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Predictors of personal exposure to black carbon among women in southern semi-rural Mozambique

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ABSTRACT

Sub-Saharan Africa (SSA) has the highest proportion of people using unclean fuels for household energy, which can result in products of incomplete combustion that are damaging for health. Black carbon (BC) is a useful marker of inefficient combustion-related particles; however, ambient air quality data and temporal patterns of personal exposure to BC in SSA are scarce. We measured ambient elemental carbon (EC), comparable to BC, and personal exposure to BC in women of childbearing age from a semi-rural area of southern Mozambique. We measured ambient EC over one year (2014–2015) using a high-volume sampler and an off-line thermo-optical-transmission method. We simultaneously measured 5-min resolved 24-h personal BC using a portable MicroAeth (AE51) in 202 women. We used backwards stepwise linear regression to identify predictors of log-transformed 24-h mean and peak (90th percentile) personal BC exposure. We analyzed data from 187 non-smoking women aged 16–46 years. While daily mean ambient EC reached moderate levels (0.9 μg/m^3, Standard Deviation, SD: 0.6 μg/m^3), daily mean personal BC reached high levels (15 μg/m^3, SD: 19 μg/m^3). Daily patterns of personal exposure revealed a peak between 6 and 7 pm (> 35 μg/m^3), attributable to kerosene-based lighting. Key determinants of mean and peak personal exposure to BC were lighting source, kitchen type, ambient EC levels, and temperature. This study highlights the important contribution of lighting sources to personal exposure to combustion particles in populations that lack access to clean household energy.

1. Introduction

Household air pollution resulting from inefficient fuel combustion for domestic energy is a leading driver of mortality and morbidity globally (Gakidou et al., 2017). Sub-Saharan Africa (SSA) has the lowest access to clean fuels and technologies for cooking, heating, and lighting (Bonjour et al., 2013; World Bank, 2018). Many households in SSA meet their daily energy needs using firewood as the primary cooking source (74%) and kerosene, also called paraffin, as the primary lighting source (69%) (Adkins et al., 2012). In Mozambique, 95% of the population was estimated to use unclean fuels for cooking in 2010 (Bonjour et al., 2013) and kerosene is commonly used in the form of a portable lamp with a glass shielding the flame (*candeeiro de vidro* in Portuguese) (Ellegård and Stockholm Environment Institute, 1997).

Fuel combustion releases a complex mixture of particulates and gases, varying according to the fuel type and combustion conditions

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(Reid et al., 2005). Black carbon (BC), a carbonaceous component of the fine fraction of particulate matter ($PM_{2.5}$), can serve as a useful indicator of this mixture of combustion-related pollutants (Janssen et al., 2011; Smith et al., 2009). Previous lab- and field-based estimates show that 7–9% of the kerosene mass burned in a lamp can be converted to particulate emissions which are 88–100% BC (Lam et al., 2012). BC from combustion of household fuels also contributes to ambient air pollution, representing 25% of the global anthropogenic BC emissions and 80% of the BC emissions in Africa (Bond et al., 2013).

Black carbon is relevant for both climate and human health goals (Shindell et al., 2012). Although BC atmospheric life time is shorter (1 week) than carbon dioxide (1 century), BC has a stronger atmospheric warming effect (i.e., forcing) (Smith et al., 2009; WHO and Scovronick, 2015). Exposure to BC and elemental carbon (EC) is associated with myriad adverse health effects such as all-cause mortality and cardiovascular hospital admissions (Janssen et al., 2011; Smith et al., 2009; WHO and Scovronick, 2015; Hoek et al., 2013; Luben et al., 2017; Magalhaes et al., 2018; Zhao et al., 2014), which can be additional to those of $PM_{2.5}$ (Janssen et al., 2011). Limited evidence exists for the health effects of BC from household fuel combustion, but emerging evidence points to its effects on high blood pressure (Magalhaes et al., 2018; Baumgartner et al., 2014) and prevalence of prediabetes/diabetes (Rajkumar et al., 2018). The use of kerosene as a source of household energy (either for lighting or cooking) has been associated with tuberculosis (Pokhrel et al., 2010; Elf et al., 2019), acute respiratory infection in children (Barron and Torero, 2017; Bates et al., 2013; Patel et al., 2019), and low-birth weight and neonatal death (Epstein et al., 2013). These effects are particularly relevant for women, who are traditionally charged with the task of domestic work and therefore most affected by the high-intensity pollution episodes (Ezzati et al., 2000; Okello et al., 2018). During cooking time, very high PM_{10} personal levels were found among Mozambican women residing in low-income suburbs using firewood (1200 $\mu g/m^3$) and charcoal (540 $\mu g/m^3$) as cooking fuels (Ellegård, 1996).

Understanding patterns in personal exposure to combustion particles and identifying potentially important sources is essential to design effective interventions to reduce exposure to household air pollution and associated health effects. However, the availability of personal exposure data in low-income populations has been scarce so far (Tonne et al., 2017), particularly in SSA (Amegah, 2018). Existing studies of personal particulate exposure in populations reliant on unclean fuels for household energy have either focused on specific cooking-related determinants or have characterized $PM_{2.5}$ (Baumgartner et al., 2011; Bruce et al., 2004; Clark et al., 2010; Dionisio et al., 2012; Hu et al., 2014; Jiang and Bell, 2008; Van Vliet et al., 2013), which is generally a less specific marker of inefficient combustion than BC. Although there are some previous assessments of personal BC or related measures (e.g., $PM_{2.5}$ absorbance) in rural areas (Baumgartner et al., 2014; Rajkumar et al., 2018; Okello et al., 2018; Van Vliet et al., 2013; Buonanno et al., 2013; Downward et al., 2016), these have been mostly limited to time-integrated personal measurements, not allowing for the characterization of daily temporal patterns of personal exposure. To address these gaps in the available evidence, our aims were to 1) characterize personal exposure to BC among women in a semi-rural area of southern Mozambique, and 2) identify predictors of exposure.

2. Material and methods

2.1. Study area and population

The study was conducted in the Manhiça district, a semi-rural area of southern Mozambique situated 80 km north from Maputo, the capital city (Fig. 1). The main occupations of the population are farming, small-scale trading and employment on the two large sugar cane estates, Maragra and Xinavane. Since 1996, the Manhiça Health Research Centre (*Centro de Investigação em Saúde de Manhiça*, CISM) runs a health and demographic surveillance system (HDSS) (Sacoor et al., 2013). For this study, 202 women of childbearing age (12–49 years) were randomly selected from the HDSS, which in 2014 covered 500 km^2 and about half of the total population and households in the Manhiça district (95,000 inhabitants distributed in approximately 22,000 households). Participants in this study are distributed in three different administrative subdivisions (or *postos administrativos* in Portuguese): "Manhiça-Sede", "3 de Fevereiro" and "Ilha Josina Machel" (Fig. 1).

Meetings with community leaders in the study area were conducted to facilitate acceptance of the study and adherence of women to the study protocol. Local trained fieldworkers visited eligible women in their household, explained the study aims, and invited them to participate. A second visit was scheduled if the woman agreed to participate. During the second visit, the nature of the study was explained in more detail and women signed (or thumb printed) an informed consent form written in local language. During this field visit, we measured the height and weight of women and we deployed air monitoring equipment. Recruitment and monitoring occurred from March 2014 to April 2015. The study protocol was approved by the National Mozambican Ethics Committee and the Hospital Clínic of Barcelona Ethics Review Committee.

2.2. Ambient monitoring

We collected 24-h ambient air samples for off-line determination of levels of $PM_{2.5}$, EC, and organic carbon (OC) once every three days during the year of the study (i.e., 115 days) using a stationary sampler located in the courtyard of the CISM facilities (Fig. A2). Sampler location in relation to participant's households is shown in Fig. 1. EC and OC are carbon-rich components of PM. While EC is considered a graphite-like carbon enriched phase, OC carbon is chemically combined with oxygen, hydrogen, and other elements, and both (together with a much lower contribution of carbonate-mineral carbon) compose the total particulate carbonaceous material (Lack et al., 2014; Petzold et al., 2013).

We used a high-volume sampler (Model MCV CAV-A/mb, MCV S.A., Barcelona, Spain; 900 × 580 × 600 mm; 20 kg) with a $PM_{2.5}$ cut-off inlet (PM1025/UNE) collection of $PM_{2.5}$ onto 15-cm quartz filters (Whatman, GE Healthcare, Buckinghamshire, UK) using a 30 m^3/h flow rate. Inlet was located at > 1 m above the ground and sampler was continuously plugged into electricity supply (Fig. A2). Sampling was programmed to run for 24 h. Daily meteorological information for the study period was available from a meteorological station located at the Maputo International Airport, located 80 km south of the study area.

Filter weighing and EC/OC determination were conducted in the Institute of Environmental Assessment and Water Research (IDÆA), in Barcelona, Spain, using previously described protocols (Amato et al., 2014; Rivas et al., 2014). Briefly, filters were pre-baked at 205 °C for 5 h before sampling. Filters were conditioned at 19–20 °C and 49–53% relative humidity for 48 h before weighing; three consecutive weights were done pre- and post-sampling using a microbalance with 1 μg sensitivity (Model LA130S-F, Sartorius AG, Germany). Filters were not refrigerated after sampling due to logistical constraints, but they were stored in an air-conditioned room at CISM facilities until shipped to Barcelona by airplane (room temperature was not recorded). Once in Barcelona, filters were refrigerated at 4 °C before the 48-h conditioning. EC/OC determination was done using a 1.5 cm^2 filter punch and applying a thermal-optical transmission (TOT) technique with the Lab OC-EC Aerosol Analyzer (Sunset Laboratory Inc., Portland, OR, USA) and the NIOSH temperature program. EC (measured with a TOT method in this study) may not be equivalent to BC (measured with an optical method in this study). Typically, BC measurements use an EC/optical absorption constant to convert the optical signal into BC mass concentration and make both measurements comparable (Lack et al., 2014). However, available equations and conversion coefficients are site- and season-specific, and none were available for our setting. Thus,

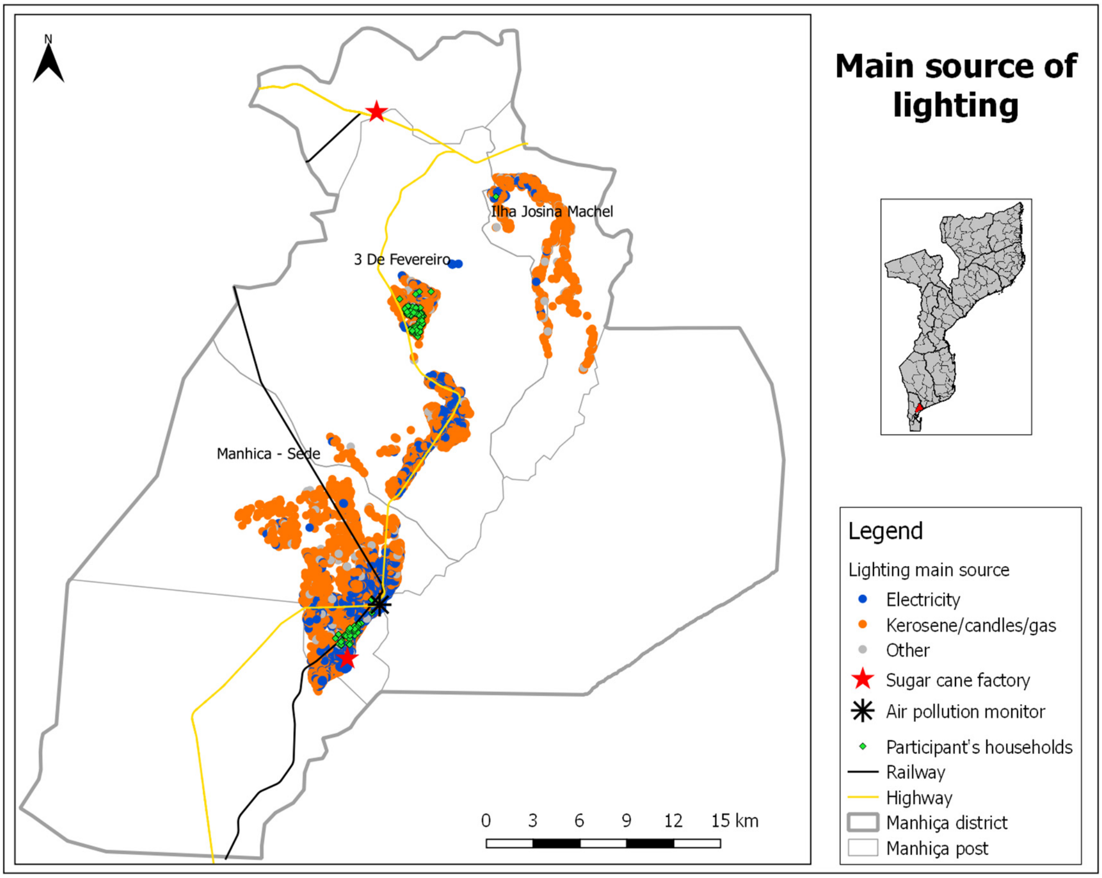

Fig. 1. Map of the study area (Manhiça district, southern Mozambique) showing the main lighting source used by the ≈22,000 households included in the health and demographic surveillance system. For household density in the study area see Fig. A1 in Appendix.
Manhiça post refers to an administrative subdivision (coming from "postos administrativos" in Portuguese).

we compare BC with EC in terms of absolute concentrations and time-variability.

2.3. Personal monitoring

Real-time 24-h personal BC concentrations were measured using the MicroAeth™ (Model AE51, AethLabs, San Francisco, CA, USA). The MicroAeth is a small (117 × 66 × 38 mm) and portable (250 g) battery-operated device based on Aethalometer optical absorption technology. Briefly, the MicroAeth pumps PM onto a glass fiber filter and an internal beam of light with 880-nm wavelength is then attenuated by deposited black particles. The flow rate was set to 50 ml/min with a sampling rate of 5 min using AethLabs software (version 2.1.1.0). We did not clean MicroAeth optical benches between deployments. Women were trained to wear the MicroAeth in a waist pouch with the inlet tube at the breathing zone during the daytime. Women were advised to leave the device nearby during sleeping time (e.g., on a table/chair). From the sampling date, we derived season, day of the week, and sunrise and sunset time.

Personal BC data obtained by the MicroAeth was post-processed using an Optimized Noise-reduction Averaging (ONA) algorithm, specially developed by the manufacturer and the US Environmental Protection Agency (Hagler, 2011). This algorithm reduces the negative values often created by the MicroAeth (Hagler, 2011). In our data, the algorithm reduced negative values from 11.8% in the raw dataset to 1.4% after processing.

2.4. Individual- and household-level characteristics

We administered a questionnaire to all women to obtain information on: 1) personal characteristics (age, education level, occupation, marital status, number of living children), 2) household characteristics (household income, materials of roof, walls and floors, type of windows and covering of kitchen, and number of bedrooms), 3) cooking/lighting habits (number of open fires per day, type of primary cooking and lighting fuel, sleeping in the cooking area), 4) cooking behavior during the monitoring day (i.e., if cooked, time of the cooking event(s), and type of cooking fuel used, if applicable), and 5) household smoking habits (if any household member usually smoked and if smoking usually occurred indoors or outdoors). All questionnaire data were double entered to avoid data entry errors. Body mass index (BMI) was calculated with measured weight divided by squared measured height. We derived literacy level from participant self-reported capabilities to read and write. We also derived kitchen type by combining kitchen location (inside/outside the house) and type of kitchen roof (covered/partially covered/not covered).

Additional household characteristics were derived from data collected as part of the HDSS maintained by CISM from almost all households (≈22,000) on: 1) household location via GPS, 2) household asset index, a measure of socioeconomic status (SES) (Howe et al., 2012), and 3) main lighting source (electricity vs. kerosene/candles/gas vs. other). Asset index was based on the sum of 13 indicators of ownership of durable assets (car, motorbike, bicycle, refrigerator, freezer, television, DVD, radio, telephone, computer, electric stoves) and livestock (pigs, goats), categorized into low/middle/high. HDSS data were used to create the following variables for buffers of 100 m, 300 m and 500 m around participants' household location using the geographic information system (GIS) software QGIS 2.18.11 and ArcGIS 10.2.1: 1) number of surrounding households, 2) household density (households/km^2), 3) proportion of surrounding households with high and low SES, and 4) proportion of surrounding households using electricity and kerosene/candles/gas.

2.5. Data analysis

All women who were contacted in the first visit agreed to take part in the study (n = 202). We excluded from analysis women missing questionnaire data (n = 2), with ≤19 h of BC data (n = 8), and with ≤80% of valid BC measurements (n = 1). We considered valid measurements those exempt from device error code other than low battery status and filter overloading. We also excluded from analysis women for whom the filter overloading error was present during the entire sampling period (n = 4). Thus, we finally included 187 women (93% of all participants; equivalent to 187 woman-day), of which we have available household location coordinates of 156.

Filter loading can be quantified by the light attenuation (ATN) value. Typically, ATN increases as the accumulation of BC particles onto the filter increases. The device starts reporting an error code of filter overloading at ATN = 125. When this occurs, the MicroAeth continues making measurements, although it can underestimate the BC concentration up to 69% if data is not corrected (Good et al., 2017). Since the loading effect occurs across the whole 0–125 ATN range, we corrected for the loading effect all BC measurements using the correction factor of Kirchstetter and Novakov (Kirchstetter and Novakov, 2007), which provides lower root mean square error if compared to other available correction equations (Good et al., 2017):

$$BC = BC_0/(0.88 \times \exp(-ATN/100) + 0.12) \quad (1)$$

Here, BC represents the corrected BC concentration used in analysis (in $\mu g/m^3$) and BC_0 represents the ONA-smoothed concentration reported by the MicroAeth (in $\mu g/m^3$).

We calculated the arithmetic mean and the 90th percentile of the 24-h BC concentration for each woman. We used Kruskal-Wallis test to assess significance of BC mean across subgroups and Pearson correlation coefficient to assess correlation between continuous variables. To explore the temporal patterns of daily BC exposure we plotted personal measurements of all participants combined and smoothed the values using a generalized additive model (GAM) function with a cubic regression spline (using the R function mgcv::gam). Ambient exposure to EC, OC, and $PM_{2.5}$ levels were assigned to each woman matching the personal and the ambient sampling dates. We assumed that the ambient levels captured by the sampler are representative of the ambient levels of all participants. When personal sampling did not overlap with an ambient measurement, we linked the personal exposure with the nearest (in time) available ambient measurement. Fifty women (27% of those included in analysis) had perfectly matching ambient data. The rest of women were matched with the previous days (32%) or with the subsequent day (41%). The mean of the gap (before or after) between personal sampling and ambient measurements was 1.1 days (SD: 0.3 days).

We used backwards stepwise linear regression to identify predictors of 24-h mean and peak (90th percentile) BC exposure. As input, we used the complete cases dataset (n = 175) using the following variables as potential predictors of personal BC exposure (as presented in Table 1): 1) marital status and number of living children, 2) physical and ventilation characteristics (walls and floor material, number of bedrooms, type of windows and kitchen), 3) prolonged air pollution exposure (occupation, sleeping in the cooking area), 4) indoor air pollution (number of open fires per day, cooking fuel used during sampling, primary lighting source, presence of secondhand tobacco smoke), 4) ambient EC levels, and 5) meteorological characteristics (temperature, relative humidity). We retained predictors using the R function MASS::stepAIC, which selects the final model based on the Akaike information criterion (AIC) (Venables et al., 2002). Mean and peak BC exposures were log-transformed (natural log transformation); results are therefore expressed as a percent change in the log-transformed

Table 1
Personal and household characteristics of women, n = 187.

Personal	Mean ± SD or n (%)
Age (years), mean ± SD	30.3 ± 7.8
Illiterate, n (%)	82 (44.3)
Education level, n (%)	
Primary (1–7 years)	107 (57.8)
Secondary (8–12 years)	8 (4.3)
None	70 (37.8)
Occupation, n (%)	
Housekeeper	166 (89.2)
Other	20 (10.8)
Marital status, n (%)	
Married/living with a partner	139 (75.1)
Single/divorced/widowed	46 (24.9)
Number of children, mean ± SD	3.0 ± 1.9
Body mass index, mean ± SD	23.8 ± 4.2
Active smoking, n (%)	0 (0)
Sleeping in the cooking area, n (%)	13 (7.0)
Household	
Income status of head of household, n (%)	
Salaried (either fixed or occasional)	112 (64.0)
None	11 (6.3)
Other	34 (19.4)
Socioeconomic status, n (%)	
Low	24 (12.8)
Middle	68 (36.4)
High	62 (33.2)
Secondhand tobacco smoke, n (%)	24 (12.8)
Floor material, n (%)	
Cement	140 (74.9)
Sand	47 (25.1)
Walls material, n (%)	
Blocks	86 (46.2)
Reed and other	100 (53.8)
Windows type, n (%)	
Glass/wood	75 (41.0)
Opened	5 (2.7)
None	98 (53.6)
Other	5 (2.7)
Kitchen type, n (%)	
Enclosed or partially enclosed	123 (66.5)
Open-air or no kitchen	62 (33.5)
Kitchen walls material (if applicable), n (%)	
Blocks	34 (21.0)
Reed and other	128 (79.0)
Number of bedrooms, mean ± SD	1.5 ± 0.9
Number of open fires per day, mean ± SD	2.0 ± 0.5
Primary cooking fuel, n (%)	
Firewood	172 (92.0)
Charcoal	8 (4.3)
Firewood & charcoal	4 (2.1)
Other	1 (0.5)
Cooking fuel used during monitoring, n (%)	
Biomass (firewood or charcoal)[a]	172 (93.5)
None used	12 (6.5)
Primary lighting source, n (%)	
Electricity	71 (38.0)
Kerosene (and/or candle)[b]	116 (62.0)
Mean distance to highway (km) ± SD	1.2 ± 0.8
Mean distance to nearest sugar cane factory (km) ± SD	12.2 ± 7.2

SD: Standard Deviation. Absolute numbers and percentage distributions for a given variable may not summed 187 and 100%, respectively, since they are considering missing values.

[a] 97% of women used firewood during monitoring.

[b] Two women reported the use of kerosene and candle and five women the use of only candle. We grouped them all in the category of kerosene for simplicity of categories.

(Barrera-Gómez and Basagaña, 2015). To assess the relative percent contribution of cooking and lighting to the BC mean and peak exposures we calculated the partial R^2 of the models before and after the stepwise selection using the R function asbio::partial.R2. As a sensitivity analysis, we repeated backwards stepwise regression 1) adding GIS-derived predictors (proportion of surrounding households using kerosene/candles/gas within 300 m, distance to highway, distance to nearest sugar cane factory) for participants with non-missing values for all variables (n = 146) to assess community use of kerosene, traffic and industry as potential predictors of personal BC exposure, and 2) using BC values within waking hours (8 am to 9 pm; 13 waking hours) to reduce the number of 5-min BC measurements with filter overloading. In bivariate and regression analyses, p-values < 0.05 were regarded as statistically significant. All analyses were conducted with Stata 14.0 (StataCorp, Texas, USA) and R 3.5.1 (the R Foundation for Statistical Computing, Vienna, Austria) using the MASS package (Venables et al., 2002).

3. Results

3.1. Participant and household characteristics

Characteristics of participants and their households are shown in Table 1. Women were all non-smokers and have a mean (Standard Deviation, SD) age of 30 (8) years. They were largely housekeepers (89%) who primarily used firewood (92%) and kerosene (62%) for cooking and lighting, respectively. Secondhand smoke was present in 13% of women's households, although smoking was reported to be mostly outdoors (54%). Almost all household roofs were made of zinc (99%), walls were made primarily of reed (52%) and floor of cement (75%). The majority of women reported to have a kitchen outside their house (89%) and few (7%) reported to sleep in the cooking area.

Geographical characteristics of participants' households comparing electricity users vs. kerosene users are shown in Table 2. Compared to electricity users, kerosene users were living in significantly less dense areas and were surrounded by a greater proportion of households also using kerosene as the main lighting source (71% vs. 40% in a 100-m radii).

3.2. Ambient concentrations and meteorological characteristics

Variability of ambient levels over the study period is shown in Fig. 2. Mean levels for $PM_{2.5}$, EC, and OC were 13.8 μg/m^3 (SD: 8.8 μg/m^3, min to max: 2.4 to 53.8 μg/m^3), 0.9 μg/m^3 (0.6 μg/m^3, 0.1 to 3.8 μg/m^3), and 4.1 μg/m^3 (3.9 μg/m^3, 0.0 to 14.8 μg/m^3), respectively. In 12% of the ambient samples, $PM_{2.5}$ levels exceeded the World Health Organization (WHO) guidelines for 24-h average, mainly during the dry season (April–September). There were high Pearson correlations between ambient EC and OC (r: 0.71; p-value < 0.001), ambient EC and $PM_{2.5}$ (r: 0.69; p-value < 0.001), and ambient OC and $PM_{2.5}$ (r: 0.94; p-value < 0.001). Correlations between ambient EC and mean temperature (r: −0.26; p-value = 0.004) and ambient EC and mean humidity (r: −0.56; p-value < 0.001) were lower. Summary statistics of ambient concentrations and meteorological characteristics linked with personal sampling are shown in Table 3. Average ambient temperature during sampling days ranged from 16 °C to 29 °C, with rainy season being significantly 4 °C warmer (25.9 °C) than dry season (21.9 °C) (p-value < 0.001).

3.3. Personal BC concentrations

Averages of the 24-h mean and 90th percentile of personal exposure to BC were 15.3 μg/m^3 (SD: 19.4 μg/m^3, min to max: 0.4 to 108.8 μg/m^3), and 30.4 μg/m^3 (56.5 μg/m^3, 0.8 to 402.1 μg/m^3), respectively. Almost all women reported to have cooked during monitoring (92%) and having removed the MicroAeth only during sleeping and/or bathing time (97%). Comparison with personal concentrations of previous studies is summarised in Table 4 and further discussed in Section 4.2. Personal mean BC concentration was significantly higher among kerosene users (18.6 μg/m^3) than electricity users (9.9 μg/m^3; p-value < 0.001) and during the dry season (15.7 μg/m^3) compared to the rainy season (15.0 μg/m^3; p-value = 0.003), but did not differ significantly between women exposed to secondhand smoke at home (17.0 μg/m^3) vs. non-exposed (15.1 μg/m^3; p-value = 0.4) or between women who cooked with biomass during sampling (15.9 μg/m^3) vs. those who did not (9.0 μg/m^3; p-value = 0.09). Among kerosene users, BC mean concentration greatly differed between those who cooked with biomass (19.5 μg/m^3) vs. those who did not (8.7 μg/m^3), but this

Table 2
Geographical characteristics of most of participants' households (83%, n = 156) in buffers of 100 m, 300 m and 500 m comparing electricity users vs. kerosene users.

	Electricity users (n = 71)				Kerosene users (n = 116)				p-Value[a]
	MIN	MED	AM	MAX	MIN	MED	AM	MAX	
Number of surrounding households									
100 m	2	10	10.8	26	1	5	7.8	27	< 0.001
300 m	20	75	80.5	186	6	33	54.6	192	< 0.001
500 m	41	173	190.4	448	18	103	129.9	428	< 0.001
Household density (households/km^2)									
100 m	6407	32,036	34,698	83,295	3204	16,018	25,066	86,498	< 0.001
300 m	7119	26,697	28,663	66,209	2136	11,747	19,429	68,344	< 0.001
500 m	5254	22,169	2441	57,409	2307	13,199	16,641	54,846	< 0.001
Proportion of surrounding households with high SES (%)									
100 m	0	45.5	44.0	83.3	0	26.7	27.5	100	< 0.001
300 m	17.4	38.3	36.5	51.1	0	29.6	29.6	51.0	< 0.001
500 m	17.0	36.1	35.0	45.5	11.8	29.8	30.0	51.7	< 0.001
Proportion of surrounding households with low SES (%)									
100 m	0	8.3	14.6	80.0	0	0	13.8	100	0.67
300 m	0	15.7	18.4	41.1	0	11.9	13.8	48.0	0.06
500 m	2.9	13.8	20.2	44.1	1.5	11.4	13.6	41.3	0.001
Proportion of surrounding households using electricity (%)									
100 m	0	57.1	57.1	100	0	16.7	24.5	100	< 0.001
300 m	1.0	46.1	45.9	78.7	0	12.5	28.2	78.4	< 0.001
500 m	1.7	39.2	43.2	68.7	5.9	28.1	29.8	83.9	< 0.001
Proportion of surrounding households using kerosene/candles/gas (%)									
100 m	0	40.0	39.7	100	0	75.0	71.2	100	< 0.001
300 m	21.3	50.0	49.8	95.7	19.6	70.2	67.0	100	< 0.001
500 m	28.2	53.7	52.0	90.2	15.6	64.8	65.5	91.2	< 0.001
Distance to highway (km)	0.09	1.3	1.4	3.1	0.02	0.8	1.00	3.2	< 0.001

MIN: minimum; MED: median; AM: Arithmetic Mean; MAX: maximum; SES: socioeconomic status (based on household assets).
[a] Kruskal-Wallis test comparing electricity users vs. kerosene users.

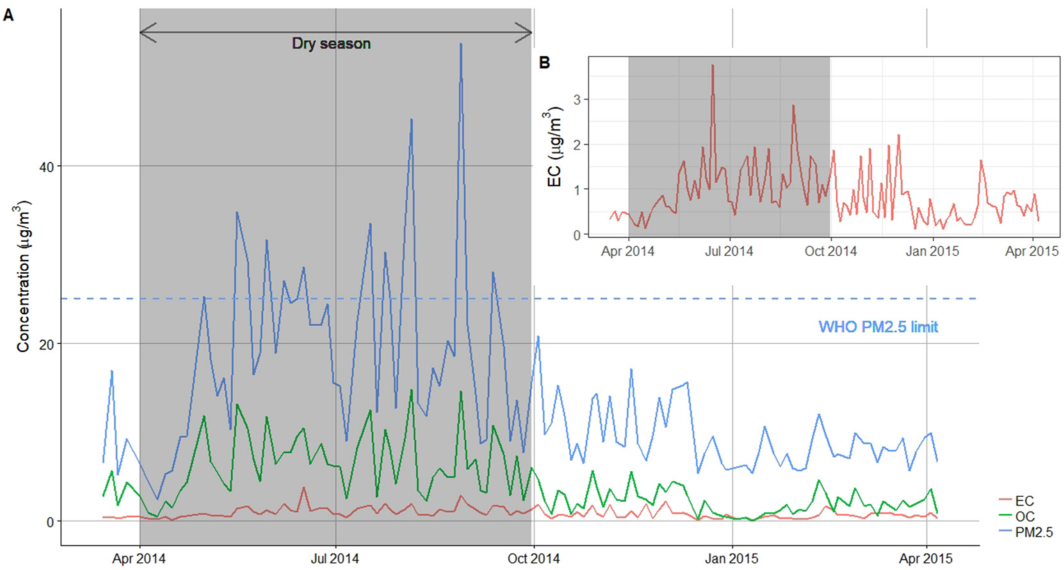

Fig. 2. Annual variation of 24-h ambient levels of elemental carbon (EC), organic carbon (OC), and fine particulate matter ($PM_{2.5}$) during the study period (panel A). Dotted horizontal blue line represents the World Health Organization (WHO) guideline for $PM_{2.5}$ 24-h average (25 µg/m^3). Enlargement of annual variation of ambient levels of EC is shown in panel B.

Table 3
Meteorological and ambient characteristics of personal exposure monitoring days.

Meteorological and ambient characteristics	n (%) or mean (± SD; minimum to maximum)
Season	
Rainy (October–March)	96 (51.3)
Dry (April–September)	91 (48.7)
Sunrise time	
Mean	5:37 am (4:49 am to 6:35 am)
Mean in rainy season	5:19 am (4:49 am to 5:57 am)
Mean in dry season	6:10 am (5:30 am to 6:35 am)
Sunset time	
Mean	5:58 pm (5:05 pm to 6:44 pm)
Mean in rainy season	6:22 pm (5:58 pm to 6:44 pm)
Mean in dry season	5:33 pm (5:05 pm to 6:02 pm)
Day of the week	
Monday	65 (34.8)
Tuesday	32 (17.1)
Wednesday	38 (20.3)
Thursday	44 (23.5)
Friday	8 (4.3)
Temperature 24-h average (°C)	24.0 (± 3.0; 16 to 29)
Temperature during 6–7 pm (°C)	25.7 (± 2.4; 19 to 29)
Humidity 24-h average (%)	66.9 (± 10.3; 40 to 94)
Humidity during 6–7 pm (%)	69.8 (± 9.2; 51 to 94)
Precipitation 24-h average (mm)	2.3 (± 15.8; 0.0 to 151.9)
EC 24-h average (µg/m^3)	0.9 (± 0.6; 0.1 to 3.8)
OC 24-h average (µg/m^3)	3.9 (± 3.4; 0.0 to 14.8)
$PM_{2.5}$ 24-h average (µg/m^3)	13.3 (± 8.9; 2.4 to 53.8)

SD: Standard Deviation; EC: Elemental Carbon; OC: Organic Carbon; $PM_{2.5}$: particles < 2.5 µm in diameter.

difference was not statistically significant (p-value = 0.17), probably due to the low sample size in kerosene users who did not cook (n = 6).

Of all women included, 50 had > 20% of the sampling period with some device error; mainly filter overloading. The ATN loadings on the filters at the end of sampling ranged from 14.5 to 318.6 (mean = 104.1, median = 87.1) (Fig. A3, panel A). Although underestimated, uncorrected BC concentrations (BC_0 in Eq. (1)) at high filter loading were significantly higher than at low filter loading (Fig. A3, panel B). To reach an ATN = 20, ATN = 80 and ATN = 125 it took averages of 4 h, 9 h and 20 h of sampling, respectively. Most of the participants (80%) had ATN < 125 half of the sampling time (Fig. A4).

3.4. Daily pattern of personal BC exposure

Daily pattern of personal exposure to BC and cooking times reported by women are shown in Fig. 3. Each woman reported only one cooking episode. Cooking times were distributed throughout the day (from 8 am to 6 pm): 8.6% between 8 and 11 am; 16.1% between 11 am-2 pm; 60.9% between 2 and 4 pm; and 14.4% between 4 and 6 pm. The plot in Fig. 3 reveals a peak between 6 pm and 7 pm, which does not correspond with the time window when most women cooked (i.e., 2–4 pm). Sunset time was before 7 pm in all monitored days, but on average sunset occurred earlier in colder (or dry season) sampling days (5:33 pm) than in warmer (or rainy season) sampling days (6:22 pm) (Table 3). When stratifying the daily time pattern by cooking × lighting (Fig. 4), the peak was much smaller for those women who did not cook during sampling and used electricity as a primary lighting source (22.6 µg/m^3, (95% Confidence Interval (95% CI): 15.9; 29.3 µg/m^3) than those women who cooked with biomass during sampling and used kerosene as a primary lighting source (50.1 µg/m^3, 95% CI: 47.6; 52.6 µg/m^3). Among all women using electricity, the peak of BC was slightly higher among those who cooked with biomass (31.4 µg/m^3, 95% CI: 29.2; 33.6 µg/m^3) than those who did not cook (22.6 µg/m^3, 95% CI: 15.9; 29.3 µg/m^3), although the peak occurred at different time windows (10–11 am for those who did not cook vs. 6–7 pm for those who cooked with biomass), likely indicating the contribution of different air pollution sources.

3.5. Predictors of personal exposure to BC

Before the stepwise selection, kerosene-based lighting partial contribution to the BC mean was 7.5% (adjusted total R^2 of 18.6%) and 6.8% to the BC peak (adjusted total R^2 of 17.6%). The contribution of biomass cooking was negligible (0.2% for the BC mean and 0.003% for the BC peak). After the stepwise selection, kerosene-based lighting partial contribution to the BC mean was 8.2% (adjusted total R^2 of 21.6%) and 7.3% to the BC peak (adjusted total R^2 of 20.1%). Significant predictors of mean BC exposure were lighting source, kitchen type, ambient EC, temperature, and number of living children (Fig. 5, panel A). Women who use kerosene (and/or candle) as the primary source of lighting had 81% higher BC exposure (95% CI: 34%; 147%) than those using electricity. Women who had an enclosed or partially enclosed kitchen had 61% (95% CI: 17%; 122%) higher BC

Table 4
Comparison of personal particulate levels in this study and previous studies either conducting time-resolved BC personal measurements in urban areas or BC-related (BC, $PM_{2.5}$, $PM_{2.5}$ absorbance) personal measurements in rural or semi-rural areas.

Study area (reference)[5]	Population	Sample size	Pollutant(s)	Time resolution	Device(s)	Sampling duration	BC (µg/m^3)			$PM_{2.5}$ (µg/m^3)			$PM_{2.5}$ absorbance (10^{-5}/m)		Time of highest peak of exposure
							AM	GM	MED[1]	AM	GM	MED[1]	AM	GM	
URBAN															
Barcelona, Spain (Rivas et al., 2014)	Children	45	BC	Time-resolved	MicroAeth[2]	48 hours	2.7								NR
Barcelona, Spain (Nieuwenhuijsen et al., 2015)	Children	54	BC	Time-resolved	MicroAeth	48 hours		1.3-2.8							8-9am
Sabadell, Spain (Pañella et al., 2017)	Children	85	BC	Time-resolved	MicroAeth	24 hours		1.64	1.7						NR
Belgium (Dons et al., 2011)	Adults	16	BC	Time-resolved	MicroAeth	7 days	1.6								5-5:20pm (women)
Flanders, Belgium (Dons et al., 2012)	Adults	62	BC	Time-resolved	MicroAeth	7 days	1.6								NR
Belgium (Louwies et al., 2015)	Nurses	55	BC	Time-resolved	MicroAeth	7 days	0.9								NR
Birmingham, UK (Delgado-Saborit, 2012)	Students and university staff	16	BC	Time-resolved	MicroAeth	16-18 hours	1.3								5:30-6:30pm
Seoul, Korea (Jeong and Park, 2017)	Children	40	BC	Time-resolved	MicroAeth	24 hours	1.9		1.5						7-8pm (girl)
Beijing, China (Zhao et al., 2014)	Adults	65	BC	Time-resolved	MicroAeth	5 days	4.8								7-8am 7-11pm
New York, USA (Cai, 2014)	Children	54	BC	Time-resolved	MicroAeth	24 hours (x6)	2.0								4:30-5pm
RURAL/SEMI-RURAL															
San Marcos, Guatemala (Bruce et al., 2004)	Women ≥38 years of age	116	$PM_{2.5}$	Time-integrated	BGI pump	24 hours						70-200			NA
Liaoning, China (Jiang and Bell, 2008)	Primary cook	5	$PM_{2.5}$	Time-resolved	TSI SidePak	15 hours (x3)				487					NR
Basse, Gambia (Dionisio et al., 2012)	Children	31	$PM_{2.5}$	Time-integrated	Casella pump	48 hours				65					NA
Santa Lucia and Suyapa, Honduras (Clark et al., 2010)	Women	59	$PM_{2.5}$	Time-integrated	SKC pump	8 hours				133	102				NA
Njombe district, Tanzania (Titcombe and Simcik, 2011)	Primary cook (women) + teacher	4 + 1	$PM_{2.5}$	Time-integrated	SKC pump	7-8 hours				14-1,574					NA
Kikati, Uganda and Kumbursa, Ethiopia (Okello et al., 2018)	Children and young and old adults	215	$PM_{2.5}$	Time-resolved	TSI SidePak, Dylos, MicroPEM, PATS+ [3]	24 hours					177.2-205.4 (adult females)				1-1:59pm (adult females)
Yunnan, China (Downward et al., 2015; Hu et al., 2014)	Primary cook (women ≥20 years of age)	163	$PM_{2.5}$ absorbance, $PM_{2.5}$	Time-integrated	BGI pump / Smoke Stain Reflectometer	24 hours (x2)					146-166		13.8 (smoky coal)	12.0 (smoky coal)	NA
Yunnan, China (Baumgartner et al., 2014)	Women ≥25 years of age	280	BC, $PM_{2.5}$	Time-integrated	Casella pump / Optical Transmissometer (OT21)	24 hours (x1-3)		5.2		9-634	5.5				NA
Brong Ahafo, Ghana (Van Vliet et al., 2013)	Primary cook	29	BC, $PM_{2.5}$	Time-integrated	BGI pump / optical reflectance measurement	24 hours	8.8			128					NA

(continued on next page)

Table 4 (*continued*)

Study area (reference)[5]	Population	Sample size	Pollutant(s)	Time resolution	Device(s)	Sampling duration	BC (µg/m³)			$PM_{2.5}$ (µg/m³)			$PM_{2.5}$ absorbance (10^{-5}/m)		Time of highest peak of exposure
							AM	GM	MED[1]	AM	GM	MED[1]	AM	GM	
La Esperanza, Honduras (Rajkumar et al., 2018)	Women	103	BC, $PM_{2.5}$	Time-integrated	SKC pump / Optical Transmissometer (OT21)	24 hours	16			100					NA
Cassino, Italy (Buonanno et al., 2013)[4]	Children	103	BC	Time-resolved	MicroAeth	48 hours	5.1		3.8						NR
Manhiça, Mozambique (our study)	Women ≥16 years of age	187	BC	Time-resolved	MicroAeth	24 hours	7.1		5.8						6-7pm

AM: Arithmetic Mean; GM: Geometric Mean; MED: Median; BC: Black Carbon; $PM_{2.5}$: particles less than 2.5 µm in diameter; NA: Non-Applicable; NR: Non-Reported. 1) Median of the sampling period average; 2) MicroAeth is referring to MicroAeth™ (Model AE51, AethLabs, San Francisco, CA, USA); 3) Participants wore paired devices; 4) Children living in 57% rural, 7% suburban, 36% urban areas in Cassino, Italy; 5) References only cited in this table are the following.

exposure than those who had an open-air kitchen or did not have a kitchen. Mean BC exposure increased by 44% (95% CI: 11%; 87%) for every 1 µg/m³ increase in ambient EC levels and decreased by 24% (95% CI: −42%; −0.7%) for every 5 °C increase in the ambient temperature. Having an additional child was associated with 9% (95% CI: −16%; −2%) lower personal BC exposure. Sleeping in the cooking area, secondhand smoke, marital status, and number of open fires were also retained in the multivariable model considering mean BC exposure, but CIs were wide and included the null.

Significant predictors of peak (90th percentile) BC exposure were lighting source, kitchen type, marital status, ambient EC, and temperature (Fig. 5, panel B). Peak exposure was 93% (95% CI: 34%; 178%) higher in women using kerosene for lighting (vs. electricity). Women who reported having an enclosed or partially enclosed kitchen were 65% (95% CI: 13%; 140%) more exposed to peaks of BC than women who reported having an open-air kitchen or not having one. Women having a spouse or partner had 55% (95% CI: 2%; 136%) higher personal BC peak exposure than those who were single, widowed or divorced. For every 1 µg/m³ increase in ambient EC levels, personal peak exposure to BC increased 55% (95% CI: 13%; 112%). In contrast, peak BC exposure decreased by 34% (95% CI: −52%; −10%) for every 5 °C increase in ambient temperature. Although secondhand smoke was also retained in the final model considering peak BC exposure, the CI included the null.

3.6. Sensitivity analysis

None of the GIS-derived variables (proportion of surrounding households using kerosene/candles/gas within 300 m, distance to highway, distance to nearest sugar cane factory) were retained in the sensitivity models (Fig. A5). Most significant predictors of mean and peak BC exposure remained the same (i.e., lighting source, kitchen type, ambient EC). Of the 187 women included in main analysis, 176 had ≥80% valid BC data during waking hours, of which 165 were complete cases. Mean and 90th percentile of personal exposure to BC during waking hours were 21.9 µg/m³ (SD: 25.6 µg/m³, min to max: 0.4 to 158 µg/m³) and 57.4 µg/m³ (108 µg/m³, 0.8 to 1005 µg/m³), respectively. Kitchen type, lighting source, and temperature were consistently significant factors influencing mean and peak personal BC exposure when only considering waking hours (Fig. A6).

4. Discussion

4.1. Main findings

To the best of our knowledge, our study provides for the first time temporal patterns of personal exposure to BC among women in sub-Saharan Africa. The highest BC peak (between 6 and 7 pm) was not explained by cooking activities, and reflects the influence of kerosene-based lighting. Lighting source, kitchen type, ambient EC levels, and temperature were the main predictors of between-person variation in 24-h mean and peak (90th percentile) personal exposure to BC. When adding relevant GIS-derived predictors into analysis (community use of kerosene and proximity to traffic and industry) or when limiting analysis to waking hours, lighting source and kitchen type remained the most significant predictors of mean and peak personal exposure to BC.

4.2. Personal BC levels

Most prior studies assessing time-resolved personal exposure to BC have been conducted in European urban areas (Table 4). In these settings, BC serves as a marker of traffic-related air pollution and has been used mostly to study the variation of personal levels across different microenvironments. In contrast, personal assessments of BC (or comparable measures) are scarce in rural or peri-urban settings in low- and middle-income countries, where BC serves as a marker of residential

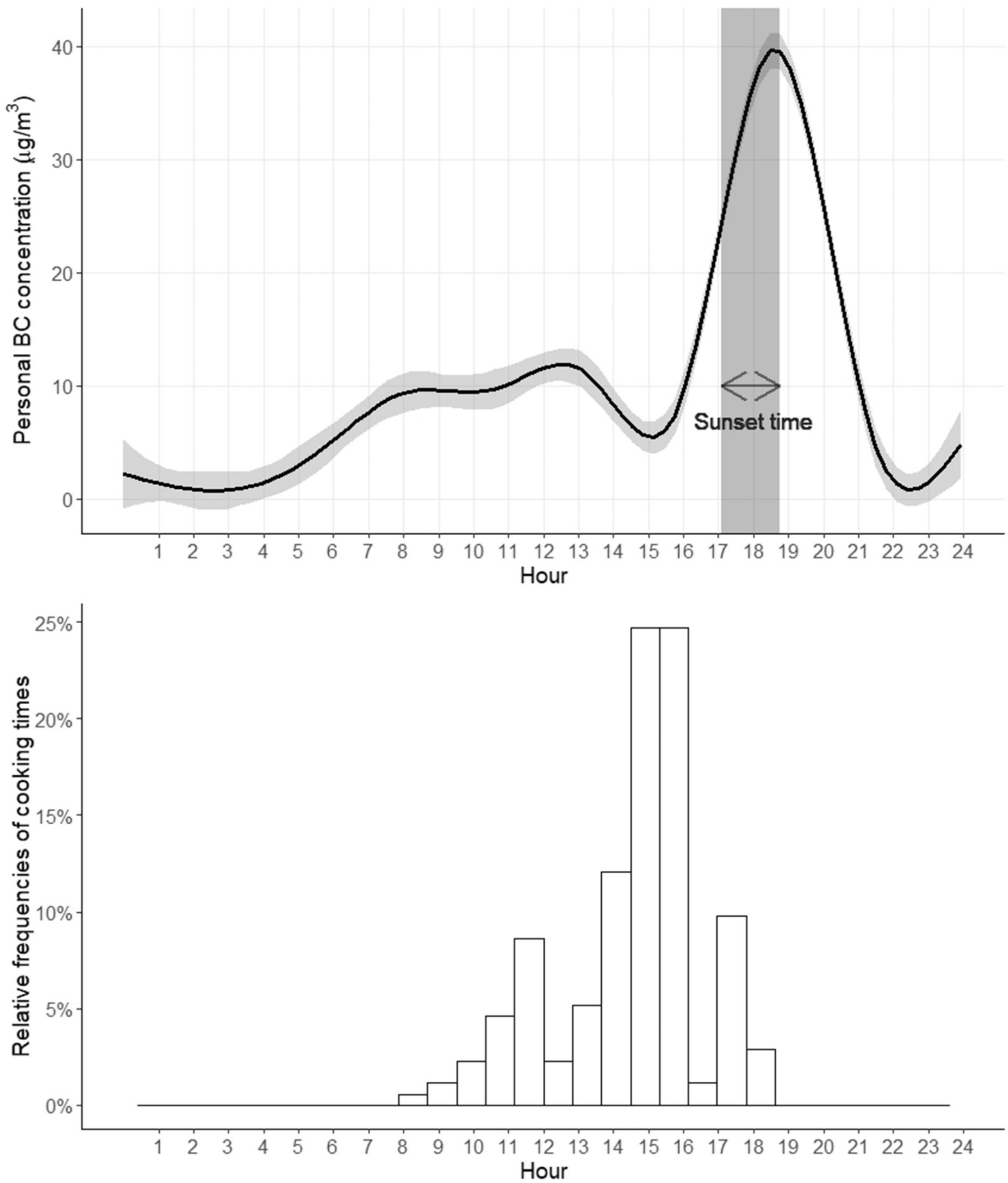

Fig. 3. Smoothed daily pattern of personal exposure to black carbon (BC) of all personal measurements combined (top) and corresponding self-reported cooking times (bottom).
Shaded band around the smoothed line represents 95% Confidence Interval (*calculated as* ± *1.96 standard error*)*. Vertical shaded area represents the range of sunset time during the sampling days*.

fuel combustion. Our daily BC personal levels observed in women from Mozambique (15 μg/m^3) are many times higher than those observed in adults and children from European cities (< 2.8 μg/m^3), children from rural Italy (5 μg/m^3) (Buonanno et al., 2013) and women from rural Ghana (9 μg/m^3) (Van Vliet et al., 2013) (see Table 4). Our BC 24-h personal levels were more comparable to levels from women in rural Honduras (16 μg/m^3) (Rajkumar et al., 2018) and 8-h levels from traffic-related workers in urban Kenya (> 19 μg/m^3) (Ngo et al., 2015).

4.3. Cooking-related predictors

A broad literature indicates that relevant determinants of personal and indoor air pollution from household fuels are the type of cooking fuel, the type of stove, time spent cooking, and the role of ventilation (Ezzati et al., 2000; Baumgartner et al., 2011; Bruce et al., 2004; Hu et al., 2014; Jiang and Bell, 2008; Brauer and Saksena, 2002). In our study, the cooking fuel used during sampling was not a predictor of personal mean or peak exposure to BC. This could be explained by the lack of variability in the cooking fuel used (94% of women used biomass). Nonetheless, having a totally/partially enclosed kitchen was associated with higher personal exposure to BC as compared to open-air kitchen, which can impact both kerosene lamp and cooking emissions. Similarly, Balakrishnan et al., 2004 found kitchen area PM_4 levels (particles < 4 μm in diameter) to be significantly higher in enclosed kitchens (666 μg/m^3) as compared to open-air kitchens (297 μg/m^3) in rural India. Also, Wylie et al. (2017) found that outdoor cooking, as compared to indoor cooking, was associated with 14.5 μg/m^3 lower median $PM_{2.5}$ personal exposure in pregnant women from urban Tanzania. However, there is a lack of standardization in kitchen type definitions, which limits comparisons across studies. For example, it is not clear if partially covered kitchens should be assigned either to indoor or outdoor cooking (Brauer and Saksena, 2002), or if not having a kitchen either means that there is another multi-tasking area assigned to cooking or that cooking is done with neighbors of the community or in

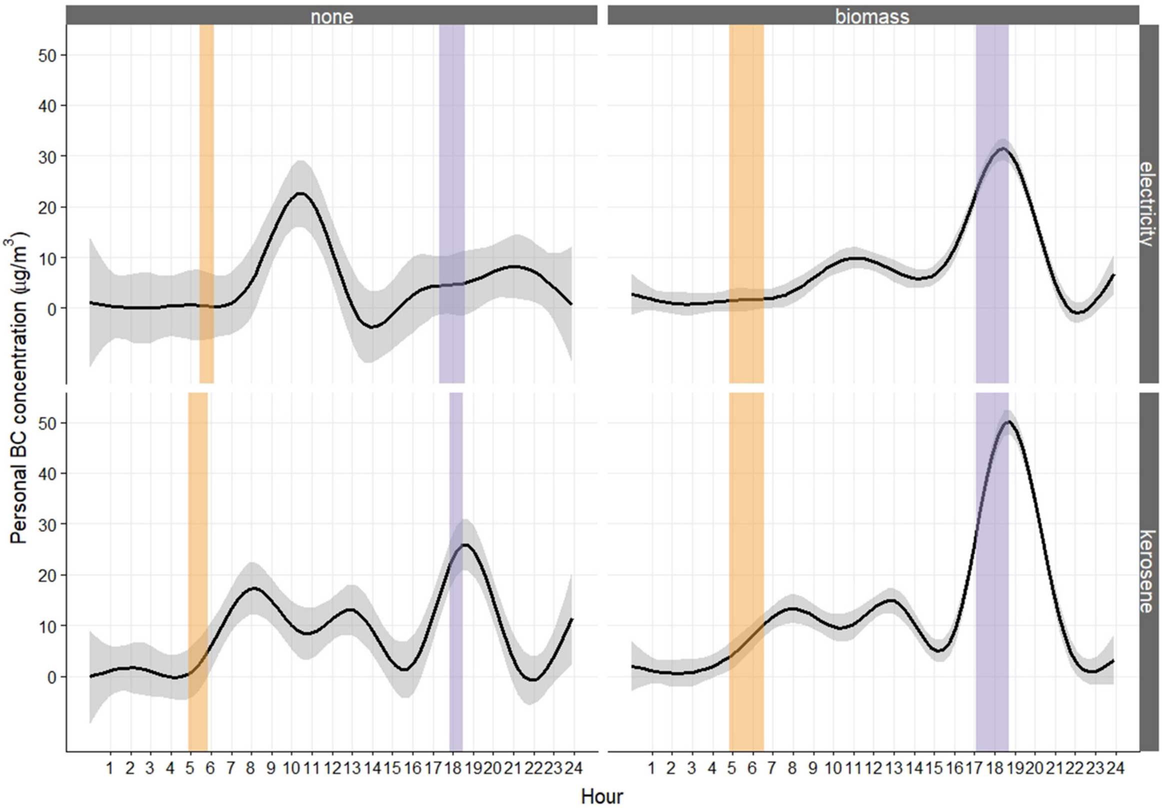

Fig. 4. Smoothed daily patterns of personal exposure to black carbon (BC) according to type of cooking fuel used during monitoring (top; none used vs. biomass) and usual lighting source (right; electricity vs. kerosene). Sample sizes for each category are: n = 6 for none × electricity, n = 6 for none × kerosene, n = 65 for biomass × electricity, and n = 107 for biomass × kerosene.

Shaded grey bands around the smoothed lines represent 95% Confidence Intervals (calculated as ± 1.96 standard error). Vertical shaded areas represent the range of sunrise (in orange; "am" period) and sunset (in purple; "pm" period) times during the sampling days in each category.

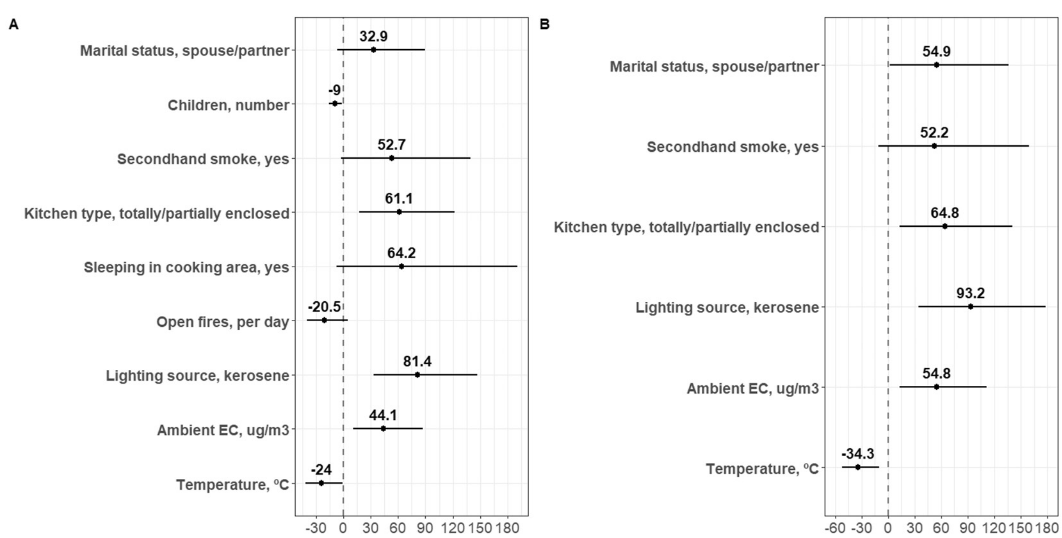

Fig. 5. Regression coefficients expressed as percent (%) relative change and 95% Confidence Intervals of selected predictors of personal mean (panel A) and 90th percentile (panel B) exposure to black carbon (BC) in women.

EC: elemental carbon. Reference categories are: single/widowed/divorced (for marital status), no (for secondhand smoke in the household), open-air kitchen (or not having one) (for kitchen type), no (for sleeping in the cooking area), and electricity (for lighting source). Ambient EC is expressed in 1 µg/m^3 increase and temperature in 5 °C increase. Analysis was based on complete cases (175 women). Estimates are from two different models containing all variables simultaneously: model panel A (i.e., BC mean ~ marital status + number of children + secondhand smoke + kitchen type + sleeping in cooking area + open fires + lighting source + ambient EC + temperature) and model panel B (i.e., BC 90th percentile ~ marital status + secondhand smoke + kitchen type + lighting source + ambient EC + temperature). Mean and percentile models explained 21% and 20% of variation, respectively.

farm plots, as reported before in rural Ghana (Van Vliet et al., 2013).

4.4. Temperature and family-related predictors

We also found temperature to be a relevant predictor of personal BC exposure. Given the strong seasonal pattern in cooking behaviors, cooking outside is more likely in warm weather, potentially explaining the observed lower personal BC values with increasing temperature. In colder temperatures, not only is cooking more likely to happen indoors, but more mass of fuel can be used and open fires may be burned longer for warmth (Dionisio et al., 2012). We lacked data regarding where participants cooked during sampling (indoors vs. outdoors), the amount of fuel used, and fire duration, preventing further exploration of the effect of temperature.

A greater number of people living in a household generally means more cooking and more exposure, especially for the primary cook. This may explain why we observed increased mean personal BC exposure among women with spouse or partner. However, we observed a modest, but significant association between increased number of living children of the participant and lower personal exposure to BC. This may reflect the greater likelihood of an older child taking on some of the cooking responsibilities, leading to lower exposure in the mother. We do not have the required information to directly assess this hypothesis (e.g., who was the primary cook during monitoring, the age or sex of the children, if children were living or not in the household).

4.5. The role of kerosene-based lighting

Our study indicates that kerosene contributes substantially to personal BC mean and peak exposures. We are not aware of previous studies considering time-resolved personal levels of BC in relation to lighting sources. However, there are four studies that considered time-integrated personal levels of BC or similar measures in rural low-middle income areas (Baumgartner et al., 2014; Rajkumar et al., 2018; Van Vliet et al., 2013; Downward et al., 2016). Van Vliet et al. (2013) found that women in rural Ghana who used kerosene lamps had 4 μg/m^3 higher personal and kitchen concentrations of BC than those who did not, although their limited sample size (n = 35) impeded the use of multivariable regression analysis. In contrast, Baumgartner et al. (2014) and Downward et al. (2016) studies had larger samples of rural Chinese women (280 and 163, respectively), but they did not explore the role of lighting, focusing instead on other relevant local sources (e.g., traffic, coal production). Rajkumar et al. (2018) focused on types of cookstoves, and found women using traditional stoves in rural Honduras had much higher daily personal BC levels (24 μg/m^3) than women using a cleaner local stove (7 μg/m^3).

4.6. Ambient levels

We observed 12% of the daily ambient (or outdoor) particulate levels exceeding those recommended by the WHO (> 25 μg/m^3). As expected, seasonality shaped the variation of particulate levels, with much lower 24-h concentrations during the rainy season which may reflect increased wet deposition or lower resuspension of PM (Rehman et al., 2011). Our $PM_{2.5}$ mean level (13 μg/m^3) is consistent with the relatively low satellite-based concentrations observed across Mozambique (from 4 to 18 μg/m^3) (Anenberg et al., 2017). Our annual EC mean level (0.9 μg/m^3) can be considered low if compared to levels found in urban Kenya (20 μg/m^3) (Gatari et al., 2019) and moderate if compared to levels observed in southern European cities (1.5 μg/m^3) (Amato et al., 2016). However, ambient air quality in SSA is expected to further worsen in the near future due to multiple factors, including an expected increase in vehicle ownership and urban and industrial expansion (Amegah and Agyei-Mensah, 2017). Facilitating access to clean household energy has been proposed as an effective way to reduce ambient levels, since combustion of residential fuels can account for 38% of ambient $PM_{2.5}$ levels in some settings in southern SSA (Chafe et al., 2014).

4.7. Alternatives to kerosene-based lighting

Facilitating access to electricity has been linked to improvements in indoor air quality (Barron and Torero, 2017; Apple et al., 2010). An experimental study in Kenya assessed indoor $PM_{2.5}$ concentrations and emission rates from different lighting appliances used by night kiosk vendors (Apple et al., 2010). They found that vendors could reduce their daily occupational $PM_{2.5}$ intake up to 80% by switching from fuel-based lamps to electricity. In a rural electrification program in El Salvador, $PM_{2.5}$ was measured overnight in the main living area of 150 households using kerosene lamps for lighting (Barron and Torero, 2017). In El Salvador, households receiving voucher discounts for connecting to the electric grid had 66% $PM_{2.5}$ reduction when compared to non-voucher recipients. These reductions in $PM_{2.5}$ indoor levels are larger than those observed in improved cookstove intervention studies, ranging from 48% for cookstoves without chimney to 63% for cookstoves with chimney (Pope et al., 2017), which highlights the potential for interventions aimed to replace fuel-based lighting in reducing exposure and associated health effects.

Grid-independent or off-grid lighting systems are increasingly implemented as cleaner alternatives to fuel-based lighting (World Bank, 2018). This is the case of mini-grids (< 10 MW) powered with local renewable resources and household lighting systems based on light-emitting diodes (LED) (Mills and Jacobson, 2011) and solar-powered lamps (Dalberg Global Development Advisors, 2013; Palit and Singh, 2011). Indeed, solar lamps provided the lowest $PM_{2.5}$ living room concentrations in Uganda when compared to other kerosene-fuelled appliances (Muyanja et al., 2017) and reduced 48-h personal $PM_{2.5}$ concentrations by 52–73% in Kenya (Ngo et al., 2015). Little is known about the potential health benefits of switching to cleaner lighting alternatives. However, a previous study conducted in Nepal found that kerosene-based lighting was three times more associated with tuberculosis than kerosene-based cooking (Pokhrel et al., 2010). Compared to cookstoves, kerosene lamps are less energy-demanding and usually used for longer and carried from place to place, increasing exposure and effective intake fraction (Pokhrel et al., 2010).

4.8. Strengths and limitations

A key strength of this study was the use of a time-resolved monitor to provide daily patterns of personal exposure to BC in a quite large sample of women from semi-rural Mozambique. In addition to insights regarding personal exposure, our study provides data on ambient levels of $PM_{2.5}$, EC, and OC throughout a year, which allowed us to evaluate the contribution of ambient EC to personal BC. In many countries in SSA air quality monitoring data are sparse and limited to urban areas (Amegah, 2018). However, our results of the contribution of ambient EC to personal BC should be interpreted with caution since our outdoor air measurements are not equally representative of ambient levels for all residents. We located the air sampler near the CISM facilities for security and accessibility reasons and to guarantee continuous electricity supply. Participants living in the "Manhiça" subdivision (Fig. 1) were living relatively close to CISM (< 5 km); however, participants living in other subdivisions (78%) were farther (≥ 20 km) and could be affected by other local emission sources not captured by the monitor.

The limitations of the study include the low variability in the type of cooking fuel used, which limited our ability to directly assess the influence of cooking fuel on personal BC exposure. Another limitation of our study is the high proportion (27%) of women with saturation of the filters over the sampling period, which typically occurs after high-intensity polluting episodes. When filter is overloaded, BC data is usually excluded to minimize bias, even at conservative cutoff limits (e.g., ATN < 75). As women with filter overloaded were the most exposed to

BC, we included them in analyses to minimize selection bias. Although BC concentrations of these women are likely to be underestimated, we corrected BC measurements using a standard equation previously applied in literature to minimize this bias (Good et al., 2017; Kirchstetter and Novakov, 2007). We lacked objective data regarding participant compliance wearing the BC monitor; relying on self-reported compliance is a potential source of exposure measurement error, but is unlikely to explain our results regarding predictors of exposure. To better explore the impact of kerosene-based lighting, ambient levels and temperature in personal exposure, our study would have benefited from more detailed questions related to the number and type of lighting appliance used (e.g., open wick, *candeeiro de vidro*), the starting time and duration of appliance use during sampling, where cooking took place (indoors vs. outdoors) and for how long the fire kept burning, and other potential combustion-related characteristics influencing personal BC exposure in this area (e.g., heating source, cookstove type, time spent daily in cooking, hours of local traffic jams and agricultural field burning).

4.9. Future studies

We used a new single filter for each woman, but in the light of our saturation issues, future studies in low-income areas with similar characteristics should consider alternative approaches to prevent filter saturation (e.g., frequent filter exchange). Future studies would also benefit from objective measures to assess wearing compliance (e.g., accelerometer) and exposure determinants through direct observation or measurement (e.g., weighting fuel pre- and post-monitoring) (Downward et al., 2016) and the use of low-cost sensor technology (e.g., the use of button-size temperature loggers to assess kerosene lamps usage) (Lam et al., 2018).

5. Conclusions

We observed high personal BC concentrations among women of childbearing age in semi-rural Mozambique, where there is limited access to clean household energy. Kerosene-based lighting was prevalent (62%) and appears to be an important source of personal BC exposure in this population. These results support the need to facilitate access to clean sources of energy for lighting to reduce the adverse climate and human health impacts of combustion particles.

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Declaration of Competing Interest

Authors have no competing interests to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.104962.

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