replaces or substitutes wood use 25% and 10% of the time in urban and rural sectors, respectively.

S2.3 Outdoor Escape Fraction ($f_{outdoor}$)

Calculation of emissions (*EM* in Equation 1 of text) includes the fraction of the emissions that escapes outdoors ($f_{outdoor}$). We found no estimates of indoor to outdoor escape fractions in the literature, but several studies have sought to characterize the penetration of outdoor particles to indoors. Emissions can be either deposited indoors, or they may be carried in indoor air transported to outdoors. During the latter journey, the emissions may deposit within the crack that leads to outdoors. However, Liu and Nazaroff[39] found a near-unity penetration rate for particles of sizes similar to those emitted from combustion; that is, crack deposition is negligible. We therefore ignore this loss source. Indoor deposition rates reported in outdoor-to-indoor modeling are 0.12 h^{-1} with uncertainty bounds of 0.09 to 0.33 h^{-1} for residential buildings.[40] Combined with estimates of air-change rates for buildings without insulation (1 h^{-1} with uncertainty bounds of 0.5-3 h^{-1}), a mass balance gives an outdoor escape fraction of 0.89. For modeling purposes we apply a triangular distribution bounded at 0.78, 1.

S3. Additional Results

S3.1 Real-Time Pollutant Concentrations

Real-time concentrations over one test are shown here to demonstrate the relative stability of kerosene lamp emissions during burning, in contrast with the highly fluctuating nature of cookstove emissions.

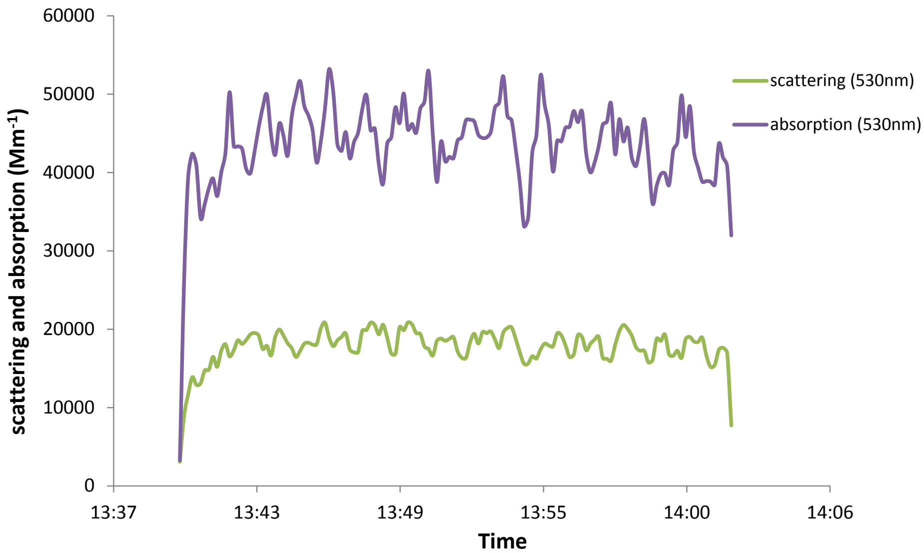

Fig. S7a. Real-time concentrations for particle optical properties over a single test (scattering and absorption). Data are averaged every ten seconds.

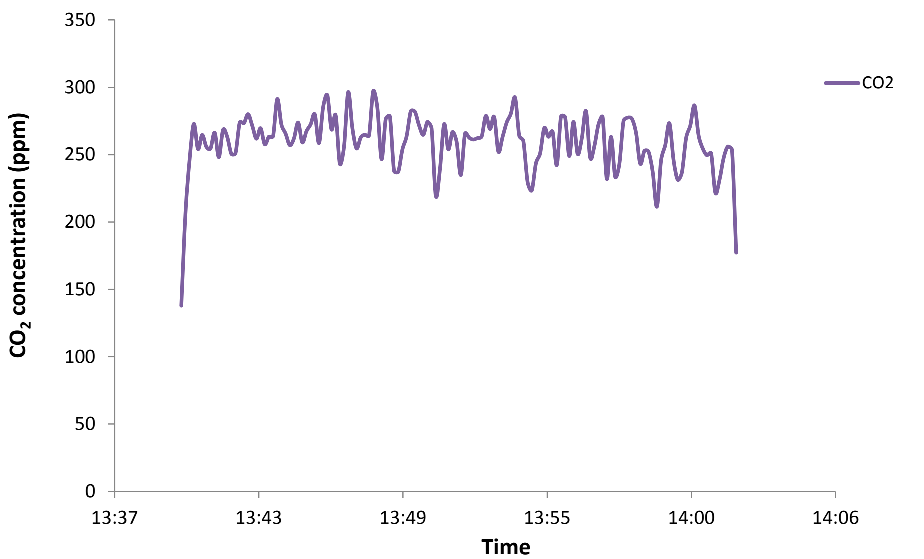

Fig. S7b. Real-time concentrations of CO_2 over a single test. Data are averaged every ten seconds.

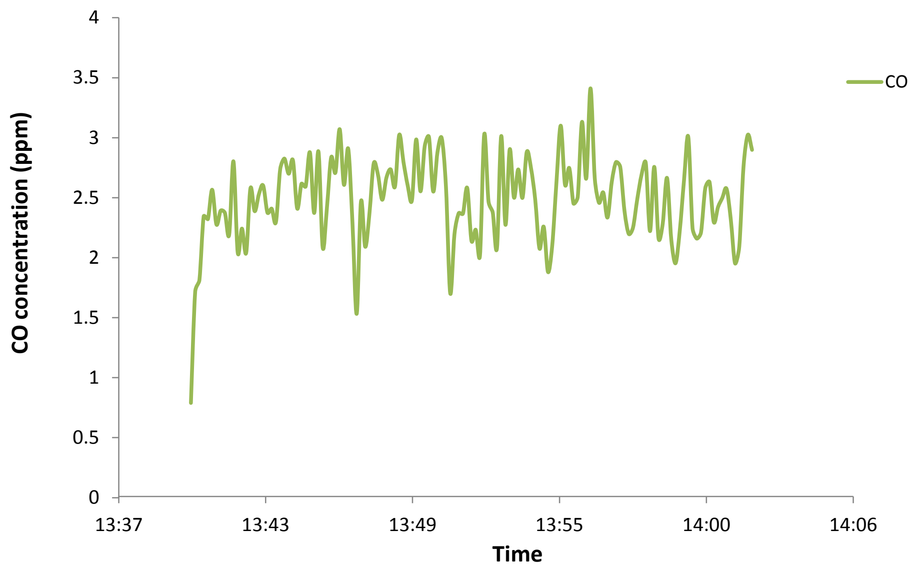

Fig. S7c. Real-time concentrations of CO over a single test. Data are averaged every ten seconds.

S3.2 Emission Factors and Aerosol Characteristics

Table S3. Lab and field-based emission factors and burn rates for simple wick and hurricane lamps

		Sample		Emission Factors					Burn Rate
				g/ kg fuel					*g fuel/hour*
		Device ID	n	**BC**	**OC**	**$PM_{2.5}$**†	**CO**	**CO_2**	
Lab	Low Wick	**Avg.**	**9**	**76 (15)**	**5 (4)**	**81 (15)**	**16 (1)**	**2800 (60)**	**6 (2)****
Simple Wick		1	3	66 (16)	6 (2)	71 (7)	16 (1)	2820 (60)	5 (1)
		2	3	89 (8)	4 (0.1)	87 (18)	18 (1)	2750 (30)	8 (0.6)
		3	3	72 (9)	4 (6)	85 (14)	16 (1)	2810 (50)	5 (0.2)*
	High Wick	3	3	110 (4)	3 (3)	95 (12)	21 (1)	2700 (5)	12 (0.4)
	Rope Wick	3	3	79 (6)	3 (4)	70 (8)	16 (1)	2790 (10)	6 (0.3)
	Ugandan Kerosene	2	3	91 (2)	2 (1)	124 (7)	16 (1)	2750 (8)	7 (0.2)
Field	Typical	**Avg.**	**7**	**90 (17)**	**0.4 (0.8)**	**93 (23)**	**11(2)**	**2770 (70)**	**7 (2)****
Simple Wick		4	4	94 (19)	1 (1)	100 (19)	12 (2)	2750 (73)	9 (3)*
		5	1	89 (-)	< 1 (-)	4 (-)	11 (-)	2770 (-)	6 (-)
		6	2	76 (-)	4 (-)	79 (-)	8 (-)	2800 (-)	6 (-)
Lab *Hurricane*	Med/High Wick	7	3	9 (1)	0.5 (0.3)	13 (3)	3 (<1)	3080 (5)	26 (1)

Numbers in parentheses represent one standard deviation

n = measurement events, * n = 2 (lab); n = 3 (field), ** n = 8 (lab); n = 6 (field)

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

† Field results represent total suspended particles (TSP)

Table S4. Lab and field-based emission ratios and aerosol optical properties for simple wick and hurricane lamps

		Sample		Ratios				Optical Properties‡		
								m^2/g	m^2/g	
		Device ID	n	**BC/ $PM_{2.5}$†**	**BC/TC**	**OC/TC**	**OC/BC**	**MAC_{BC}**	**MSC_{PM}**	**SSA**
Lab *Simple Wick*	Low Wick	**Avg.**	**9**	**0.95 (0.23)**	**0.95 (0.05)**	**0.06 (0.05)**	**0.06 (0.05)**	**7.0 (0.6)**	**2.5 (0.5)**	**0.27 (0.01)**
		1	3	0.94 (0.18)	0.91 (0.01)	0.09 (0.03)	0.09 (0.02)	7.0 (0.8)	2.2 (0.4)	0.26 (0.01)
		2	3	1.06 (0.31)	0.96 (<0.01)	0.04 (0.01)	0.04 (<0.01)	7.2 (0.7)	2.9 (0.6)	0.28 (<0.01)
		3	3	0.86 (0.08)	0.96 (0.07)	0.04 (0.07)	0.05 (0.08)	6.8 (0.2)	2.2 (0.1)	0.28 (0.01)
	High Wick	3	3	1.07 (0.15)	0.97 (0.03)	0.03 (0.03)	0.03 (0.03)	7.1 (0.1)	3.1 (0.4)	0.29 (<0.01)
	Rope Wick	3	3	1.15 (0.21)	0.97 (0.04)	0.04 (0.05)	0.03 (0.05)	7.0 (0.2)	3.0 (0.5)	0.27 (<0.01)
	Ugandan Kerosene	2	3	0.73 (0.04)	0.98 (0.01)	0.02 (0.01)	0.02 (0.01)	7.1 (0.2)	2.1 (0.1)	0.29 (<0.01)
Field *Simple Wick*	Typical	**Avg.**	**7**	**1.02 (0.3)**	**1.0 (0.01)**	**<0.01 (0.01)**	**< 0.01 (< 0.01)**	**11.1 (1.6)**	**1.9 (0.6)**	**0.17 (0.01)**
		4	4	0.9 (0.1)	1.0 (<0.01)	<0.01 (<0.01)	< 0.01 (<0.01)	10.7 (1.2)	1.8 (0.4)	0.17 (-)
		5	1	1.0 (-)	0.98 (-)	0.02 (-)	0.02 (-)	10.3 (-)	1.8 (-)	0.16 (-)
		6	2	1.4 (0)	1.0 (-)	<0.01 (-)	< 0.01 (-)	11.5 (-)	3.1 (-)	0.17 (-)
Lab *Hurricane*	Med/High Wick	7	3	0.66 (0.05)	0.95 (0.03)	0.05 (0.03)	0.06 (0.04)	6.5 (0.1)	1.1 (0.1)	0.20 (0.00)

Numbers in parentheses represent one standard deviation

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

† Field results represent total suspended particles (TSP)

‡ MAC – mass absorbance cross section (530 nm), MSC – mass scattering cross section, SSA – single scattering albedo

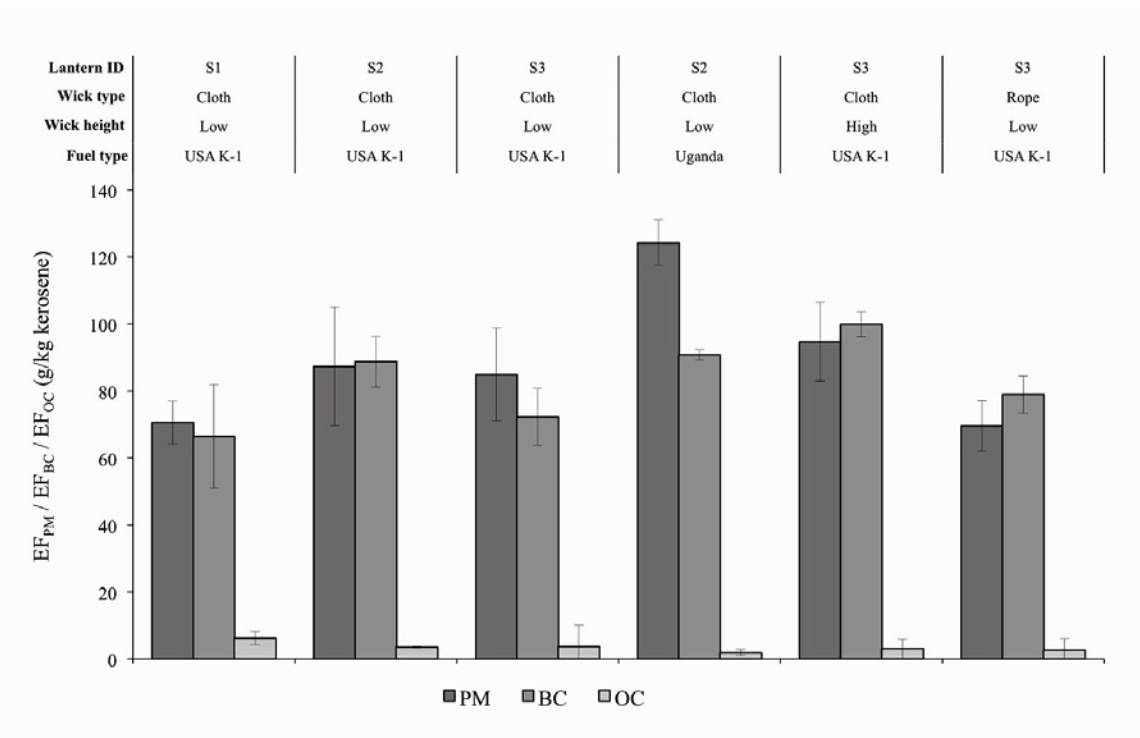

Fig. S8a. $PM_{2.5}$, BC and OC emission factors from simple wick lamps tested under lab conditions. Errors bars represent ± 1 standard deviation of repeated tests.

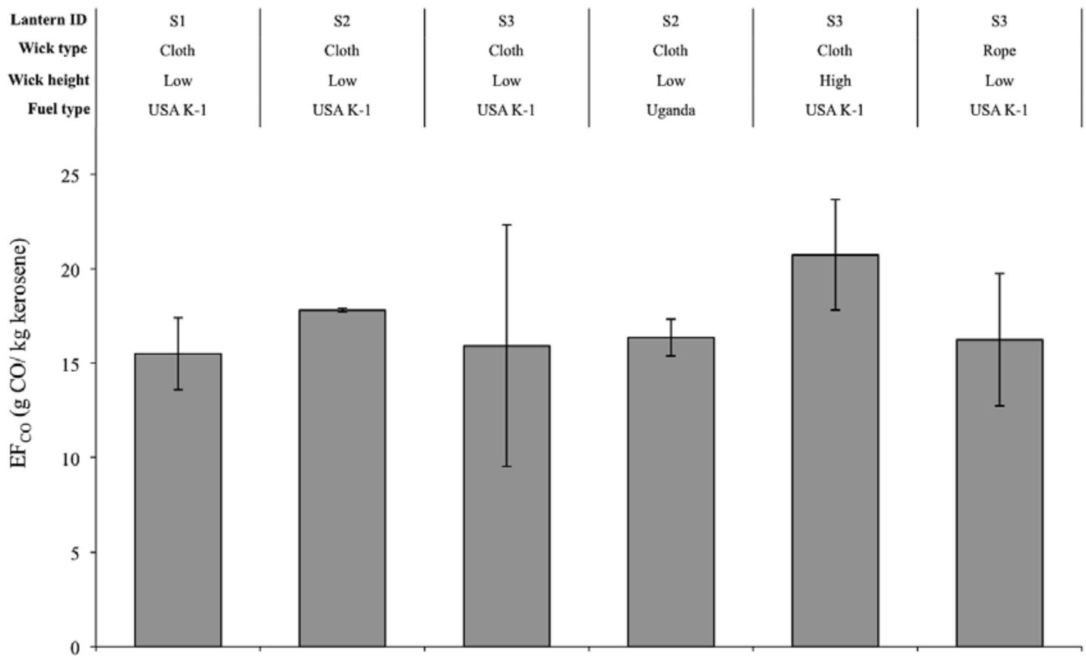

Fig. S8b. CO emission factors from simple wick lamps tested under lab conditions. Errors bars represent ± 1 standard deviation.

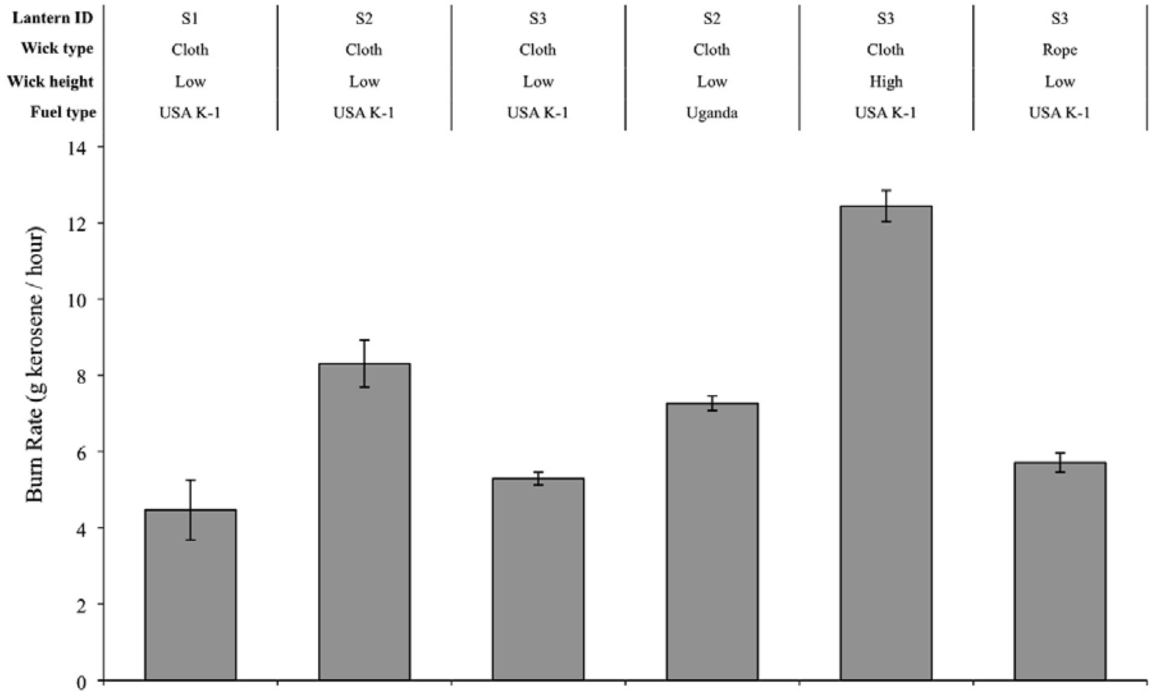

Fig. S8c. Burn rates from simple wick lamps tested under lab conditions. Error bars represent ± 1 standard deviation.

S3.3 Impact Estimates

S3.3.1 Global BC emission

Table S5 presents assumptions and BC emission for 19 regions that were based on the 17 regions used in a common macroeconomic model (Integrated Model to Assess the Global Environmental or IMAGE, RIVM, 2001). The two additional regions, China and India, were separated from East Asia and South Asia, respectively. Country groupings in these regions may be slightly different than other common aggregations such as those used by the United Nations. The figure below shows the results of a 10,000-run Monte Carol simulation. Uncertainties determined with the Monte Carlo simulation, which are used in the text, differ slightly from the simple combination of uncertainties shown in Table S5.

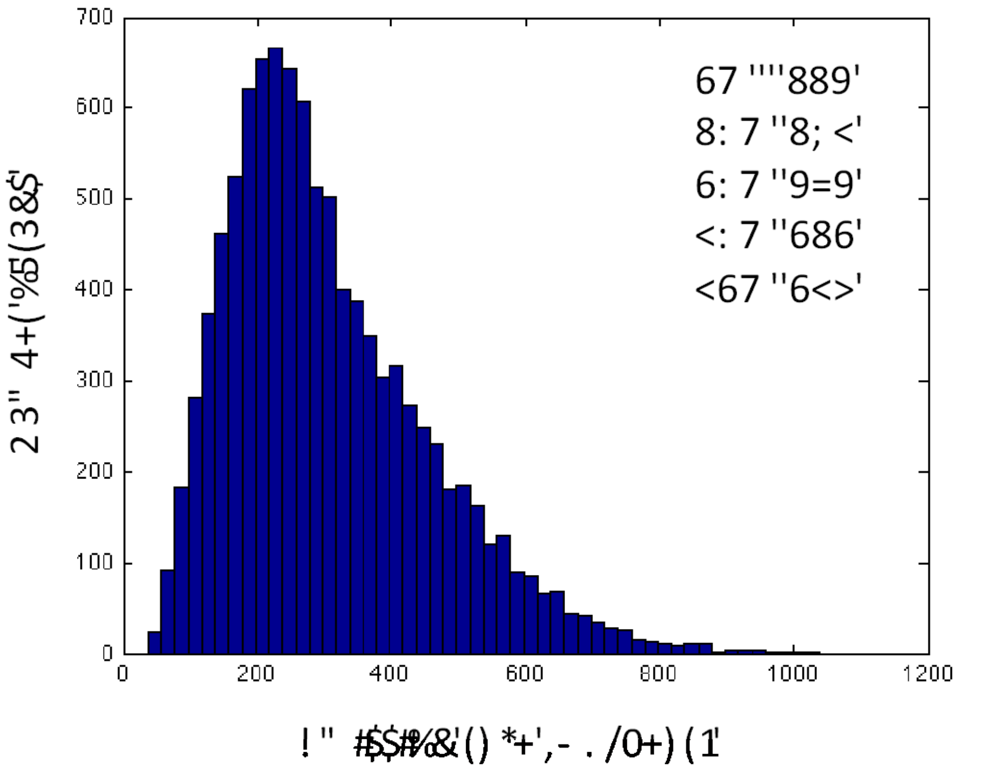

Figure S9. Frequency distribution and percentiles of the global BC emission rate based on a Monte Carlo simulation of 10,000 runs.

Table S5. Assumptions for 17 global regions. Values in parentheses for f_{light} and f_{device} are the bounds of a triangular distribution. Values in parentheses for emissions show lower and upper estimate bounds with a simple uncertainty combination; these are not the same as those obtained with the Monte Carlo analysis.

	Fraction of residential kerosene used for lighting (f_{light})	**Fraction of kerosene used by simple wick lamps (f_{device})**	**Black carbon emissions[a] (EM_{BC})**
			Gg/year
Canada	0 (0, 0)	0 (0, 0)	0 (0, 0)
USA	0 (0, 0)	0 (0, 0)	0 (0, 0)
Central America	0.277 (0.029, 0.866)	0.5 (0, 0.7)	13 (0, 41)
South America	0.256 (0.023, 0.8)	0.5 (0, 0.7)	3 (0, 10)
Northern Africa	0.615 (0.099, 1)	0.6 (0.3, 0.9)	19 (0, 35)
Western Africa	0.245 (0.039, 1)	0.6 (0.3, 0.9)	32 (0, 132)
Eastern Africa	0.526 (0.084, 1)	0.6 (0.1, 0.9)	12 (0, 25)
Southern Africa	0.01 (0.001, 0.05)	0.6 (0.3, 0.9)	0 (0, 0)
OECD Europe	0 (0, 0)	0 (0, 0)	0 (0, 0)
Eastern Europe	0 (0, 0)	0 (0, 0)	0 (0, 0)
Former USSR	0 (0, 0)	0 (0, 0)	0 (0, 0)
Middle East	0.006 (0.001, 0.02)	0.25 (0.1, 0.5)	1 (0, 4)
South Asia (excl. India)	0.521 (0.054, 1)	0.8 (0.7, 0.95)	40 (3, 79)
India	0.21 (0.05, 0.52)	0.8 (0.7, 0.95)	116 (23, 291)
East Asia (excl. China)	0 (0, 0)	0 (0, 0.4)	0 (0, 0)
China	0.8 (0.5, 1)	0.8 (0.25, 0.95)	13 (4, 18)
Southeast Asia	0.026 (0.003, 0.08)	0.8 (0.5, 0.8)	14 (0, 43)
Oceania	0 (0, 0)	1 (1, 1)	0 (0, 0)
Japan	0 (0, 0)	0 (0, 0)	0 (0, 0)
Total			**263 (30, 678)**

a - Totals, especially uncertainty bounds, are different from those reported in the main text because this is a simple combination of uncertainties, while the text reports results of Monte Carlo simulations.

S3.3.2 Radiative Forcing

Table S6a. Specific Forcing Pulse (GJ/g) quantifying forcing in four latitude bands from 17 emitting regions, for direct forcing by black carbon in the atmosphere. Uncertainties (1-σ) are in brackets.

Atmosphere	**60N+**	**30-60N**	**0-30N**	**S.Hemis.**
Canada	0.15 (0.062)	0.62 (0.263)	0.04 (0.02)	0.002 (0.001)
USA	0.09 (0.04)	0.6 (0.25)	0.14 (0.06)	0.01 (0)
Central America	0.03 (0.01)	0.21 (0.09)	0.83 (0.37)	0.1 (0.04)
South America	0.01 (0)	0.02 (0.01)	0.17 (0.07)	1.01 (0.45)
Northern Africa	0.04 (0.02)	0.4 (0.22)	0.78 (0.44)	0.03 (0.01)
Western Africa	0.01 (0.01)	0.05 (0.03)	0.88 (0.49)	0.28 (0.16)
Eastern Africa	0.01 (0)	0.03 (0.02)	0.71 (0.4)	0.4 (0.22)
Southern Africa	0 (0)	0.01 (0)	0.07 (0.04)	1.16 (0.65)
OECD Europe	0.18 (0.08)	0.48 (0.2)	0.14 (0.06)	0.01 (0)
Eastern Europe	0.18 (0.07)	0.55 (0.23)	0.14 (0.06)	0.01 (0)
Former USSR	0.22 (0.09)	0.56 (0.24)	0.07 (0.03)	0 (0)
Middle East	0.06 (0.03)	0.51 (0.28)	0.58 (0.33)	0.02 (0.01)
South Asia	0.03 (0.02)	0.23 (0.13)	0.96 (0.54)	0.06 (0.03)
East Asia	0.07 (0.03)	0.48 (0.2)	0.27 (0.11)	0.02 (0.01)
Southeast Asia	0.02 (0.01)	0.08 (0.05)	0.56 (0.31)	0.3 (0.17)
Oceania	0 (0)	0 (0)	0 (0)	0.98 (0.55)
Japan	0.06 (0.04)	0.54 (0.3)	0.1 (0.06)	0.01 (0.01)

Table S6b. Specific Forcing Pulse (GJ/g) quantifying forcing in four latitude bands from 17 emitting regions, for forcing by black carbon deposited on snow. Uncertainties (1-σ) are in brackets.

Cryosphere	**60N+**	**30-60N**	**0-30N**	**S.Hemis.**
Canada	0.12 (0.11)	0.25 (0.15)	0 (0)	0 (0)
USA	0.06 (0.05)	0.12 (0.07)	0 (0)	0 (0)
Central America	0.01 (0.01)	0.02 (0.01)	0 (0)	0 (0)
South America	0 (0)	0 (0)	0 (0)	0.02 (0.01)
Northern Africa	0.02 (0.01)	0.06 (0.03)	0 (0)	0 (0)
Western Africa	0 (0)	0.01 (0.01)	0 (0)	0 (0)
Eastern Africa	0 (0)	0.01 (0.01)	0 (0)	0 (0)
Southern Africa	0 (0)	0 (0)	0 (0)	0.01 (0.01)
OECD Europe	0.12 (0.11)	0.04 (0.03)	0 (0)	0 (0)
Eastern Europe	0.12 (0.11)	0.07 (0.04)	0 (0)	0 (0)
Former USSR	0.22 (0.2)	0.27 (0.16)	0 (0)	0 (0)
Middle East	0.04 (0.03)	0.14 (0.08)	0 (0)	0 (0)
South Asia	0.01 (0)	0.11 (0.06)	0.01 (0.01)	0 (0)
East Asia	0.04 (0.05)	0.1 (0.06)	0 (0)	0 (0)
Southeast Asia	0 (0)	0.01 (0)	0 (0)	0 (0)
Oceania	0 (0)	0 (0)	0 (0)	0.05 (0.03)
Japan	0.04 (0.02)	0.03 (0.02)	0 (0)	0 (0)

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