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# Cool roofs: High tech low cost solution for energy efficiency and thermal comfort in low rise low income houses in high solar radiation countries

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ABSTRACT

Cool roofs are most effective in reducing cooling loads and alleviating overheating in locations with high solar radiation and external air temperature. This paper presents results of an experimental study of a low income house in Jamaica and a computational study in three countries around the equator: Jamaica, Northeast Brazil (Recife) and Ghana. A case-study typical of single storey houses in Jamaica was monitored before and after the installation of a cool paint on the roof; on days with average solar radiation intensity of ~420 W/m$^2$ and ambient air temperature of ~28 °C, internal ceiling surface temperature is reduced by an average of 6.8 °C and internal air temperature by 2.3 °C. Monitoring results were used to calibrate successfully an EnergyPlus model; similar models were developed for Ghana and Brazil differing in size and/or construction to reflect country specific practices. Annual simulations indicate that internal ceiling surface temperatures are reduced on average by 3.2–5.5 °C and internal air temperatures by 0.75–1.2 °C. Cooling demand simulations (setpoint 24 °C) indicate similar annual potential savings in the three locations (~190 kWh/m$^2$/year) although estimated $CO_2$ emissions reduction differ reflecting electricity generation fuels. Aging of the cool roof has an impact reducing load savings by 22–26 kWh/m$^2$/year.



## 1. Introduction

Many factors influence the energy demand of a building including its purpose, intended use and location. The thermal properties of the materials used for the external walls and roof can have a major influence on the surface temperature and in turn the amount of heat conducted through the surface of the building. A cool building surface (roof and/or walls) uses a coating with high thermal emissivity and solar reflectance properties to decrease the solar thermal load of a building thus reducing its energy requirements for cooling. Many experimental and modelling studies have been published that compare building energy efficiency benefits of cool roofing techniques [1–3] with computational and experimental studies reporting positive results for residential buildings [4–6].

Most studies focus on the improvement of residential buildings in well developed economies driven by legislation to reduce $CO_2$ emissions by buildings [7,8]. There are few studies focussing on areas where poorly insulated buildings combined with high solar radiation levels create uncomfortable internal conditions for the most vulnerable populations [9,10]. When these populations can afford it, they install add-on air conditioning systems which increase electricity demand. Therefore additional evidence from intervention studies and climate related design guidance is needed to demonstrate the effectiveness of cool roofs as their performance depends both on climatic conditions and the characteristics of the building stock.

Cool materials are most effective in locations with high solar radiation and external air temperature. This paper presents results of an experimental and computational study for low income houses

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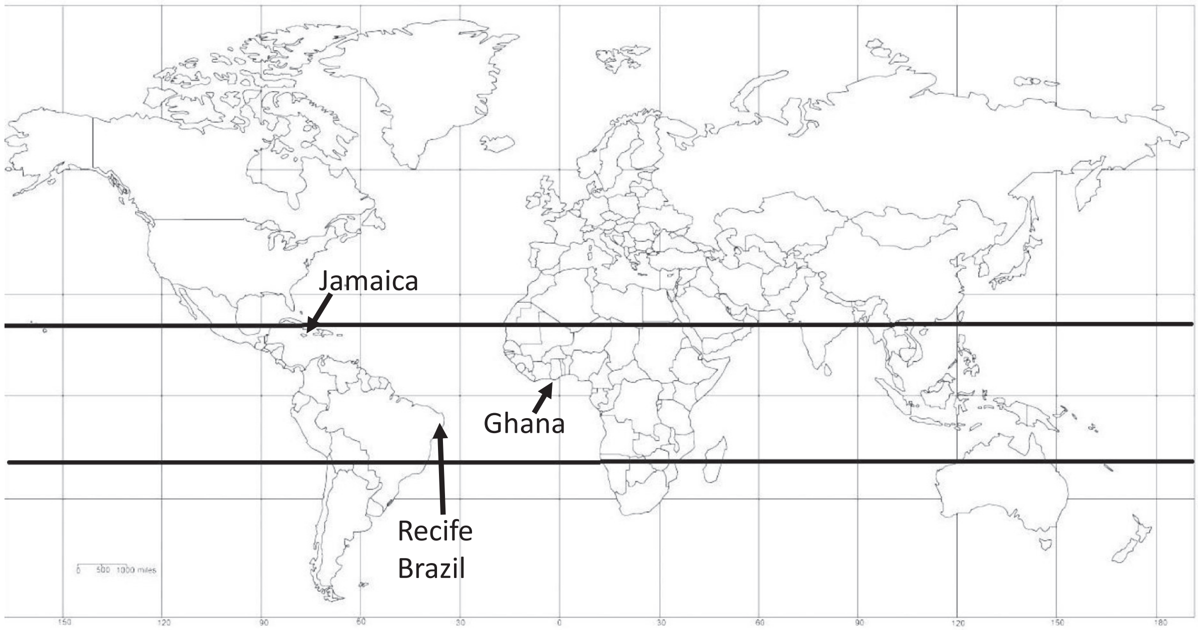


**Fig. 1.** Location of case-studies.

in one country, Jamaica, and computational studies in another two countries with tropical climate: Northeast Brazil (Recife- Pernambuco State) and Ghana (Fig. 1). The targeted countries are around the equator with high solar radiation intensity throughout the year (4–6 kWh/m$^2$) and high external air temperatures leading to high cooling demand in buildings or overheating conditions especially in poorly insulated buildings where cool materials are most effective [11]. In Brazil, voluntary building guidelines [12] recommend a U-value of up to 2.00 W/m$^2$·K while in Ghana and Jamaica even higher values are derived due to the lack of insulation in the concrete/brick walls and concrete/metal roofing. There is evidence that overheating is experienced in buildings in these countries and add-on air-conditioning is installed where it is affordable. However, in some cases (Jamaica) high electricity rates (48% increase between 2010 and 2014) prohibit air-conditioning due to operational costs even if capital costs were affordable [13] while electricity power cuts are common in some countries. Studies suggests that a 25% cooling energy demand reduction is possible in non- residential buildings located in the targeted regions. [11].

This paper first presents an intervention experiment in a house in Jamaica (Portmore). The house was monitored before and after the application of the cool roof paint. Data from the experiment were used to calibrate a model developed using EnergyPlus. The developed model was then used to quantify improvement of the internal thermal environment in low rise typical houses in the three case-study countries as well as quantification of potential electricity and carbon savings by avoiding installation of air-conditioning to achieve thermal comfort conditions.

## 2. Experimental case study in Jamaica and monitoring results

### 2.1. Description of case-study and applied cool roof

The experimental case-study building is a typical example of many low-income single storey semi-detached houses built in Jamaica. The surrounding area is an urban context comprising low-rise buildings with a minimum contribution to the shading of the case-study building. The floor plan is shown in Fig. 2; photos of the house are presented in Fig. 3.

A commercially available cool paint suitable for flat roofs was applied to the roof of the house in Jamaica. This paint is included in cool roof rating databases [14,15] with the following characteristics:

- Initial solar reflectance: 0.82, reduced to 0.72 after three years.
- Thermal emittance: 0.90.
- Initial Solar Reflectivity Index (SRI): 160, reduced to 90 after three years.

After a prior cleaning, a primer coat was applied on the precast concrete slab on 22nd March 2017. Due to the bad weather condition, the three layers of the cool paint were applied from the 31st March 2017 to 16th of April 2017. Fig. 4 shows the roof before and after the application of cool roof.

### 2.2. Experimental monitoring procedure

The purpose of monitoring was to acquire data from an operational house pre- and after intervention. Monitoring focussed on surface temperature of the ceiling and air temperature inside the house. Some weather data (air temperature, relative humidity and global solar irradiance) were measured to facilitate the calibration of the computation model. An on-site survey was carried out to determine the geometry (including areas of windows and doors) and construction of the house as well as equipment (including lighting) as sources of internal heat gains. It was not possible to carry out more detailed monitoring of the occupants behaviour and use of the house due to limited funding but the occupant has provided a schedule of normal activities.

Preliminary measurements started in September 2016 while all monitoring sensors were in place in January 2017. As mentioned before the cool paint was applied between 22 March and 16 April 2017 and monitoring continued until July 2017, to include periods before and after the installation of the cool roof of data acquisition. Internal and external roof surface temperatures were

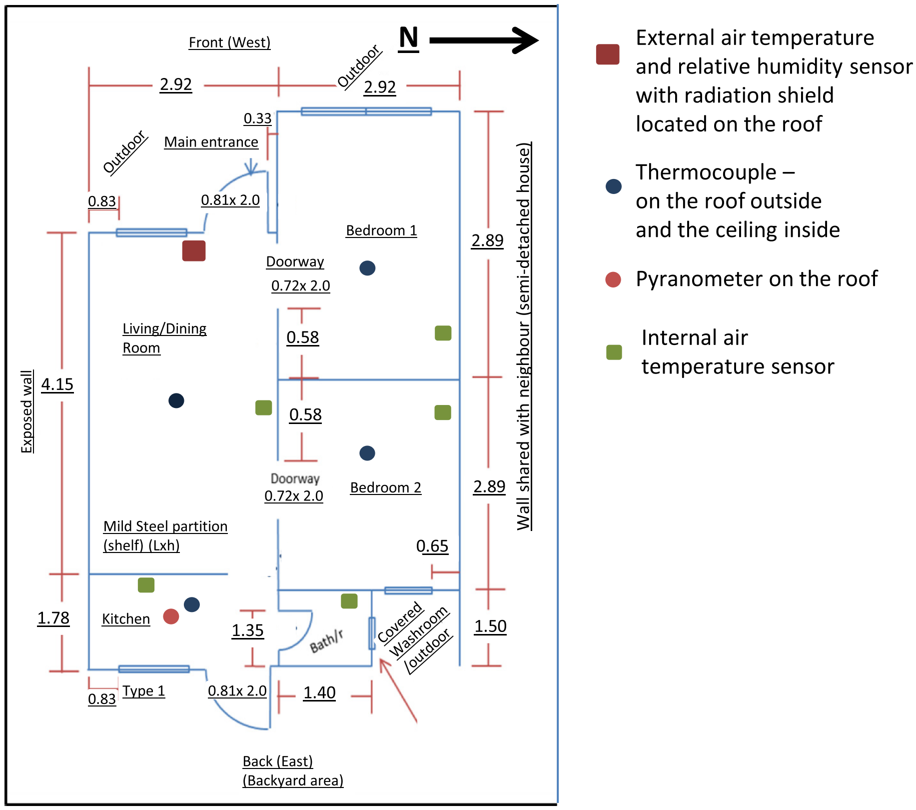


**Fig. 2.** Floor plan of the case-study house in Jamaica with a floor area of 36 $m^2$ (dimensions in m). Position of measurement points are indicated.


**Fig. 3.** Case-study house in Jamaica photos. The position of the weather station is indicated. The AC unit is not working.

measured with thermocouples linked with a Campbell Scientific CR10x datalogger with accuracy of ±0.05% of the full-scale input range, at 4 locations outside and 4 inside (see Fig. 2). Internal air temperature was measured at four locations (living room, 2 bedrooms and kitchen) with HOBO UX100-003 dataloggers with accuracy ±0.21 °C. External air temperature and relative humidity were measured on site also using a HOBO UX100-003 datalogger shielded and ventilated (see Fig. 3). Data were recorded at 5 min interval and averaged to one hour for the analysis. Global solar irradiance was measured on site with a pyranometer CMP 3 from Kipp & Zonen; for the case-study, the small spectral range from 300 to 2800 nm and the maximum operational irradiance of 2000 W/$m^2$ are sufficient. The output range is 0 to 30 mV with a sensitivity of 5 to 20 $\mu$V/W/$m^2$. By measuring global solar irradiance all elements of solar radiation are included in the measurements as it was not possible to measure the components in more detail.

### 2.3. Monitoring results

Fig. 5 presents measured air and inside ceiling surface temperature of the living room and solar radiation intensity before and after painting. It should be noted that global solar irradiance was measured and this is used for the graph of Figs. 5 and 6. There is a difference in the sun's inclination between March and April and this might have affected the incident solar radiation on the roof. Nevertheless, this difference is small for the results presented which are chosen to be as close in time as possible. Average solar


**Fig. 4.** Roof of the case-study house in Jamaica.

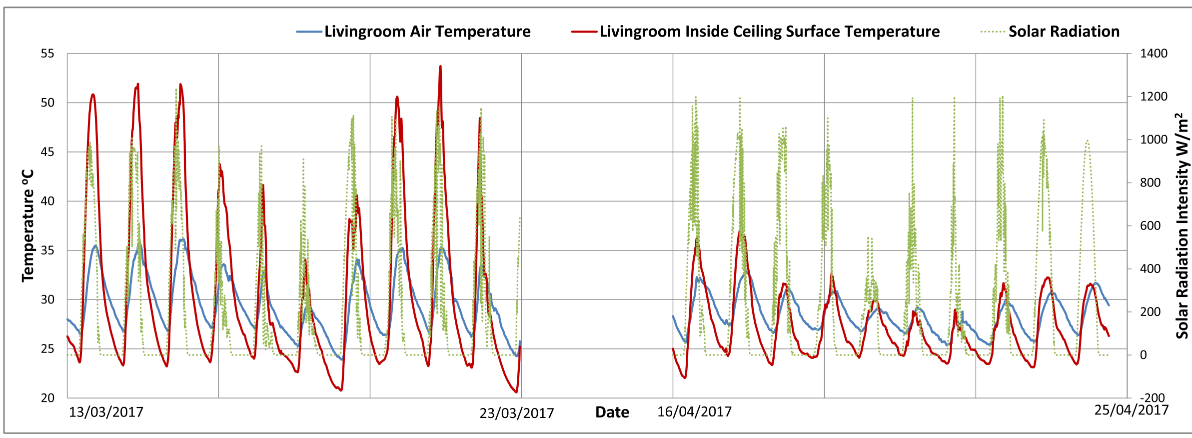


**Fig. 5.** Living room air and internal ceiling surface measured temperature for pre-application (13th March 2017 to 23rd March 2017) and post-application (16th April 2017 to 25th April 2017) of cool roof. Measured solar radiation intensity is indicated.

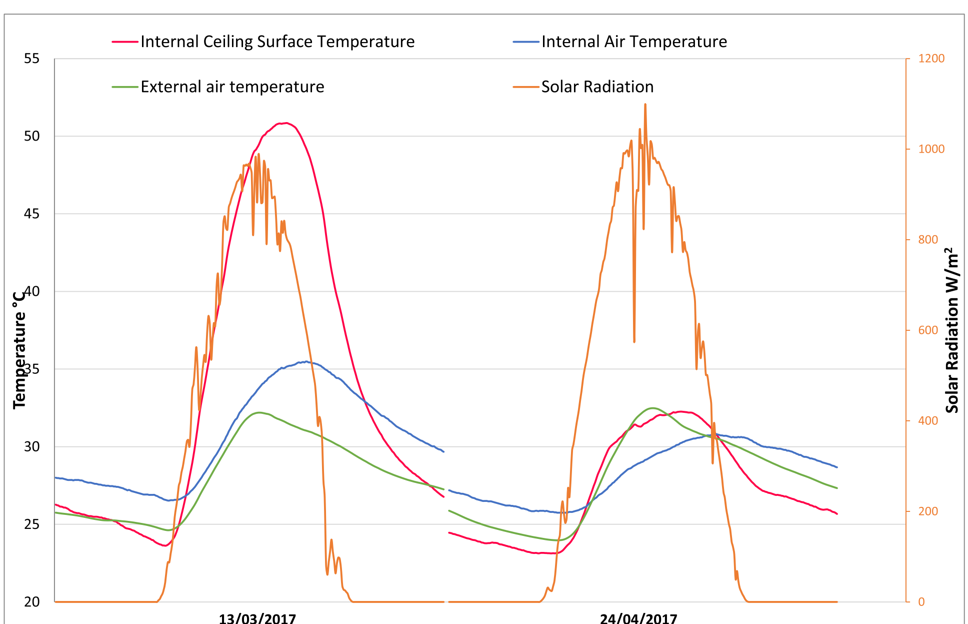


**Fig. 6.** Two days measured results of solar radiation intensity, living room air and internal ceiling surface temperature for pre-application (13th March 2017) and post-application (24th April 2017) of cool roof.

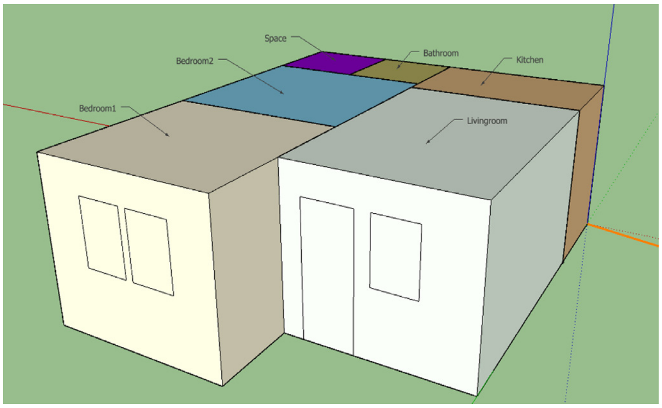


**Fig. 7.** Thermal zones of the house in Jamaica.

radiation intensity during day time and average external air temperature were lower in March (average of 407 W/m$^2$ and 27.4 °C) than in April (average of 428 W/m$^2$ and 27.9 °C). The curves indicate that ceiling surface temperature and internal air temperature are lower in April (after paint period) for higher solar radiation intensity and higher outside air temperature.

In order to give a further insight of the pre and after cool roof application conditions, Fig. 6 presents measurements on two days. The first day (13 March) is before and the second day (24 April) after the application; both days have similar external average air temperature (27.4 °C on 13 March and 28.2 °C on 24 April) and average global solar radiation intensity during daytime (416 W/m$^2$ on 13 March and 428 W/m$^2$ on 24 April).

Internal ceiling surface temperature was higher on the 13 March compared to 24 April by a maximum of 18.6 °C and an average of 6.8 °C. The internal air temperature shows that after applying cool paint, the living room is on an average cooler by 2.3 °C.

## 3. Development of computational model of the houses

### 3.1. Methodology of model development of the house in Jamaica

A model of the experimental house was developed using EnergyPlus [16] and OpenStudio [17]. The house was modelled into six thermal zones shown in Fig. 7. The local survey provided information on the materials of the external envelope so that thermal characteristics were calculated (Table 1); the internal heat gains are based on input from the occupant for the schedule. Maximum internal gain is 3 kW but 2 kW are due to the gas burner and the rest lighting, occupancy and appliances.

The house is a naturally ventilated building controlled by the occupants who provided data of the opening schedules. To simulate this, the airflow network model of EnergyPlus was used which offers the ability to simulate multi zone air flows. Fig. 8 shows the airflow network used in the multizone air flow calculation. Wind pressure coefficients applicable to this case-study (low-rise buildings) were obtained from CIBSE Guide A [18]. The infiltration varies during the day due to air pressure differences which are calculated hourly from the air temperature and wind data of the weather file. A reference condition should be implemented to initiate the calculation of both models. Due to the lack of blower door test in the experimental case-study house, the initial infiltration of both buildings is based on the Jamaican regulation. According to the National Building Code [19] the infiltration rate for buildings shall be assumed to be 0.0017 L/s per m$^2$ of the gross exterior wall. For the simulation of cool roof, the simpler way is to neglect the thickness and thermal properties of the cool paint and redefine the solar absorbance of the exterior roof surface. This approach is commonly used [20] when modelling paints and other surface treatments as three coatings of conventional cool paint add up to only about 1 mm of thickness when dry. Although the solar reflectance of the conventional roof could not be measured as no samples are available, the value is taken as 0.15 due to the colour and composition. A solar absorbance of 0.85 corresponds to a grey precast concrete surface. Initial solar reflectance on the cool paint specified as 0.82, so after painting the solar absorbance value is fixed at 0.18. The only difference of the before and after painting in the models is the roof's solar absorbance.

### 3.2. Calibration of the model

A Meteonorm [21] weather file for Kingston, Jamaica was modified using the on-site measured weather parameters which include air temperature, relative humidity and global horizontal radiation. In addition to the Global Horizontal Irradiance (GHI) measured, weather files to be used with EnergyPlus require the Direct Normal Irradiance (DNI) plus the Diffuse Horizontal Irradiance (DHI) linked with the following formula (where $\theta$ is the solar zenith angle): $GHI = DHI + DNI \times \cos\theta$. For a sunny day, it is common to assume 20% of the value measured by the pyranometer comes from the diffuse component, and 80% from the direct [22]. In Jamaica, the climate is globally sunny all over the year; the assumption is reasonable for the period of simulation for the calibration. The modified weather file covers the period from mid January 2017 to mid June 2017 to cover both pre- and after- cool roof periods. The modified whether file was used only for calibration purposes while the typical whether file for Jamaica was used for the modelling presented in Section 4. Calibration of the model is performed by comparing the experimental observations and simulations of the internal ceiling surface temperature and the indoor air temperature, statistically.

With the modified weather file with actual climatic data from mid-January to mid-June, the simulation results can be compared to the on-site measured data fairly. Calibration of the model is performed by comparing the experimental data and simulation results of the ceiling temperature (internal surface) and the indoor air temperature. For example, the upper graph of Fig. 9 presents the results of three days' simulation of a conventional roofing for the indoor temperature and the inside ceiling surface temperature of the bedroom 1. The on-site-monitored temperatures are in solid lines, and their corresponding EnergyPlus simulation values (labelled EP in the graph legend) are in dashed lines. At first sight, the simulation results seem to provide a good representation of the measured data. The computed air temperatures and ceiling surface temperature are close to the measured temperatures.

The same graph is drawn for after painting, Fig. 9 lower graph, which exemplifies the comparison between the measured and simulation temperature values with the cool roof. The only difference of the before and after painting model is the roof's solar absorbance. The roof solar absorptivities are set to 0.85 before and 0.18 after the application of the paint.

The accuracy of these results is essential to review the effects of cool roofs on thermal comfort and cooling energy demands. Simulations are run and operational details of the model are changed until the minimum accepted error for a building of this nature is achieved. Trial and error approach is adopted until the simulation results are within a reasonable margin (10%). The results show good agreements for the overall period, especially after roof refurbishment (Fig. 10). Before painting, simulations under-predict internal air temperatures while the prediction of internal ceiling surface temperature is split between over and under-prediction. From mid-January to mid-March (before painting), 75.1% of the hourly points are in the 10% margin. Before the use of the cool coating, there is a mean difference of living room indoor air temperature

**Table 1**
External fabric and thermal data for the three case-study houses.

| | Jamaica | | | Ghana | | | Recife-Brazil | | |
|---|---|---|---|---|---|---|---|---|---|
| Orientation | Exposed facades with windows: East-West<br>Blind exposed facade : North | | | Exposed facades : East-West<br>Blind exposed facade : North | | | Exposed facades with windows : NE and SW | | |
| Floor/Roof area $m^2$ | 36 | | | 36 | | | 91 | | |
| Volume $m^3$ | 88 | | | 88 | | | 236 | | |
| Exposed to ambient ext wall area $m^2$ | 54.5<br>three walls, facing north/east/west | | | 54.5<br>three walls, facing north/east/west | | | 65<br>two walls, facing north-east and south west | | |
| Window area $m^2$ | 6 single glazed windows – ($5 = 0.7 \times 0.98$ $m^2$, $1 = 0.42 \times 0.43$ $m^2$) 3.6 $m^2$ | | | 6 single glazed windows – ($5 = 0.7 \times 0.98$ $m^2$, $1 = 0.42 \times 0.43$ $m^2$) 3.6 $m^2$ | | | 6 single glazed windows – ($1.5 \times 2$ $m^2$) = 18 $m^2$ | | |
| Window opening schedule | Manually controlled according to occupancy | | | Manually controlled according to occupancy | | | Manually controlled accroding to occupancy | | |
| Occupants | 1 | | | 1 | | | 4 | | |
| Occupancy Schedule | Working occupant: at home at night and weekends | | | Working occupant: at home at night and weekends | | | Working family: : at home at night and weekends | | |
| Internal heat gains | Lighting: 70 W<br>Equipment: 1960 W (kitchen: 1800 W) | | | Lighting: 70 W<br>Equipment: 1960 W (kitchen: 1800 W) | | | Lighting: 145 W<br>Equipment: 2700 W (kitchen: 2400 W) | | |
| | Material | Thickness [cm] | U-Value [W/$m^2$K] | Material | Thickness [cm] | U-Value [W/$m^2$K] | Material | Thickness [cm] | U-Value [W/$m^2$K] |
| **Walls** | Precast concrete | 4 | 5.91 | Mud brick | 19 | 2.48 | Clay brick with plaster | 14 | 2.48 |
| **Roof** | Precast concrete | 8 | 5.68 | Metal sheet with plaster | 4 | 5.68 | Terracotta tile without ceiling | 2 | 4.55 |
| **Floor** | Concrete with tiles | 10 | 4.19 | Concrete | 10 | 4.19 | Concrete with tiles | 10 | 4.19 |

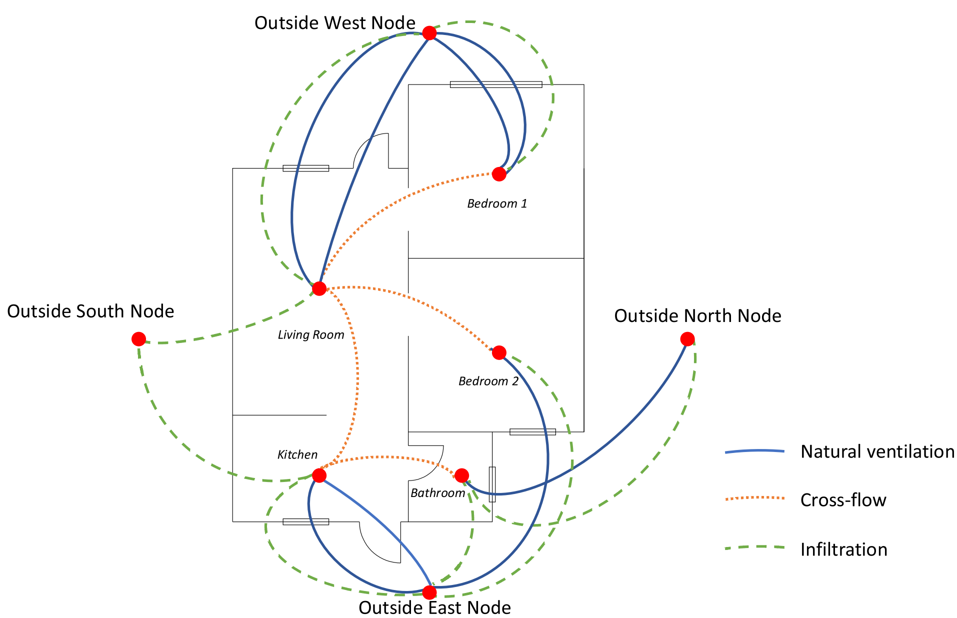


**Fig. 8.** Plan view of the airflow network showing possible airflow pattern.

of 2.3 °C. For the second period (mid-April to mid-June), 99.3% of the hourly points are in the 10% margin. After the painting, there is a mean difference of living room indoor air temperature of 1.1 °C.

As mentioned before, the results show good agreements for the overall period, especially after roof refurbishment. However, many factors can create some uncertainties. First, the measured data is expected to be more random as it is prone to sudden changes in weather conditions which can often occur multiple times within an hour, while the simulation only uses the weather data recorded at hourly intervals. Moreover, the assumption of 80% of the global horizontal radiation is direct is not all the time accurate. Cloudiness level is not measured and difficult to evaluate. Inclement weather and lack of direct solar radiations can explain some differences between the measurement and the simulation. Besides, the uncertainties about the occupancy schedule and occupant behaviour could easily explain some of the observed differences with the measured temperature evolution.

The accuracy of the simulation was also checked using the Mean Bias Error (MBE) and the Coefficient of Variation of the Roof Mean Square Error (CVRMSE). These indices are defined as follows:

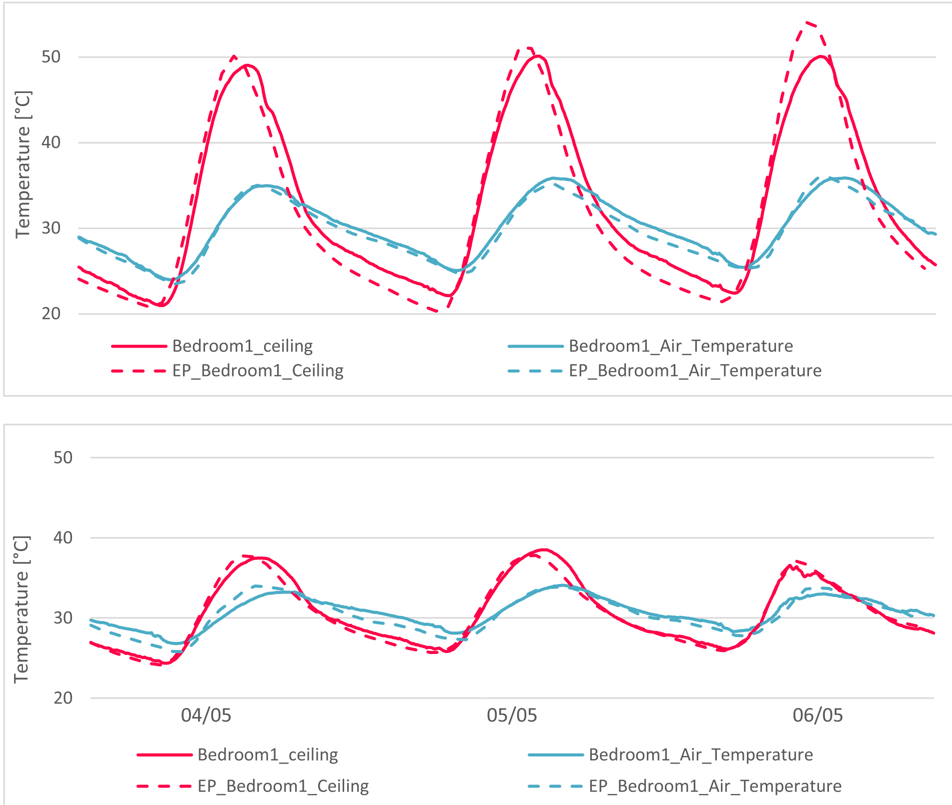


**Fig. 9.** Monitored (solid line) and simulated (dashed line) Internal Ceiling Surface and Air Temperature in the bedroom 1 for 3 days before (upper) and after (lower) painting.

**Table 2**
Mean Bias Error (MBE) for air temperature and internal ceiling surface temperature before and after painting.

| MBE | Air Temperature | | Internal Ceiling Surface Temperature | |
|---|---|---|---|---|
| | Before | After | Before | After |
| **Living room** | 7.8% | 3.9% | 7.6% | 5.7% |
| **Bedroom1** | 8.1% | 5.1% | 6.3% | 4.8% |
| **Bedroom2** | 8.9% | 5.9% | 7.5% | 8.9% |
| **Kitchen** | 8.8% | 5.1% | 7.6% | 4.4% |

**Table 3**
Coefficient of variation of the roof mean square error (CVRME) for air temperature and internal roof surface temperature before and after painting.

| CVRMSE | Air Temperature | | Internal ceiling surface temperature | |
|---|---|---|---|---|
| | Before | After | Before | After |
| **Living room** | 8.3% | 4.5% | 12.0% | 7.6% |
| **Bedroom1** | 8.9% | 5.8% | 8.4% | 6.0% |
| **Bedroom2** | 9.9% | 6.8% | 11.1% | 12.6% |
| **Kitchen** | 8.2% | 5.6% | 10.8% | 5.6% |

$$MBE = \frac{\sum_{i=1}^{N} (M_i - S_i)}{\sum_{i=1}^{N} M_i} \qquad CVRMSE = \frac{\sqrt{\sum_{i=1}^{N} (M_i\_S_i)^2 / N}}{\bar{M}}$$

with $M_i$ and $S_i$ are measured and simulated data at instance i, respectively; $\bar{M}$ is the sample mean of the measured data $\bar{M} = \frac{\sum_{i=1}^{N} M_i}{N}$; and N is the sample size (1631 for hourly based calibration before painting and 1295 with the cool roof). The results are shown in Tables 2 and 3. ASHRAE [23] recommends an MBE of less than 10% and a CVRMSE of less than 30% relative to hourly calibration. These results indicate that the model is successfully calibrated.

### 3.3. Development house models for Recife-Brazil and Ghana and weather files used

An EnergyPlus model was developed for the case-study house in Recife, northeast Brazil. The floor plan is shown in Fig. 11 and is a real low income house. The construction of the external fabric is shown in Table 1. Internal heat gains were provided by the occupant to determine the schedule and magnitude.

An EnergyPlus model was developed for the case study house in Ghana. In this case, local survey was based on a hostel residential building which was modelled but did not offer a direct comparison with the other two case-studies. Therefore, the house in Jamaica was used as the base for the geometrical dimensions and the fabric materials were changed to reflect local practices [24].

Meteonorm weather files were used in the simulations for the three locations; Kingston (Jamaica), Recife (Brasil) and Accra (Ghana). Climates are similar with high air temperatures and solar radiation intensity throughout the year. The annual average air temperature is 27.8 °C in Kingston, 27.4 °C in Recife and 26.9 °C in Accra. The annual average global solar radiation intensity is 241.2 W/m$^2$ in Kingston, 235.7 W/m$^2$ in Recife and 238.7 W/m$^2$ in Accra. The distribution for different months is shown in Fig. 12 indicating seasonal differences.

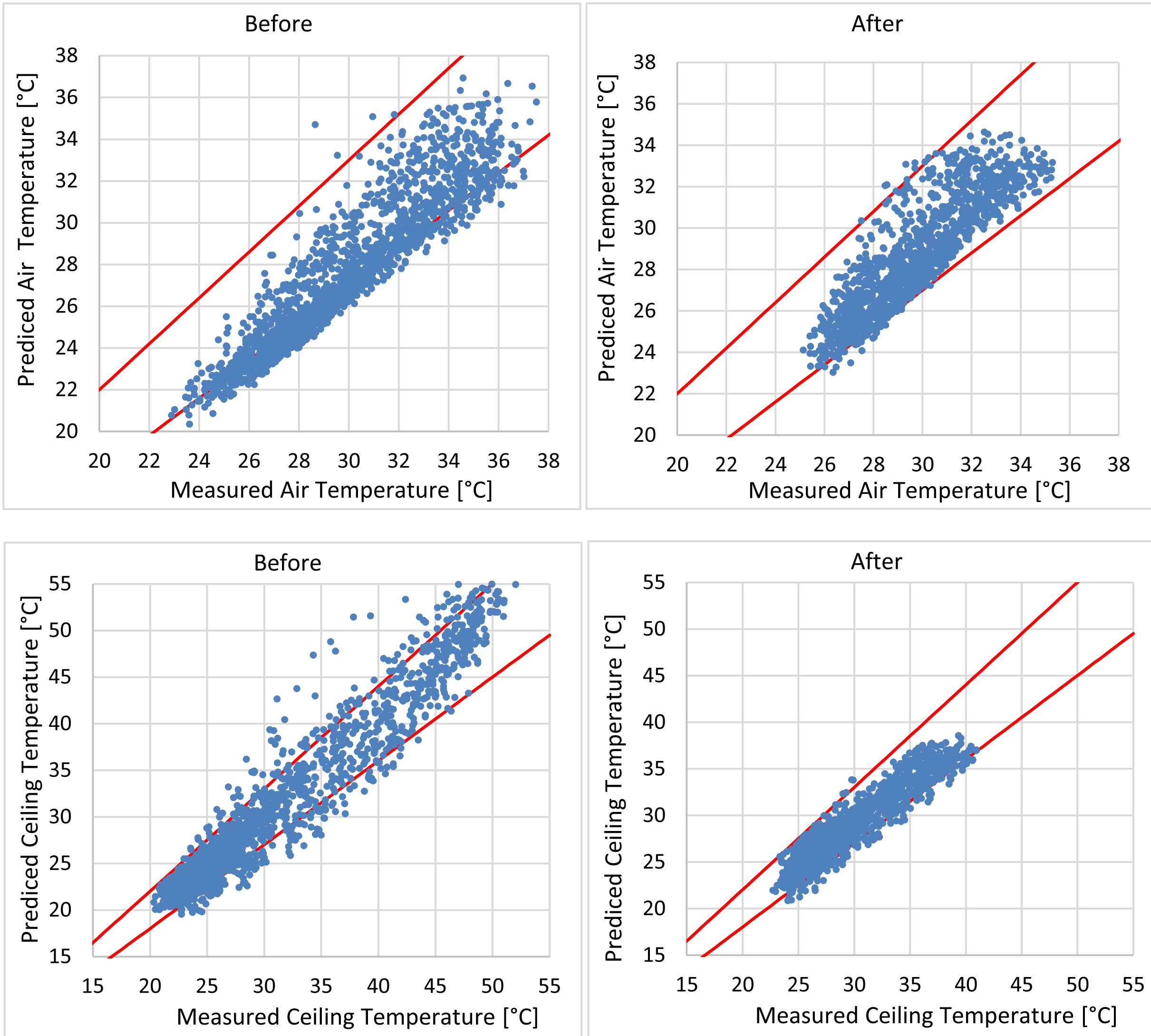


**Fig. 10.** Simulated vs. measured values of internal air temperatures and internal ceiling surface temperatures before and after the application of cool paint.

## 4. Simulation results and discussion

The simulation results presented in this section show the impact of external climatic conditions interlinked with construction methods of the three locations, potential energy savings if refrigerative cooling system is installed and the importance of maintenance of the cool roof.

### 4.1. Improvement of thermal comfort

Table 4 shows the average monthly reduction of roof, ceiling and inside air temperature for the three case-studies. All the results due to the implementation of a cool roof indicate significant reduction in average temperature throughout the year. External roof surface temperature reductions are consistent with solar radiation intensity and correlate with monthly fluctuations. For example, the average external roof surface temperature is reduced by approximately 7 °C in the three countries with lowest reductions in June/July in Recife, July to September in Ghana and December/January in Jamaica. Internal ceiling surface temperature reductions also reflect seasonal solar radiation intensity variations but are also influenced by roof construction. Internal ceiling surface temperatures are reduced by approximately 5.5 °C in Ghana and Jamaica and 3.2 °C in Recife-Brazil due to the higher insulation level of the roof, resulting in lower U-value (see Table 1). Internal air temperatures are reduced by 1.2 °C in Jamaica, 1.4 °C in Ghana and 0.75 °C in Recife-Brazil. Insulation and heat capacity is higher in the Brazil case-study for both walls and roof resulting to lower U-value (see Table 1), while the Jamaica and Ghana case-studies differ in the heat capacity and insulation (U-value) of the walls. These averaged results indicate that the impact on thermal comfort by a cool roof is greater for poorly insulated roofs and high heat capacity walls as they are fewer temperature fluctuations.

The above discussion was based on averaged reductions over all hours in every month. As expected the highest reduction occurs during the hours with high solar radiation intensity. The largest internal ceiling surface temperature reduction was predicted for Jamaica, 24.4 °C reduction, while in Ghana the peak reduction was 23.7 °C and in Recife (Brazil) 14 °C. The largest external roof surface temperature reduction was also predicted in Jamaica, 32.4 °C reduction while in Ghana the peak reduction was 30.7 °C and in Recife (Brazil) was 31.8 °C. The highest reduction in Jamaica is a combination of high solar radiation intensity and high ambient air temperature (see Fig. 12). The biggest reduction takes place in Jamaica on the 4th of March which is the day with the highest solar radiation; during two hours, the solar radiation intensity reached

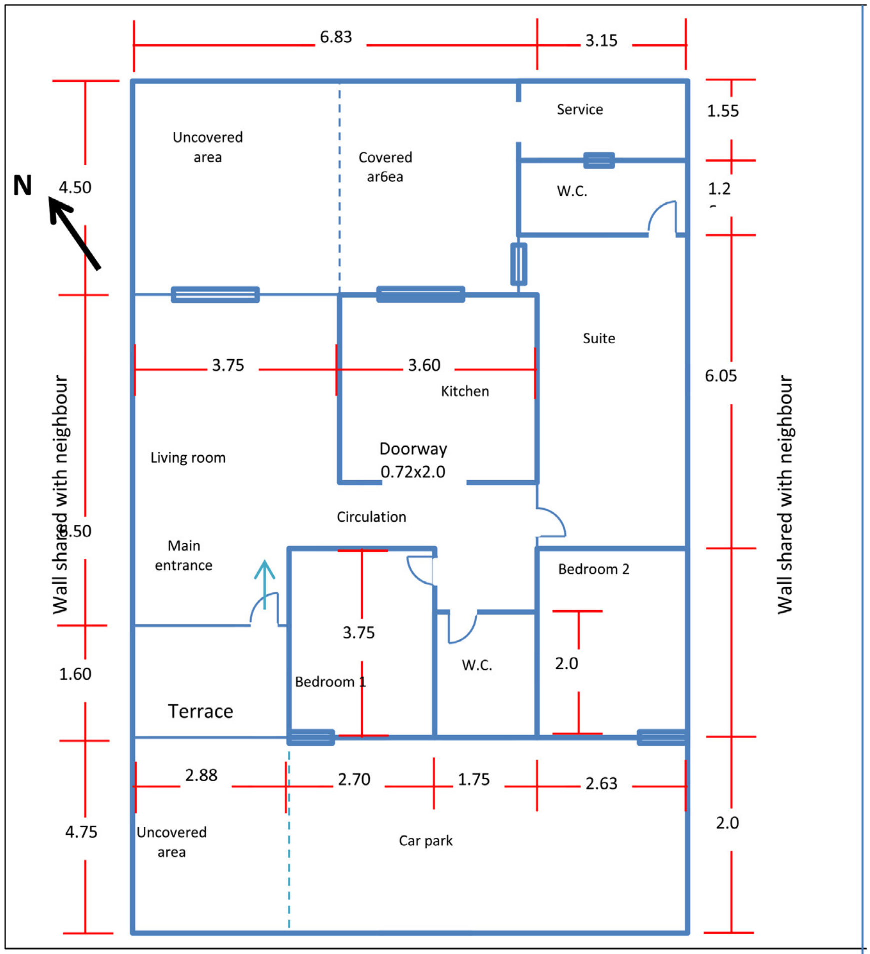


**Fig. 11.** Floor Plan of the case-study house in Recife-Brazil with a floor area of 90 $m^2$ (dimensions in m).

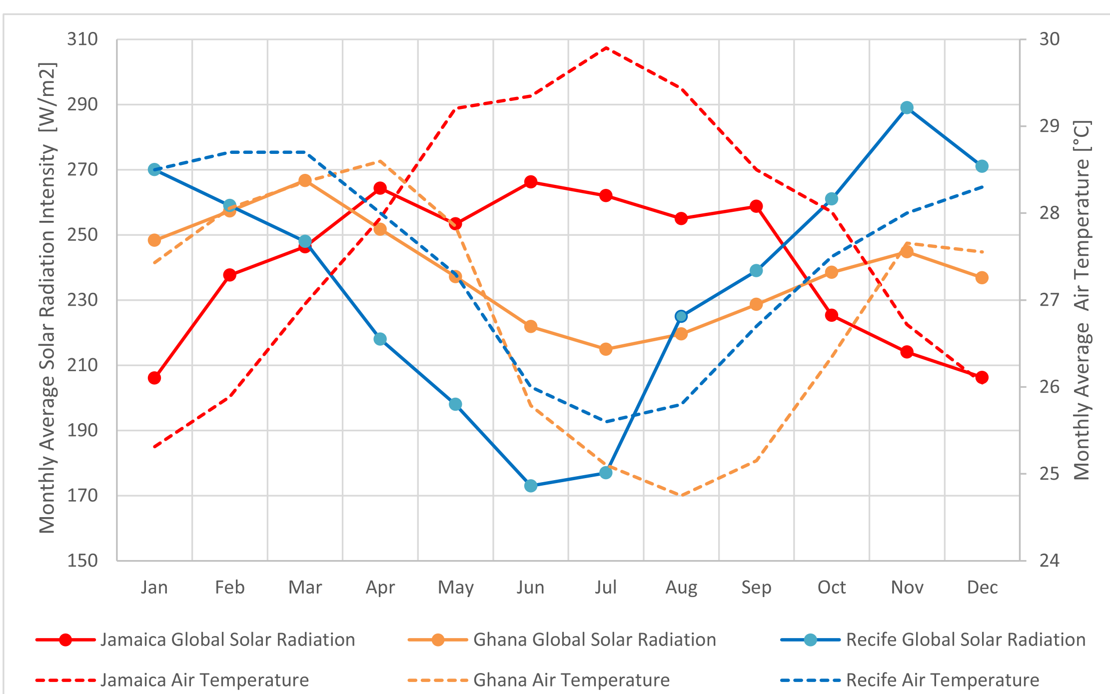


**Fig. 12.** Monthly average solar radiation intensity and external air temperature (from weather file) in the three case-study locations.

**Table 4**
Monthly average (24 hrs) roof, ceiling and internal temperature reduction for SR 0.15 and SR 0.82.

| Delta T | Jamaica | | | Ghana | | | Recife-Brazil | | |
|---|---|---|---|---|---|---|---|---|---|
| | Roof surface | Ceiling surface | Inside air | Roof surface | Ceiling surface | Inside air | Roof surface | Ceiling surface | Inside air |
| ***Jan*** | *5.9* | *4.7* | *1.0* | *7.5* | *6.0* | *1.5* | *7.9* | 3.8 | 0.9 |
| ***Feb*** | *6.6* | *5.3* | *1.1* | *7.4* | *5.9* | *1.5* | *7.5* | 3.6 | 0.8 |
| ***Mar*** | *7.2* | *5.7* | *1.2* | *7.9* | *6.3* | *1.5* | *7.4* | 3.5 | 0.8 |
| ***Apr*** | *7.8* | *6.2* | *1.3* | *7.3* | *5.9* | *1.6* | *6.7* | 3.2 | 0.6 |
| ***May*** | *7.3* | *5.8* | *1.2* | *7.5* | *6.0* | *1.6* | *5.8* | 2.8 | 0.6 |
| ***June*** | *7.4* | *5.8* | *1.2* | *7.0* | *5.9* | *1.6* | *5.0* | 2.5 | 0.6 |
| ***July*** | *7.3* | *5.8* | *1.2* | *6.0* | *4.8* | *1.0* | *5.1* | 2.5 | 0.6 |
| ***August*** | *7.4* | *5.8* | *1.2* | *6.2* | *5.0* | *1.1* | *6.1* | 3.0 | 0.7 |
| ***Sep*** | *7.6* | *6.1* | *1.3* | *6.4* | *5.1* | *1.2* | *6.6* | 3.2 | 0.8 |
| ***Oct*** | *6.9* | *5.5* | *1.2* | *6.8* | *5.5* | *1.3* | *7.3* | 3.5 | 0.9 |
| ***Nov*** | *6.5* | *5.1* | *1.1* | *7.1* | *5.7* | *1.4* | *8.0* | 3.8 | 0.9 |
| ***Dec*** | *5.9* | *4.7* | *1.0* | *7.3* | *5.8* | *1.5* | *7.8* | 3.6 | 0.8 |

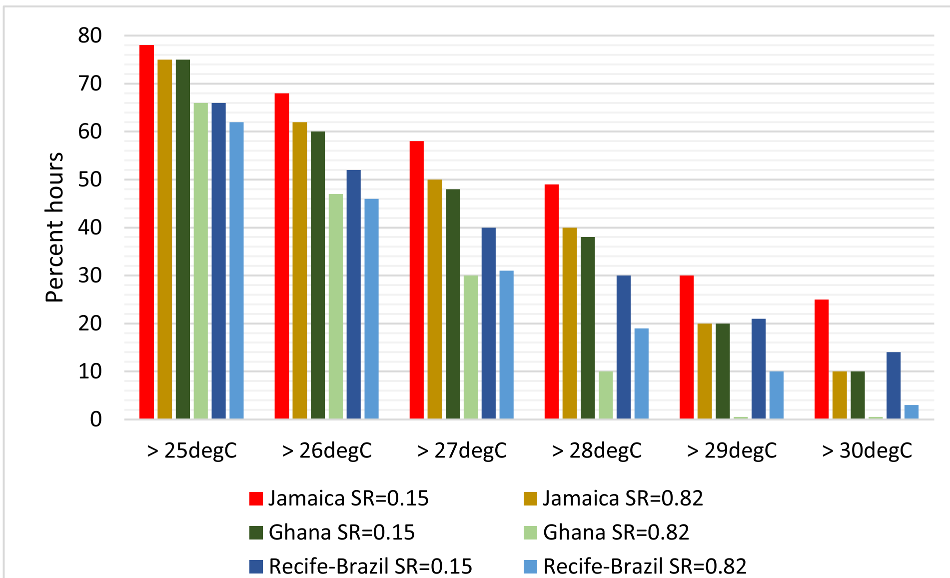


**Fig. 13.** Simulation results of percentage time (h in a year) that operative temperature exceeds 25–30 °C inside the three low-income houses.

1096 W/m$^2$. This impact of external weather conditions combined with the absence of insulation resulting to a high U-value of the external envelope (Table 1), also results to the highest reduction in the internal ceiling surface temperature.

The average and maximum peak reductions are not the only criteria for thermal comfort. It is important to know for how long the temperature exceeded a certain temperature threshold; operative temperature is usually used as an index. The overheating hours during the year in the case-study houses were calculated and presented in Fig. 13 as a percentage of time that internal operative temperature exceeds 25, 26, 27, 28, 29 and 30 °C during the year for the two albedo values (0.15 representing the roof without cool paint and 0.82 representing the roof with cool paint). As observed, internal operative temperatures exceed a threshold value of 25 °C for more than 65% of the time without cool roof in all case-studies reaching almost 80% in Jamaica. This can be compared to the acceptable overheating criterion of 5% of the working time over 25 °C [18]. In all cases and for all threshold temperatures an improvement can be observed due to the impact of the cool roof. There are variations between the case-studies because of different ambient conditions and construction of the houses but nevertheless the impact of the cool roof is significant, reaching an improvement of almost 30% in the case of Ghana for the threshold of 28 °C.

### *4.2. Energy savings if cooling is provided*

The cooling loads to maintain houses at 24 °C are simulated before and after the implementation of the cool roof. Average annual ambient air temperature is 1 °C higher in Jamaica (28 °C) than Ghana and Recife-Brazil (27 °C). Average annual global solar radiation intensity is similar for the three locations (241 W/m$^2$ in Jamaica, 239 W/m$^2$ in Ghana and 236 W/m$^2$ in Recife-Brazil).

The case-study houses are geometrically similar in Jamaica and Ghana but the walls in Ghana are better insulated (5.91 W/m$^2$k in Jamaica, 2.48 W/m$^2$k in Ghana). The house in Brazil is larger in size, volume and external wall areas; however it has two external walls exposed in contrast to the Jamaica and Ghana case-study which have three external walls exposed. The walls and roof are better insulated in the Brazil case-study than the other two cases (see Table 1). These differences impact on the cooling energy demand.

The cooling load simulation results are presented in Table 5 in kWh/m$^2$/year for an air-conditioned floor area of 36 m$^2$ for Jamaica and Ghana and 90 m$^2$ for Recife-Brazil. As expected, the annual cooling demand decreased with the cool roof. Despite the differences in the geometrical details and construction of the three case-studies the reduction of cooling demand normalised per floor area is remarkably similar.

Fig. 14 presents the monthly cooling demand for the three case-studies. The implementation of cool roofing techniques has a pos-

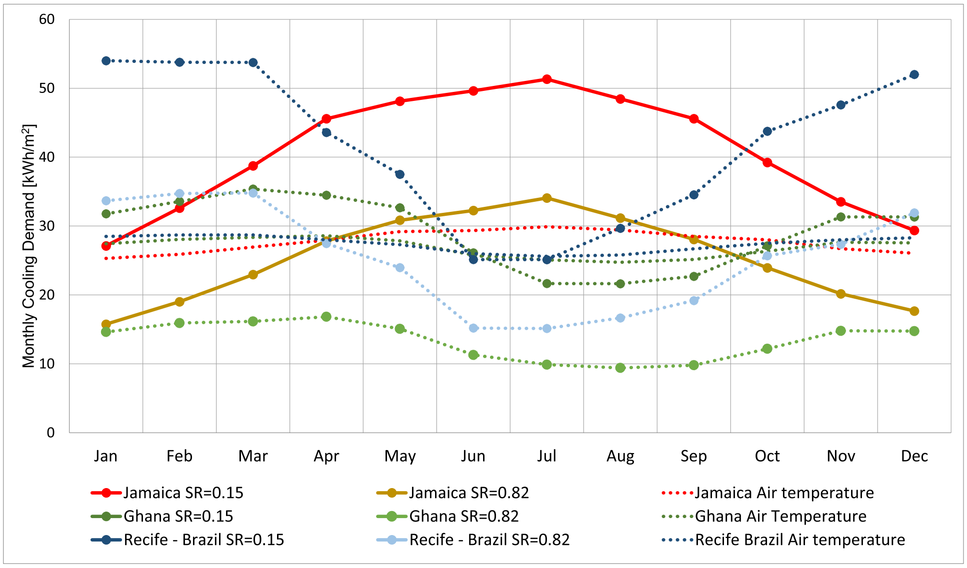


**Fig. 14.** Simulated cooling energy demand through the year for the low-income houses.

**Table 5**
Simulated cooling energy demand for the case-studies for a set-point 24 °C.

| Case-study | Cooling demand ($kWh/m^2$/year) | | Saving ($kWh/m^2$/year) |
|---|---|---|---|
| | Without cool roof | With cool roof | |
| **Jamaica** | 496 | 308 | 188 |
| **Ghana** | 354 | 163 | 191 |
| **Recife-Brazil** | 500 | 305 | 195 |

itive benefit throughout the year. The average outdoor air temperature (dashed lines) has been plotted showing the monthly variations in the three locations. Since all locations have high air temperature and solar radiation intensity throughout the year, the monthly savings remain high throughout the year. However, the effectiveness of cool coatings is slightly more noticeable during the hottest and sunniest months from April to September in Jamaica and from November to May in Ghana and Recife-Brazil.

Because of the climatic and thermal characteristics, cooling loads are higher in Jamaica than Ghana. They are also higher in Recife-Brazil because of the geometrical and thermal characteristics of the house; it is more insulated than Jamaica and Ghana but has bigger volume and exposed walls to the ambient and therefore both losses through conduction and convection are higher. Despite these differences, the annual potential savings are similar; 188 $kWh/m^2$/year in Jamaica, 191 $kWh/m^2$/year in Ghana and 195 $kWh/m^2$/year in Recife-Brazil, indicating the high potential of cool coatings in the three locations irrespective of the small differences in climatic conditions and local construction practices for housing.

In terms of $CO_2$ emissions reduction, an estimation was carried out assuming a Coefficient of Performance (COP) of 3 for the air-conditioning system and available emissions of electricity generation in the three locations. The $CO_2$ emission factors from electricity are taken as 0.2147 $kgCO_2$/kWh for Ghana, 0.07961 $kgCO_2$/kWh for Jamaica and 0.0926 $kgCO_2$/kWh for Brazil [25]. Potential savings are 50 $kgCO_2/m^2$/year in Jamaica, 13.5 $kgCO_2/m^2$/year in Ghana and 6 $kgCO_2/m^2$/year in Brazil reflecting the fuels used in the three countries for electricity generation. Therefore, although the savings due to the cool roof have similar energy consumption for cooling (assuming the same cooling system used), the environmental impact per unit area is by far highest in Jamaica. Nevertheless, the housing stock in Ghana and Brazil is more extensive (size of country and populations), therefore aggregated impact has a high potential in these countries too.

### 4.3. Impact of cool roof aging

All other parameters being equal, an important factor for the performance of cool painting is the change of its properties (solar reflectance and emittance) due to aging. There are several factors influencing its performance such as impact of ultra-violet (UV) radiation as well as accumulation of dirt. The cool paint used in the study has a measured solar reflectance loss of 0.1 measured using the accelerated aging method as required by cool roof rating databases [14,15]. This is consistent with results reported in the literature. Solar reflectivity losses were studied [26] to compare accelerated and natural aging losses for a large number of samples as well as the impact of climatic conditions. The study [26] found that for coatings applied in the field (rather than laboratory) the mean loss in solar reflectivity varies between 8 and 27% with a mean value of 17%. The percentage of loss is also dependent on initial solar reflectivity and climatic conditions; the higher initial value the highest loss while paints in hot and humid climates suffer higher losses than more temperate climates. Literature results report very little loss of thermal emittance due to aging [27]. It has also been reported that most of the solar reflectivity losses occur during the first three years of exposure mainly due to the accumulation of dirt. Therefore, cleaning or re-applying the cool coating should be included in the maintenance plan for the roof. Simulations with solar reflectivity loss of 0.1 were run to mimic possible losses at the end of the first year to gauge whether a re-application would provide benefits. The results are similar for the three locations. The average difference in internal ceiling surface temperature due to the reduction of solar reflectivity is approximately 3.9 °C. The average internal air temperature difference is 0.4 °C for the peak internal air temperature and 0.8 °C for the operative temperature. Cooling load reduction is also lower by 22–26 $kWh/m^2$/year and assuming a COP of 3 it results to additional electricity cost of about 8 $kWh/m^2$/year or 280 kWh per house in Jamaica and Ghana and 720 kWh per house in Recife-Brazil. This can be used as guideline for local residents as an incentive to clean and/or re-apply the paint more frequently.

## 5. Discussion

A study of the benefits in terms of reducing overheating and reducing cooling load demand in low income houses for three locations with high solar radiation intensity and ambient air temperatures during the year was presented. The locations were selected because of their climatic conditions and data gathering was possible due to existing collaborations.

Thermal models of the three case-studies were created using EnergyPlus with the input parameters of geometry, construction and operation schedules based on data gathered locally. An experimental study was carried out in Jamaica where the house was monitored before and after the application of a cool roof. This field study provided evidence on the reduction of surface and air temperatures and data were used for the calibration of the created thermal model.

The model was used to simulate the performance of the cool roof in the three locations, Jamaica, Ghana and Recife-Brazil, where average monthly ambient temperature ranged from 25 to 30 °C and monthly average solar radiation intensity ranged from 170 to 290 W/m$^2$. The three models differ in construction to represent local practices and therefore fabric thermal resistance is different with U-values ranging between 2.48 and 5.91 W/m$^2$K so in general much higher than recent energy efficiency guidelines would recommend. Measurements have demonstrated that substantial reduction on internal ceiling surface temperature and internal air temperature was achieved in the Jamaican case-study for similar external conditions of solar radiation and ambient temperature, thus improving the operative temperature after the application of the cool roof. Feedback from the occupants confirmed the improvement from day one of the application, possibly due the reduction of the radiant component of thermal comfort.

Thermal simulations predict reduction in surface and internal air temperatures in the three locations, with average monthly reductions of 5 to 8 °C in roof temperature, 2.5 to 6.2 °C in internal ceiling surface temperature and 0.6 to 1.6 °C in internal air temperature. Peak reductions were higher reaching 32.4 °C for external roof surface temperature and 24.4 °C for the internal ceiling surface temperature–reflecting the low thermal resistance of the roof construction.

Although the case-study houses are naturally ventilated, in many cases, air conditioning would be installed by the occupants in these regions when they can afford it. The reduction of cooling load demand due to the installation of cool roof was simulated assuming a set-point temperature of 24 °C throughout the 24 h. Similar substantial reduction was predicted for all three locations at approximately 180 kWh/m$^2$/year reflecting the similar climatic conditions and in general low thermal resistance of the fabric. An estimation of $CO_2$ emissions reduction was calculated assuming a COP of 3 for the air-conditioning and electricity generation factors of each country. As expected the $CO_2$ emissions reduction is highest in Jamaica at 50 kg$CO_2$/m$^2$/year because imported oil is mainly used for electricity production. The reduction is lower in Brazil and Ghana at 6 and 13.5 kg$CO_2$/m$^2$/year respectively, mainly because of the high percentage (80% in Brazil) of hydropower contribution to electricity generation.

The study also examined the loss in thermal comfort and/or electricity savings due to the aging of the roof. Electricity savings can be reduced by 7.5% due to aging.

Based on the results of this study, actions supporting policy, regulations and user engagement/information could be initiated for two categories of stakeholders. The main beneficiaries are low income residents who experience overheating in their houses. Capital costs of cool paints is slightly higher than normal paints but unskilled labourers can apply it. Maintenance is low but cleaning might be needed annually to restore high solar reflectivity properties lost by accumulation of dirt. For non air-conditioned houses, the resulting improved internal thermal comfort will increase quality of life and in particular for young and old who has reduced thermal comfort threshold limit compared to healthy adults. Also, sleep conditions will improve with adults sleeping better and therefore can be more productive the following day. For air-conditioned houses, reduction of electricity bill will result for the occupants and energy security improvement for countries that rely on imported fuels for electricity.

## 6. Conclusions

Application of cool paints on the roof of poorly insulated low income houses in regions with high solar radiation intensity and ambient temperatures throughout the year will:

(A) Significantly improve thermal comfort in naturally ventilated houses and
(B) Reduce energy demand in air-conditioned houses

Improvements in thermal comfort and reduction of energy demand will depend on the geometry of the houses, construction methods impacting on their thermal performance, and use of the houses impacting on internal heat gains.

The technical work will continue by examining different parameters affecting the performance of cool paintings such as increased insulation in the new houses resulting to lower U-values, application on the walls with different constructions and the impact of relative humidity levels in the resulting thermal conditions in the house.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cdc.2018.07.003.

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