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Contrasting indoor and ambient particulate matter concentrations and thermal comfort in coal and non-coal burning households at South Africa Highveld

J.A. Adesina [a,*], S.J. Piketh [a], M. Qhekwana [a], R. Burger [a], B. Language [a], G. Mkhatshwa [b]

[a] Climatology Research Group, School of Geo- and Spatial Science, Unit for Environmental Science and Management, North-West University, Potchefstroom 2520, South Africa
[b] Eskom, Air Quality, Climate Change, and Ecosystem Management Research, Research Testing, and Development, Cleveland, 2022, South Africa

HIGHLIGHTS

- PM_4 measurement was carried out in two households in a community located in the proximity of three coal-fired plants.
- National Ambient Air Quality Standard was exceeded in both houses during the winter.
- SFB house recorded PM_4 indoor concentration higher than the NSFB during the winter season.
- The indoor/outdoor correlations for PM_4 were significant in summer.
- NSFB house experienced thermal comfort in both summer and winter while the SFB house did not.

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GRAPHICAL ABSTRACT

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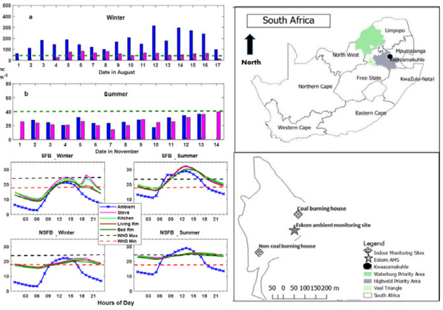

ABSTRACT

One of the key challenges noted in the sustainable development goals for good health and wellbeing (SDGs 3) is both ambient and household air pollution. Household solid fuel combustion represents one of the biggest threat to human health in South Africa. This study helps to understand the impact of solid fuel burning in an indoor and ambient environment. Continuous monitoring of particulate matter (PM_4) was carried out in two houses, one used coal as a primary source of energy, while the other did not. For solid fuel burning (SFB) house the winter PM_4 average 24-h concentration ranges between 60.9 $\mu g\,m^{-3}$ and 207.5 $\mu g\,m^{-3}$ while at non-solid fuel burning (NSFB) house it ranges between 15.3 $\mu g\,m^{-3}$ and 84.2 $\mu g\,m^{-3}$. In both houses, the national ambient air quality standard (NAAQS) for PM2.5 (40 $\mu g\,m^{-3}$) were exceeded during winter. The summer PM_4 levels ranged between 17.4 $\mu g\,m^{-3}$ and 36.6 $\mu g\,m^{-3}$ in the solid fuel burning house and between 14.2 $\mu g\,m^{-3}$ and 39.9 $\mu g\,m^{-3}$ at the non-solid fuel-burning house. During mornings and evenings, indoor concentrations were higher than the outdoor; these periods coincide with the fuel-burning pattern in this community. In the mid-afternoon, the outdoor PM levels sometimes went higher than the indoor levels, perhaps as a result of the pollution from the power plants in the neighbourhood. Using the linear regression model, there were no significant correlations between indoor/outdoor PM_4 concentrations during the winter, but there were good correlations for both houses during the summer. There was an observed difference in the thermal comfort at the SFB and NSFB. The temperature at SFB went below the World Health Organisation standard in winter and above during the summer while at NSFB, the temperature was managed within the standard in both seasons.

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* Corresponding author.
E-mail address: joseph.adesina@nwu.ac.za (J.A. Adesina).

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1. Introduction

Research has consistently shown that particulate matter (PM) is detrimental to human health (Bruce et al., 2015; Cohen et al., 2017; Jimoda, 2012; Ng et al., 2014). In particular, the use of solid fuels for household cooking is hazardous to human health, causing both diseases and premature deaths (Lim et al., 2012). The World Health Organization estimated that about 3 billion people use fire from biomass, kerosene, and coal. This inefficient cooking is claimed to be responsible for about 4 million premature deaths each year (WHO, 2018). It has been known that apart from the health risks, global climate change and environmental impacts result from PM emitted into the atmosphere (Edwards et al., 2004; Tai et al., 2010). Though the number of people having access to electricity fell from 1.7 billion in 2000 to 1.1 billion in 2016, electrification in sub-Saharan Africa is just 43% (IEA, 2017). While in Europe, America and Western Pacific the population relying on solid fuel for cooking was found to decrease between 1980 and 2010, in Africa, the population dependent on solid fuels is increasing (Bonjour et al., 2013). The 2019 progress report on sustainable development goals (SDGs Goal 3) shows that there has been a major improvement to human health as the fight against communicable diseases, maternal and child mortality are now yielding positive results. Nevertheless, the report stated that both ambient and household air pollution led to the death of about 7 million worldwide in 2016 and that sub-Saharan Africa has the highest mortality rate. The high mortality rate was associated with the large population that still rely on polluting fuels for cooking (UN, 2019).

In developing countries, low-income communities are subject to elevated health risks due to their exposure to high concentrations of PM (Barnes et al., 2009; Bruce et al., 2000; Mdluli, 2008). Previous studies have found that poor air quality persists throughout the year in these communities. A diverse set of local sources, including, solid fuel combustion, dust entrainment, biomass burning, vehicular emissions, indiscriminate waste burning, and industrial sources contribute to the air pollution (Annegarn et al., 2002, 1998; Mdluli and Vogel, 2010; Scorgie et al., 2003; Worobiec et al., 2011). Since most low-income community dwellers cannot afford the cost of electricity or other forms of clean energy, they resort to the use of wood, agricultural residue, coal and animal dung for cooking and space heating (Masekoameng, 2014; Mugabo, 2011; Nkomo, 2005). Indoor air pollution results in high levels of exposure to the inhabitants due to the high intake fraction of the pollutants that are emitted into the house directly (Burger et al., 2015; Diapouli et al., 2011; Ferro et al., 2004; Lim et al., 2012). The fuel type also is a significant determinant of the emissions. In South Africa, wood and coal are the two dominant fuel types (Nkosi et al., 2017). The use of coal is very prevalent around the Highveld due to the presence of numerous coal mines (Langerman et al., 2018).

In addition to emissions to the atmosphere, southern Africa is also situated under the tropical atmospheric circulations (Hadley cells), resulting in persistent subtropical anticyclonic circulation and thus widespread atmospheric stability causing air circulation to be resisted (Piketh et al., 1999; Tyson et al., 1996a, 1996b). The vertical mixing over the interior plateau is inhibited by absolutely stable layers causing increasing concentrations of PM and other pollutants (Freiman and Piketh, 2003; Seinfeld and Pandis, 2016; Zunckel et al., 2000). Over the South African Highveld region, surface inversions (100–250 m AGL) occur almost every night (Held, 1996; Parker and Raman, 1993). The consequence of this is that of elevated PM concentration since emitted particles are trapped below the boundary layer (Alade, 2011; Seinfeld and Pandis, 2016).

South Africa has declared three Air Quality Priority Areas (Fig. 1), one of which is the Highveld Priority Area (DEA, 2007). These areas currently or are likely shortly to exceed the ambient air quality Standards (DEA, 2016). The Highveld Priority Area (HPA) is characterized by high concentrations of industrial and non-industrial pollutants (Garland et al., 2017; Hersey et al., 2015; HPA, 2016). To combat the challenges arising from the poor air quality in South Africa, the Department of Environmental Affairs put forward the option for air quality offsets. Offsets are atmospheric emission reduction tools meant to counterbalance the undesirable environmental degradation activities (Suvantola, 2005). The main goal is to lower the ambient concentrations of atmospheric pollutants and improve thermal comfort in the household environment. These offsets were published as Air Quality Act amendments in relation to National Environmental Management (Government Notice No. 33 on 18 March 2016 and updated in 2017).

Four main factors are considered in evaluating comfort in the indoor environment: visual, acoustic, indoor air quality and thermal (Pereira et al., 2014). Thermal comfort cannot be adequately assessed by the ambient temperature alone, especially in wintertime (Nguyen et al., 2014). World Health Organisation (WHO) recommended a standard range of temperature for thermal comfort with a minimum of 18 °C and maximum of 24 °C (WHO, 1987).

Major industries that produce air pollutants in the HPA were required to implement these offsets by 2025 in about 40,000 households (Eskom, 2017). Langerman et al. (2018) reported on a

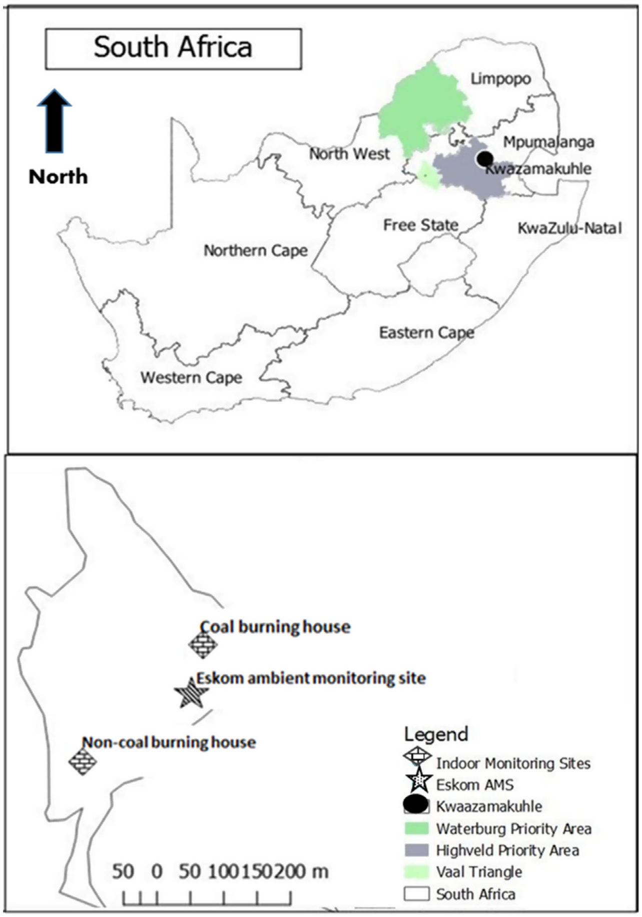

Fig. 1. Location of KwaZamokuhle a low-income settlement in Mpumalanga Highveld Priority Area with an expanded view of the relative spatial distribution of households in which sampling was undertaken during winter and summer 2017.

Table 1
Classification of the households where sampling took place in Kwazamokuhle during winter (August 1–17, 2017) and summer (November 1–14, 2017).

House type	Interior finishing	Number of occupants	Energy carriers	Nearby outdoor PM4 sources	Study classification
Formal RDP	Ceiling, plastered walls	4	Electricity	Next to unpaved road	NSFB
Formal RDP	No ceiling, walls not plastered.	3	Electricity, coal, wood.	Waste burning	SFB

pilot study conducted in 2015 at Kwazamokhule and Hendrina to ascertain the effectiveness of these offsets. Their study supported the efficacy of these offsets but wondered if the number of limitations involved can be overcome soon.

This Highveld Priority Area includes nine local municipalities, three district municipalities, and one metropolitan city. The area is known for high concentrations of pollutants from commercial, industrial and domestic sources (Alade, 2011). Kwazamokhule village, located in eastern of the priority area (Fig. 1) was selected as the study location, as it is representative of both socio-economic and environmental factors related to the poor air quality. It is within the impact zone of power stations, making it very suitable for the study. In a recent investigation, Chidhindi et al. (2019) modeled the contributions of three nearby coal-fired plants to the concentrations of pollutants measured at Kwazamokuhle. Their results showed a 13% contribution to SO_2, 17% NO_X and just 0.2% of $PM_{2.5}$-from the power pants, indicating that almost all the $PM_{2.5}$ in the township may be from other sources, probably from anthropogenic activities such as solid fuel combustion within the community. In terms of Urban Environmental Health Interventions towards the Sustainable Development Goals (SDGs), this study will further help to understand better the relationship between the indoor and outdoor PM concerning the type of energy (electricity and coal combustion) used in households.

2. Site description and experimental procedure

2.1. Site

KwaZamokuhle (26.1338° S, 29.7339° E) is situated in the Mpumalanga Province of South Africa (Fig. 1). The township is located between two trade centres, Middleburg 48 km North-North-East (NNE) and Ermelo 50 km South-West (SW). The settlement has a population of ~20,400 people with 5874 households. It has an ambient monitoring station which provides measurement for the ambient concentrations of criteria pollutants. Two similar Rural Development Programme (RDP) houses were selected as the experimental sites (Table 1). These are government structures consisting of a kitchen area joined to a living room, bedroom (one or two), two doors and five windows. The roof is made of corrugated iron but without ceiling and the wall is constructed of concrete blocks without plastering. The monitoring took place simultaneously in the two houses. The NSFB house uses electricity as their main energy carrier having plastered walls and ceiling. The SFB, on the other hand, has neither plastered wall nor ceiling and depend solely on the use of solid fuel combustion, in particular coal.

2.2. Particulate matter measurements for the Indoor environment

The mass concentration of indoor particulate matter was continuously measured using the SidePak AM510 (TSI Incorporated, Shoreview, MN, USA) single-channel photometric instruments (TSI, 2012). The laser diode is operated at a wavelength of 670 nm. The instrument records particle size ranges from 0.1 to 10 μm and an aerosol concentration range from 0.001 to 20 mg m^{-3}. The temperature and relative humidity operating ranges of the instruments were 0 to 50 °C and 0 to 95%, respectively, making it suitable for use in South African conditions. The monitors were factory calibrated by the manufacturer to the respirable fraction of Arizona test dust (ISO 12103-1). The SidePak AM510 has interchangeable impactors. However, sampling for this study focused on respirable participles (PM_4) and was thus conducted using the 10 mm nylon Dorr-Oliver cyclone inlet. The inlet required a flow rate of 1.7 L min^{-1} ± 5% to obtain the 50% cut point for the 4 μm particle size fraction (Sensidyne, 2003). A five-minute logging interval was selected. The shorter averaging period allowed for the detection of subtle changes in particulate loadings over the sampling period.

Before and during deployment periods the instruments were checked according to manufacturer specifications: i) factory calibration checks, ii) leak tests, iii) flow calibrations, iv) zero calibrations, and v) general instrument settings check (date, time, logging interval, set calibrations).

Data were downloading coincided with maintenance and site visits. Data were retrieved from the instruments as ASCII text files using the TrakPro™ software (TSI, 2019). Measurements above the upper limit of detection were removed from the data. Data in this study have been corrected with a previously calculated photometric correction factor of 0.715 for a similarly characterized settlement (Language et al., 2016). The PM_4 has been shown to be approximately equal to $PM_{2.5,}$ and so will be used as a reference for discussion purposes (Language et al., 2018; Piketh et al., 2018). Moreover, in this study, we compared $PM_{2.5}$ measured from a local ambient monitoring station with the outdoor PM_4 measurements, and the result shows no significant difference.

2.3. Outdoor environment particulate measurements

The MetOne ES-642 instrument was used to measure particulate concentration outside the two houses simultaneously. It uses a highly sensitive forward scatter laser nephelometer to measure real-time particulate concentration, having a measurement range of 0 to 1000 μg m^{-3}. The instrument was also operated with a Dor-Oliver cyclone inlet with the same article cut-size. The accuracy of the instrument is ±5% based on a traceable PSL 0.6-micron reference standard (MetOne, 2011). Four ES-642 were placed outside the houses used for the study to establish the ambient concentrations of PM4 and to determine if ambient PM4 levels had a directional bias due to sources located upwind. Instruments were placed in each of the four main cardinal wind directions (north, south, east and west) of the houses.

2.4. Temperature and relative humidity monitoring

Thermochron® iButton RS1923I-F5 temperature and relative humidity sensors were installed in the living room, bedroom and kitchen and stove of each house at 1.6 m above the floor. The multiple room sensors were intended to assess the thermal comfort experienced within the house environment. In addition, a sensor was placed at a distance of 10 cm from the chimney of the solid fuel burning stove to detect when the stove was in use. Placing the sensor a few centimetres away from the chimney prevents the plastic casing of the sensor from being damaged by direct contact with the hot chimney, but is close enough to identify when the stove is in use. The south-facing, external wall of each house was allocated an iButton to record the outdoor ambient temperatures.

The temperature sensors have a range of −20 to 85 °C at a 0.5 °C resolution with a temperature precision of ±0.5 °C and timing precision of ±2 min per month. ColdChain TD Multiprofiler CTMD software was selected as an interface for programming and downloading the data from the sensors. The sensors logged temperatures and humidity at 10-minute intervals.

2.5. Statistical analysis

The ratio between indoor and outdoor concentration is a tool that can be used to evaluate the difference between both (Huang et al., 2007; Li and Lin, 2003). The I/O relationship is usually considered not to be enough evidence of the relationship between indoor and outdoor concentrations (Bennett and Koutrakis, 2006). Using a linear regression model is regarded as a better approach (Mohammadyan et al., 2017; Wichmann et al., 2010). The coefficient of determination (R^2) can be used to explain to what degree the outdoor is affected by the indoor concentration. The slope of the regression line corresponds to the fraction of the indoor-generated PM_4 passing through the vents to the outdoor environment while the intercepts are taken as the contributions from other sources (Diapouli et al., 2011). Particles of small aerodynamic diameter are expected to easily penetrate through gasp in the walls (Clayton et al., 1993; Nazaroff, 2004) while a larger percentage exit through the chimney. We, therefore used the Pearson paired *t*-test to explore this.

3. Results and discussion

3.1. Seasonal indoor PM4 concentration

3.1.1. Diurnal variation of PM4 concentration

The diurnal variation of the indoor PM_4 levels for NSFB and SFB houses during winter and summer are shown in Figs. 2 and 3, respectively. In South Africa, winter sets in from May and through to August, while summer sets in from November through to February (SA, 1997). There is a bi-modal peak in the PM_4 concentrations identified during both seasons although the peak is more pronounced during the winter and particularly at SFB. During the winter, in the NSFB, the PM_4 levels increased between 03 h00 and 07 h00 (peaking around 05 h00 at ~130 μg m^{-3}) and between 15 h00 and 18 h00 in the evening (peaking around 16 h00 at ~220 μg m^{-3}) while at SFB there was increment between 05 h00 and 10 h00 (peaking around 08 h00 at ~500 μg m^{-3}) and in the evening between 17 h00 and 23 h00 (peaking around 19 h00 at ~1200 μg m^{-3}). Thus, there was an increased particulate loading for approximately 7 h period during morning and evening at NSFB and about 11 h period at SFB. The maximum concentration at SFB is four times higher than that at the NSFB during the morning peak and about five times during the evening peak. The extended increment of PM_4 in the evening could be attributed to space heating activities taking place at night during winter.

During the summer these peaks are less pronounced, even though they are identifiable. At NSFB the increased concentration occurs between 04 h00 and 08 h00 (peaking around 06 h00 at ~40 μg m^{-3}) and in the evening between 17 h00 and 21 h00 (peaking at 18 h00 at ~90 μg m^{-3}). At SFB the concentration increased between 05 h00 and 09 h00 (peaking around 07 h00 at ~40 μg m^{-3}) and in the evening between 16 h00 and 21 h00 (peaking around 17 h00 at ~120 μg m^{-3}). There were eight and 9 h of increased PM_4 concentrations at NSFB and SFB, respectively.

3.1.2. Daily variation

The daily averaged indoor PM_4 indoor mass concentration for the two households are presented in Fig. 4. It shows that the 24-h average exceeded the NAAQS 24-h $PM_{2.5}$ standard of 40 μg m^{-3} on all the days captured at the SFB during the winter and most of the days at the NSFB. At SFB the concentration ranges between 60.9 μg m^{-3} to 207.5 μg m^{-3} while at NSFB it ranges between 15.3 μg m^{-3} and 84.2 μg m^{-3}. During the summer indoor concentration were cleaner with the 24-h average seldom exceeding the ambient air quality standard in both houses. The concentrations ranged between 17.4 μg m^{-3} and 36.6 μg m^{-3} in the SFB house and between 14.2 μg m^{-3} and 39.9 μg m^{-3} at the NSFB.

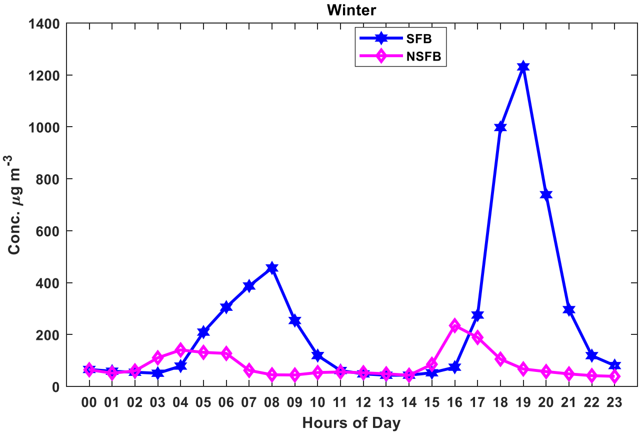

Fig. 2. Diurnal variation of the hourly mean indoor PM4 (μg m^{-3}) at NSFB and SFB houses. Sampling period fourteen days during winter (1–17 August 2017). Bars indicate one standard deviation.

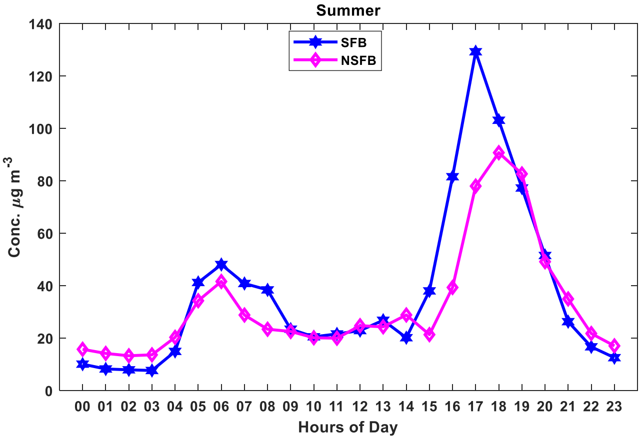

Fig. 3. Diurnal variation of the hourly mean indoor PM4 (μg m^{-3}) at NSFB and SFB houses. Sampling period fourteen days during early summer (1–14 November 2017). Bars indicate one standard deviation.

The SFB house during the winter recorded PM_4 concentrations higher than the NSFB for all the days. The levels were sometimes as high as five times that of the NSFB. The long hours of coal-burning were responsible for these high values. The situation was quite different in summer where the PM_4 concentrations at both houses were comparable. The residents of the SFB are, therefore, at greater health risk, especially during the winter.

3.2. Seasonal outdoor PM_4 concentration

The outdoor PM_4 mass concentrations were measured in each cardinal direction during winter and summer and are presented in Fig. 5(a & b), respectively. Eight ambient monitors were used for sampling out of which one developed a fault during the winter campaign while two developed a defect during the summer

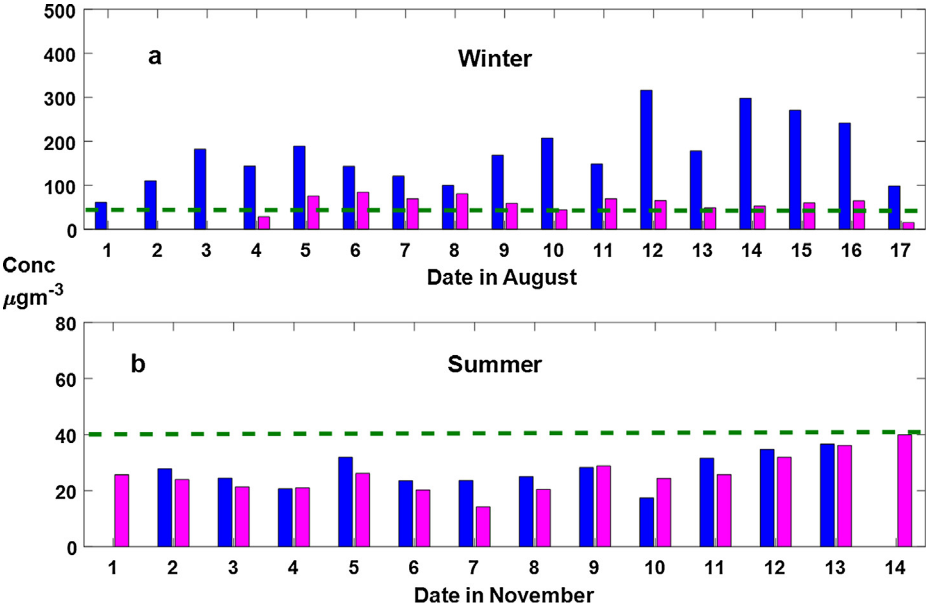

Fig. 4. Indoor daily average PM_4 concentrations at the NSFB and SFB households (a) during winter (August 1–17, 2017) and (b) summer (November 1–14, 2017). The green dotted line is the South African NAAQS 24-h PM2.5 at 40 µgm^{-3}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

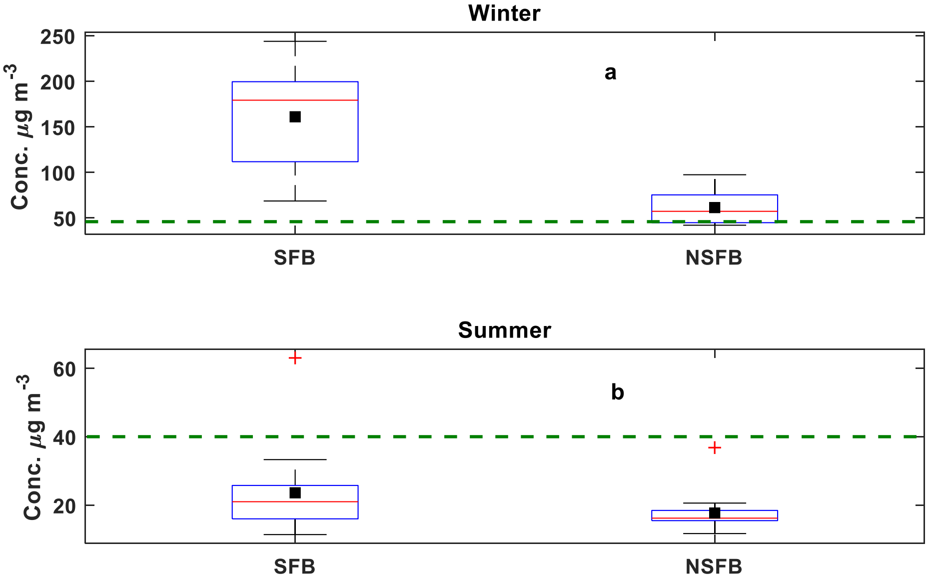

Fig. 5. The boxplot of the combined outdoor measurements at SFB and NSFB (a) Winter (b) Summer. The central red mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the red '+' symbol; black squares are mean; the dashed line is the South African NAAQS 24-h PM2.5 limit (40 µg m^{-3}). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

campaign. The measurements from all the outdoor instruments were averaged for each house and for different seasons. These are presented in Fig. 5(a & b), respectively. The recorded mean PM_4 concentrations were below the NAAQS of $PM_{2.5}$ 24 h average (40 µg m^{-3}) during the period. The mean concentrations of the PM_4 values of SFB were higher than that of the NSFB during the winter and both were above NAAQS. The difference may be attributed to the location of specific PM sources in close proximity to the houses. During the summer, the outdoor PM_4 concentrations were similar but lower than during the winter.

The diurnal outdoor PM_4 concentrations (Figs. 6 & 7) are similar to the indoor. The morning and evening peaks which corresponds to the burning pattern of the community are clearly seen at both seasons. During the burning episodes, the PM_4 concentrations were higher at SFB than that at NSFB. The high levels of PM_4 were recorded between 04 h00 and 08 h00 in the morning and between 15 h00 and 20 h00 in the evening. In addition to this, during winter we have a mid-afternoon peak at NSFB and at SFB during the summer. Since the coal-fired plants have been said earlier to make very little contributions of PM to the community, the mid-afternoon peak may be as a result of PM contributed from the vicinity of the measurement sites during the study period. Moreover, if the mid-afternoon peak was due to long-range transport of PM then it should be common to both sites.

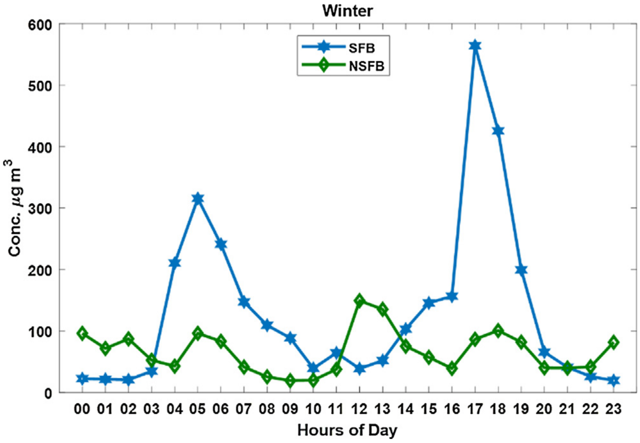

Fig. 6. Diurnal pattern of the combined mean hourly averaged outdoor PM_4 mass concentrations (µg m^{-3}) measured during winter at NSFB and SFB houses.

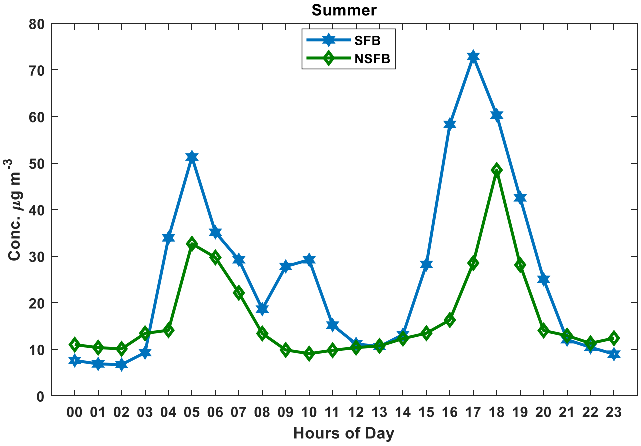

Fig. 7. Diurnal pattern of the combined mean hourly averaged outdoor PM_4 mass concentrations (µgm^{-3}) measured during summer at NSFB and SFB houses.

3.3. Indoor and outdoor relationships

The I/O ratios of PM_4 at both houses for both seasons range between 1.2 and 1.9 (Table 2). This ratio is lower during winter than summer at NSFB but higher during winter than summer at SFB. During the winter, the meteorology enhances the trapping of the emitted PM_4 as vertical dispersion is suppressed, and wind speeds are low (Langerman et al., 2018). This might particularly have contributed to the higher ratio at SFB during winter. Other related works found the ratio to be smaller, but in their cases, the source originates from outdoor rather than indoor (Funasaka et al., 2000; Riain et al., 2003).

In the linear regression model, R^2 was very low in winter at both houses. During this season, most houses have their ventilations like doors and windows closed most part of the day. During the summer when there was cross ventilation, R^2 were higher 0.66 and 0.79 at NSFB and SFB respectively. During the winter contributions from the surrounding to the outdoor PM_4 were higher at both houses than the summer as indicated by the intercept. The slope also showed that there was more exchange of flow between indoor and outdoor PM_4 during the summer than the winter. The good summer correlations were also seen in the low *p*-values unlike during the winter.

3.4. Contributions of criteria pollutants

We evaluated whether the criteria pollutants (PM_{10}, NO_2, O_3, and SO_2) measured at the monitoring station could be related to indoor measurements at both houses. To do this, we first checked if the $PM_{2.5}$ concentrations measured at the monitoring station is comparable to the PM_4 concentrations measured outdoors at the two houses using the Analysis of Variance (ANOVA). The F-value was less than the F-critical for the average concentrations of $PM_{2.5}$ measured the monitoring station compared to the PM_4 average concentrations measured outdoors at both houses during the seasons. We accepted the null hypothesis that the outdoor PM_4 concentrations for both houses were comparable to the $PM_{2.5}$ measured at the monitoring station. We then proceeded to find the statistical relationship between the hourly concentrations of the indoor measurements at each house and the ambient hourly concentrations of the criteria pollutants as measured from the monitoring station. Results (Table 3) shows that the criteria pollutants did not make any significant contributions to the indoor concentration of the PM_4. This result is similar to a study carried out in Beijing, where the criteria pollutants did not make any substantial contribution to the indoor $PM_{2.5}$ levels (Huang et al., 2015).

Table 2
The statistical relationship between the indoor and outdoor hourly mean measurements indicating the intercept, slope, p-value, R^2 and the indoor/outdoor ratio.

House	Period	Intercept	Slope	*p*-value	R^2	I/O
NSFB	Winter	80.1	0.0	0.95	<0.01	1.4
SFB	Winter	130.7	0.9	0.04	0.17	1.9
NSFB	Summer	1.8	1.8	<0.001	0.66	1.9
SFB	Summer	−1.4	1.5	<0.001	0.79	1.2

Table 3
Statistical relationship between the ambient concentrations of criteria pollutants PM_{10}, NO_2, O_3, SO_2 and the measured PM_4 indoor concentrations at NSFB and SFB.

Location	Pollutant	Winter				Summer			
		Intercept	Slope	R^2	*p-value*	Intercept	Slope	R^2	*p-value*
NSFB	PM_{10}	101.	0.080	0.004	0.80	59.1	−0.116	0.014	0.58
	NO_2	19.7	−0.018	0.006	0.87	7.35	−0.002	<0.001	0.91
	O_3	55.1	0.005	<0.001	0.96	80.0	0.153	0.019	0.52
	SO_2	65.5	−0.053	0.004	0.76	N/A	N/A	N/A	N/A
SFB	PM_{10}	118.	−0.053	0.038	0.36	60.0	−0.125	0.034	0.39
	NO_2	19.6	−0.001	0.022	0.48	7.32	−0.001	<0.001	0.93
	O_3	55.9	−0.001	<0.001	0.93	82.9	0.056	0.005	0.73
	SO_2	64.5	−0.013	0.010	0.64	N/A	N/A	N/A	N/A

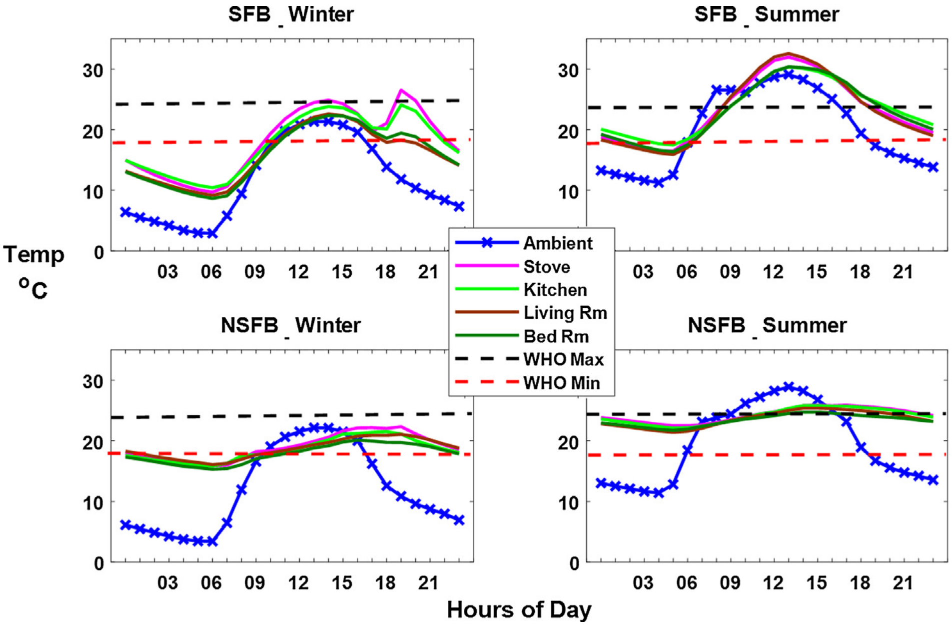

Fig. 8. Showing the mean indoor and ambient temperature measured during winter and summer at SFB and NSFB at various locations within the house. The black line (dotted) is WHO maximum temperature (24 °C), and the red line (dotted) is WHO minimum temperature (18 °C) guideline ranges for thermal comfort. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.5. Thermal comfort

The diurnal pattern of the measured ambient temperature at both houses using the temperature buttons showed variability with the hours of the day. During winter, the temperature is at a minimum at 07 h00 and peaks at 14 h00 (Fig. 8). Summer was a bit different with an earlier minimum at ~06 h00 a maximum at 15 h00. WHO recommended a range of 18 °C to 24 °C (WHO, 1987) for indoor thermal comfort. During the winter, the average indoor temperature at SFB was within the WHO range for about twelve hours (10 h00 to 22 h00). The summer indoor temperatures were different, in that they were mostly either lower or higher than the WHO recommended range. The temperature was higher from about 10 h00 to 20 h00 and lower from 04 h00 to 7 h00, making about eleven hours of temperature falling within the WHO range.

At the NSFB house, the average indoor temperature was maintained at a value above the recommended minimum standard during the winter except for a few hours of early morning. During summer, the average indoor temperature was maintained within an acceptable standard of minimum comfort also. The thermal comfort enjoyed at NSFB could be explained in terms of the air quality offsets. This gave access to electricity for space heating and the house ceiling which conserves heat within the house.

The average indoor temperature in the SFB during the winter followed the temperature of the stove closely. The stove temperature suggests that burning stops sometime around 00 h00 and consequently the indoor temperature drops below the 18 °C mark till it reaches a minimum of 8.6 °C. For approximately 10 h (00 h00 to 10 h00), the occupants were exposed to thermal discomfort. This may be due to lack of money to buy enough coal to keep up the space heating. During the summer the indoor average temperature went as high as 32.5 °C during the day and temperature generally above 25 °C from 10 h00 to 20 h00 (10 h) even when the ambient temperature has gone down it takes quite a while for the indoor temperature to come within the thermal comfort range.

4. Conclusion

Two RDP houses were selected to study the relationship between indoor and outdoor PM_4 concentration. One of the houses relied solely on solid fuel combustion while the other used electricity. The measurements were carried out during the winter and summer seasons, indoors and outdoors to determine if there exists a significant difference between the PM_4 indoor and outdoor concentrations. The study has revealed that during the summer when solid fuel is burnt infrequently, the indoor concentrations in both houses were similar, whereas, during the winter when large quantities of solid fuel are consumed for space heating, the levels can be higher by factors between two and five at the SFB house. The diurnal variations of indoor levels show a bimodal pattern coinciding with the cooking pattern in the community (i.e. morning and evening).

Due to high ambient pollution in the community during the winter (as most houses burn solid fuel) and meteorological conditions not favouring dispersion of pollutants, there was no significant correlation between the indoor and the ambient PM_4 concentration at both houses. During the summer, when there was a cleaner ambient environment coupled with favourable meteorological conditions, there were significant relationships between the indoor and outdoor PM_4 concentrations at both houses.

The thermal comfort was very low at the SFB house, where there were neither ceiling nor plastering of the walls, and where space heating is effected by solid fuel burning. The indoor temperature went below the WHO minimum standard for many hours during the day/night. During the summer, it went above the maximum limit for several hours, unlike the NSFB, where the indoor temperature was maintained for many hours within the WHO standard either during the winter or summer. Hence there is a need for environmental health interventions in this community and such communities in South Africa and sub- Saharan Africa in general.

Conflicts of interests

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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