RESEARCH

Heat stress: adaptation measures in South African informal settlements

JAN MARAIS HUGO

ABSTRACT

Globally extreme weather events are experienced most acutely in cities. While formal settlements can respond to such events, informal settlements are often vulnerable and ill-prepared. Sub-Saharan Africa is rapidly urbanising with informal settlements that require effective climate change adaptation measures. Two climate adaptation strategies for informal dwellings are considered for their success under 2100 Intergovernmental Panel on Climate Change (IPCC) climate scenarios. Using existing data collected from informal dwellings in South Africa, the findings from a digital simulation study reveal that cool roof paints can currently lower excessive heat stress conditions by 42–63% when applied to high thermal mass dwellings with poorly insulated lightweight corrugated sheeting roofing. However, for the future 2100 climate scenarios this strategy only lowers excessive heat stress conditions by 12–17%. This calls for the development of integrated multifaceted heat stress adaptation strategies for informal settlements in Sub-Saharan Africa.

PRACTICE RELEVANCE

This study assessed heat stress conditions and the application of two financially and practically feasible heat stress adaptation strategies in informal dwellings in South Africa. This involved assessing the efficacy of using cool roof paints and improved thermal insulation under current and future climate change-affected conditions. The findings reveal that Southern African informal dwellings experience extreme heat stress 32% of the time. Predicted climate change-affected conditions will increase heat stress exposure up to 40% over a full year. The study reveals that cool roof paints can improve the performance of uninsulated, low thermal mass homes in temperate climates by lowering heat stress conditions by 42–63%, yet this climate change adaptation strategy is only an interim solution with limited success (12–17% improvement) under future 2100 climate change-affected conditions. As a result multilayered integrated heat amelioration strategies are needed in informal communities.

CORRESPONDING AUTHOR:
Jan Marais Hugo
Architecture Department, University of Pretoria, Hatfield Campus, Hatfield, ZA
jan.hugo@up.ac.za

KEYWORDS:
adaptation; albedo; climate change; cooling; dwellings; heat plan; heat stress; informal settlements; overheating; South Africa

TO CITE THIS ARTICLE:
Hugo, J. M. (2023). Heat stress: adaptation measures in South African informal settlements. *Buildings and Cities*, 4(1), pp. 55–73. DOI: https://doi.org/10.5334/bc.269

1 INTRODUCTION

Between 2000 and 2019 climate change-related extreme weather events resulted in a global cost of US$2.56 trillion as well as the loss of 475,000 lives (Eckstein *et al.* 2021). Although highly visible events typically capture public attention, heat stress events are often under-represented (Eckstein *et al.* 2021), with little done to address them (Baruti & Johansson 2020). Yet the impacts of higher temperatures and heat stress exposure present economic costs (Razzak *et al.* 2022), increased negative health implications (Wright *et al.* 2021) and have adverse effects on inhabitants' wellbeing (Chersich *et al.* 2019). This paper considers heat stress exposure in a South African informal settlement and reports on the efficacy of using two building-related adaptation measures to lower heat stress exposure under current and future 2100 climate scenarios.

While cities play a major role in the proliferation of climate change (IPCC 2022), these contexts also exhibit increased vulnerabilities to climate change impacts due to increased densities (Dodman *et al.* 2019), extensive resource networks and dependencies (Broersma *et al.* 2013), and future growth (UN 2019). Although several studies note the climate change vulnerability of urban environments (Brandt *et al.* 2021; Dodman *et al.* 2019), informal urban environments are typically excluded from climate change response strategies (Satterthwaite *et al.* 2020).

In Southern Africa, similar to other low to middle-income regions, informality largely represents urban and economic development (Dodman *et al.* 2019). Therefore, as Pieterse (2011) highlights, informality is increasingly considered the principal development mechanism in this region. While the UN (2019) projects that significant urbanisation will take place in Africa, in this region urbanisation is not typically associated with economic growth in the formal sector that leads to increased formal employment and socio-economic improvements (Anderson *et al.* 2013). Southern African cities are becoming more informal in nature.

The shift towards informality in Southern African cities is certainly a concern, while many governments of poor to middle-income countries aspire to eradicate informality, achieving such a goal is slow (Pieterse 2011). While transitioning towards more formal urban conditions is vital, employing strategies to lower the climate change-related risks in these informal settings is needed.

The built environment can potentially lower, or exacerbate, exposure to hazards, *e.g.* higher ambient temperatures, extreme heat days or, in worst cases, extreme heatwaves. Cool roof paint technologies are proven effective cooling measures to adapt the thermal envelope of dwellings (Vellingiri *et al.* 2020), yet this technology is typically prioritised for contexts with high solar radiation and excessively high temperatures. Incorporating these technologies with high-thermal-mass construction materials is typically assumed as effective climate adaptation solutions (Kolokotroni *et al.* 2018). Limited studies have considered the application of cool roof technologies in temperate climates, such as the South African interior region, as well as in poorly insulated, light-weight structures typically found in informal settlements.

This study examines adaptation strategies for heat stress in informal dwellings in Tshwane, South Africa. The use of cool roof paints and insulation is verified with digital simulation models based on indoor thermal data. These digital simulation models enable these adaptation measures to be tested before their implementation. This can identify and lower the risk of mal-adaptation. The long-term efficacy of these adaptations is also tested using 2100 climate change projected conditions based on the IPCC (2000) A2 SRES (Special Report on Emissions Scenarios) scenario family.

2 HEAT STRESS RISK IN INFORMAL SETTLEMENTS

As noted above, cities are both drivers of climate change and also highly vulnerable to its impacts (Dodman *et al.* 2019). As a result, both climate change mitigation and adaptation must be undertaken in cities to ensure their long-term viability (IPCC 2022). To prepare for climate change impacts, a framework towards understanding risk is needed. This risk assessment framework is defined by the IPCC (2022) as an integrated analysis of (1) the scale of the hazard, (2) the nature and extent of vulnerability and (3) the exposure level. Building on the basic risk definition, risk can be defined as the frequency and magnitude of hazards themselves, the vulnerability of the group or entity and the exposure to the specific hazard (IPCC 2022; Simpson *et al.* 2021). Simpson *et al.* (2021) continue, arguing that adaptive capacity is also a risk mitigation or perpetuating factor. Understanding the built environment's impact on exposure levels to climate change hazards and the users' adaptive capacity to implement response measures is critical when identifying climate change adaptation measures.

Although cities are vulnerable to a variety of risks, heat stress is a critical concern, especially in the Southern African region as this sub-tropical region is experiencing 1.5–2 times the global average temperature increases (DEA 2013). In this region heat stress hotspots will therefore significantly expand (Garland *et al.* 2015) only to be further exacerbated by the increased occurrence and intensity of heatwaves (Russo *et al.* 2016). These higher ambient temperatures have several impacts such as increases in heat stress exposure, solar radiation, extreme weather events and vector diseases (Wright *et al.* 2021). As noted by Kimemia *et al.* (2020) these higher temperatures have adverse physiological impacts ranging from mild effects (discomfort and loss in efficiencies) to much larger health impacts (heat cramps, heat syncope and heat stroke). Other impacts as also include increased occurrence of violent behaviour (Chersich *et al.* 2019), loss of livelihoods and employment opportunities (Adegun & Ayoola 2022; Razzak *et al.* 2022), and adverse changes in the local ecology (Kotharkar *et al.* 2018).

Buildings can lower or increase inhabitants' exposure to various health risks. While the built environment can contribute to general comfort and wellbeing, the access to and choice of building materials can increase the inhabitants' exposure to heat stress and diurnal thermal variations (Mabuya & Scholes 2020; Teare *et al.* 2020). In a field experiment of low-cost housing, indoor temperatures sensors in shack dwellings reported temperature variations of up to 14 K (Mabuya & Scholes 2020), while temperatures reaching 35°C were documented in low-cost government housing in Johannesburg, South Africa (Naicker *et al.* 2017).

Kapwata *et al.* (2018) and Kimemia *et al.* (2020) report that high levels of heat stress within dangerous to critically dangerous ranges are prevalent in informal dwellings in rural or urban settings. While Nutkiewicz *et al.* (2022) argue that the building envelope is the principal driver of heat stress exposure, Kapwata *et al.* (2018) and Kimemia *et al.* (2020) emphasise the need for appropriate response strategies, such as national and regional heat response plans, as well as using appropriate heat amelioration measures for informal neighbourhoods such as cool roof paints. Adegun & Ayoola (2022) conclude that dwellings in both affluent and poor neighbourhoods employ at least one passive heat amelioration strategy, but only the wealthy can afford active cooling measures (*i.e.* air-conditioning). This accentuates that dwellings of the urban poor must include effective passive cooling strategies.

In response to the higher thermal conditions many studies have considered diverse response measures. Vellingiri *et al.* (2020) consider multiple response measures to lowering heat stress in dwellings in Ahmedabad, India, concluding that diverse adaptation measures will be needed such as applying cool roof paints, additional insulation and in some cases completely redeveloping houses. Yet notably, Vellingiri *et al.* find that cool roof paints can lower indoor mean temperatures by 1 K, promoting these paints as cost-effective and easily implementable solutions. In a similar field experiment Kolokotroni *et al.* (2018) undertook a study in Jamaica, Ghana and Brazil (Recife), where all these contexts have high solar exposure and excessively high temperatures, and concluded that cool roof technologies are effective at lowering the indoor temperatures of high thermal mass structures with low insulative qualities by 0.6–1.6 K. However, in temperate climates conflicting results exist. Kimemia *et al.* (2020) advocate the use of cool roof technologies in shack dwellings with low thermal mass and suggest this can minimise heat stress exposure and lower maximum indoor temperatures by as much as 10 K. Conversely Nutkiewicz *et al.* (2022) conclude that while cool roof paints can lower heat stress incidents by as much as 91%, in temperate climates such as Johannesburg there is limited need for this technology.

While several heat stress amelioration measures are available and many studies are being initiated to lower heat stress exposure, more research on the effectiveness of these strategies is needed. This can inform practice and limit the application of climate change mal-adaptation measures, particularly in vulnerable informal settlements.

3 METHODS

As part of a larger research initiative, the Built Environment and Public Health Nexus project, this study is premised on a pragmatism paradigm and aims to reflect reality as closely as possible and inform practice (Denscombe 2008). The research design involved a mixed-method approach with a quantitative focus. This involved the visual analysis and documentation of existing informal dwellings, continuous monitoring of the indoor environments and the digital simulation of selected houses.

3.1 CONTEXT

The project was undertaken in Melusi, a rapidly growing informal settlement in Tshwane, South Africa. This city is part of the Gauteng city-region (Mubiwa & Annegarn 2013), a rapidly densifying urban region in South Africa. Melusi represents a typical informal settlement, which rapidly developed since 2008, and has 27,000 residents (160 people/ha), which is seven times the average density of the surrounding formal neighbourhoods (22 people/ha). The built fabric of Melusi includes corrugated sheeting houses and masonry structures. Similar to a typical informal settlement, Melusi experiences overcrowding, poor-quality housing, lack of tenure, limited vegetation and limited infrastructure provision (Alja'afreh *et al.* 2022; Pieterse 2011; Satterthwaite *et al.* 2020).

3.2 SAMPLE SELECTION AND DATA COLLECTION

The study started with an observational analysis and the documentation of 10 selected dwellings in the settlement. The sample selection was drawn from the densest portion of the settlement and focused on uninsulated corrugated iron sheeting homes as the most vulnerable to temperature increases. A non-probability sampling method was used to recruit 10 homeowners. The houses were documented using photographs, drawings, reflective diaries and a structured checklist. Figures 1–4 illustrate two typical dwellings from the sample selection. From the collected data, detailed documentation of the homes was developed noting the building geometries, site conditions, material uses and performance characteristics, envelope articulation, occupancy densities, and indoor thermal loads.

Figure 1: Typical informal dwelling (type H3).

Figure 2: Typical informal dwelling (type H4).

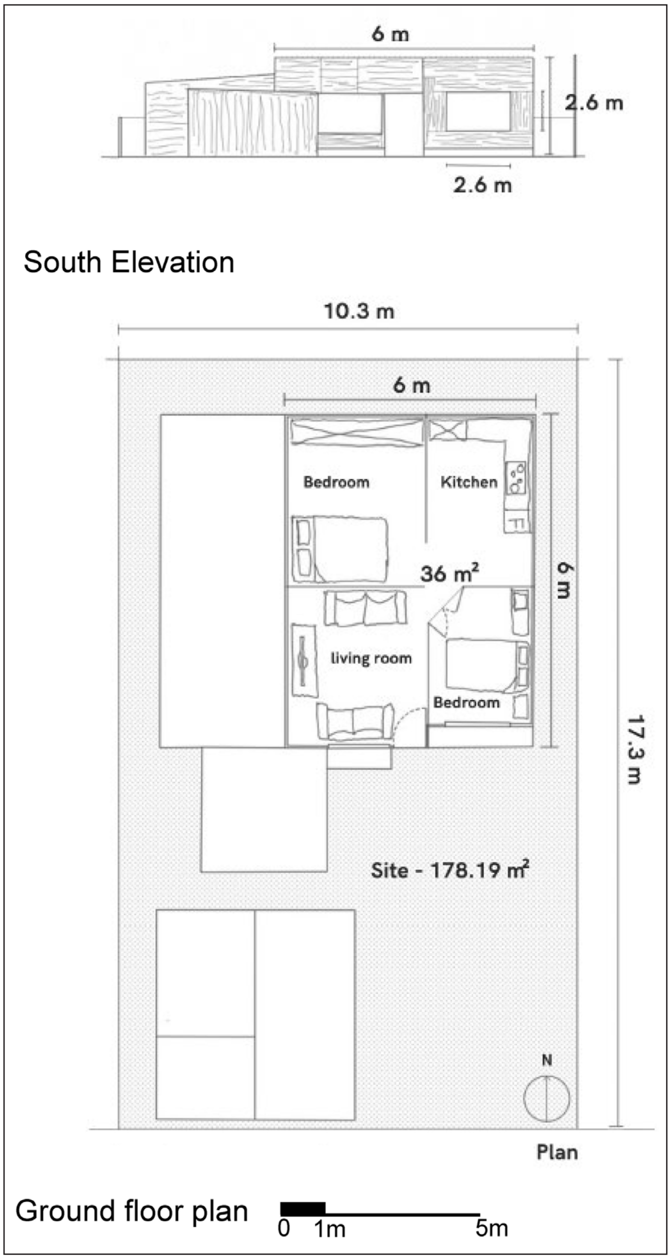

Figure 3: Plan and elevation of dwelling H3.

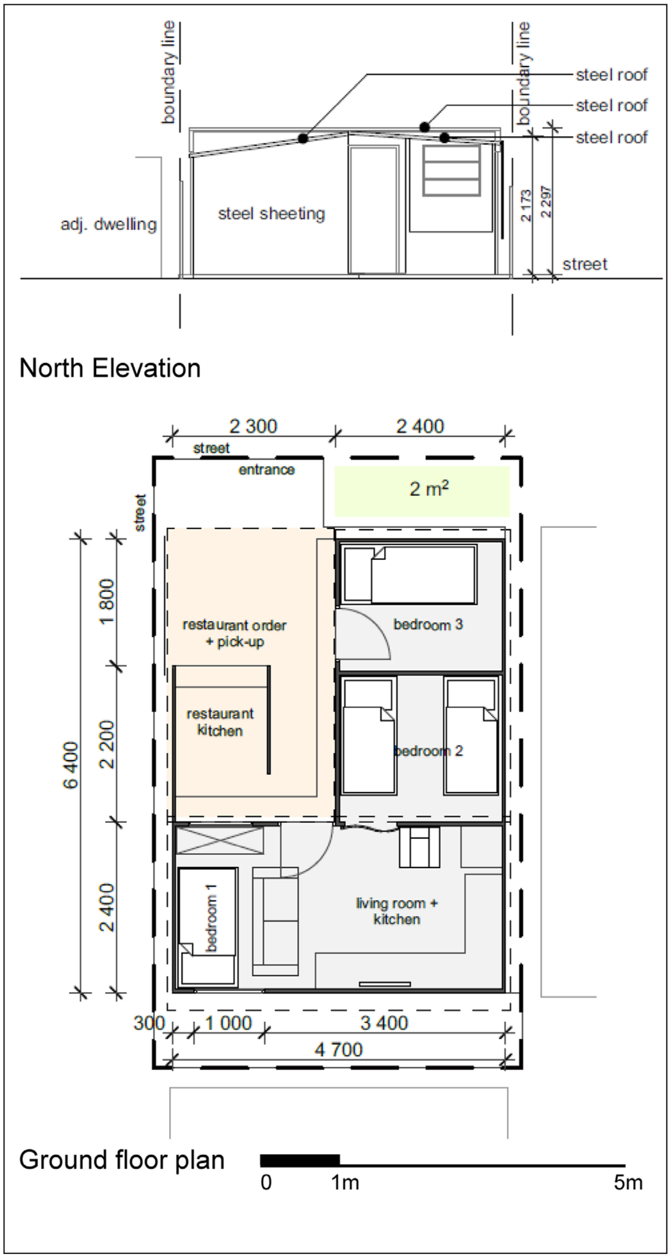

Figure 4: Plan and elevation of dwelling H4.

Along with the observation data, the indoor environments of the house were monitored using temperature and humidity loggers. SSN-22 USB loggers with an accuracy of ±3% relative humidity and ±0.3°C temperature were used. These loggers were located in a shared room, typically a kitchen/living room, and positioned between 1000 and 1600 mm above ground level. These loggers were positioned away from any glazing and additional heat sources to prevent any thermal interference. A weather station installed within 800 m of the dwellings collected local microclimatic data. The data were collected by a student cohort on a monthly basis from November 2021 to June 2022.

3.3 SIMULATION MODELS

Similar to other studies, the simulation study used the collected building and indoor environmental data to develop validated digital models (Hugo *et al.* 2021; Skelhorn *et al.* 2016). Two dwellings were selected to develop as simulation models and test heat stress amelioration strategies. These two dwellings were chosen as they represent two conditions (1) a highly exposed structure and (2) a dwelling using a shaded veranda as a typically used thermal adaptation strategy (Figures 5 and 6). The simulation models were developed using Integrated Environmental Solutions (IESve) as a modelling programme: it is an ISO 7730-validated analysis tool using the Energy plus simulation engine (IES 2018).

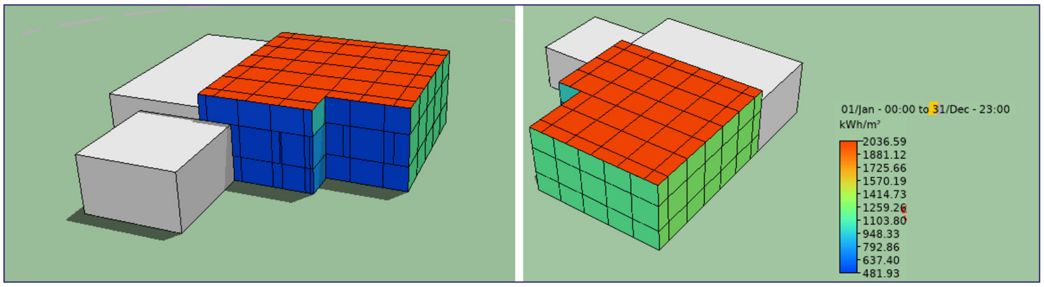

Figure 5: Thermal simulation model of dwelling H3.

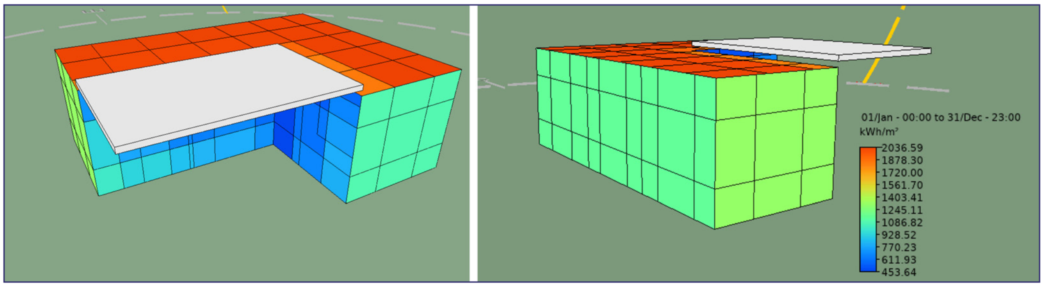

Figure 6: Thermal simulation model of dwelling H4.

Table 1 shows the modelling parameters of the two homes simulated in the study. The basic building geometry, material use, occupancy, lighting and plug load density were documented during several site visits. In cases where the building characteristics or use were not clearly visible, assumptions were made. In terms of the building use schedule, SANS 10400XA-Annexure B (SABS Standards Division 2022), occupancy type H4 (dwelling house), were used. Finally, ventilation and infiltration rates could not be measured on-site and were assumed, within a range of existing studies (Sherman & Dickerhoff 1998), and adjusted to achieve high correlation (Pearson's *R*) with the measured data.

Table 1: Simulation model characteristics.

Note: ACH = air changes per hour.

BUILDING CHARACTERISTIC		DWELLING H3	DWELLING H4	REFERENCES
Geometry		See Figure 3	See Figure 4	Observed
Floor area (m^2)		36.0	25.9	Observed
Floor area to volume ratio		38.5%	43.7%	Observed
Roof	Material *R*-value Reflectivity	0.5 mm corrugated steel 0.14 m^2k/W 0.3	0.5 mm corrugated steel 0.14 m^2k/W 0.3	Observed
Wall	Material *R*-value Reflectivity	0.5 mm corrugated steel 0.14 m^2k/W 0.3	0.5 mm corrugated steel 0.14 m^2k/W 0.3	Observed
Floor	Material *R*-value	50 mm concrete 0.25 m^2k/W	50 mm concrete 0.25 m^2k/W	Observed
Windows	Glazing Glass frames *U*-value Window to floor ratio	6 mm single glazing Steel frame 5.17 W/m^2K 10.0%	6 mm single glazing Steel frame 5.17 W/m^2K 9.1%	Observed
Population density (m^2/person)		7.2	5.3	Observed
Occupancy schedule		As per SANS10400XA-2 H4 occupancy	As per SANS10400XA-2 H4 occupancy	SANS 10400XA-2021
Plug load density (W/m^2)		27.8	70.0	Observed
Lighting density (W/m^2)		2	6	Observed
Ventilation rate (l/person/s)		2.0	5.0	Assumed
Infiltration rate (ACH)		1.0	6.5	Assumed
Mechanical ventilation		None	None	Observed
Cooking heat source		LP gas	LP gas	Observed

The IESve simulation model is a dynamic simulation model replicating the thermal performance of the selected homes and providing data for heat stress analyses. The simulation used a weather file developed from the Proefplaas weather station, located 12 km from the site, using *Meteonorm* (Meteonorm 2022). The simulations also tested future climate change-affected scenarios: these were based on the Intergovernmental Panel on Climate Change's (IPCC) *Emissions Scenarios Report* replicating the A2 SRES scenario family which posits a heterogenous, regionally orientated scenario with little greenhouse gas mitigation, continuous global population growth and rapid land-use changes (IPCC 2000; Meteotest 2018). In this scenario, the South African average temperature is expected to increase by between 4 and 6°C by 2100 (DEA 2013).

The IESve model is based on a balanced thermal model:

$$(Qext + Qint) - (Qinf + Qevap + Qconv + Qcond) = 0 \tag{1}$$

where *Qext*, the thermal gains due to meteorological conditions, including *Qint*, all the internal heat sources from occupants and equipment, make up the thermal gains. The model then simulated any thermal losses through infiltration (*Qinf*), evaporation (*Qevap*), convection (*Qconv*) and conduction (*Qcond*). The sum of the thermal gains and losses results in a simulation model revealing any excess energy retained or discarded through the building's thermal envelope.

The total external thermal gains (*Qext)* used a local EnergyPlus weather file that includes thermal gains and losses due to radiation, airflow, and latent and sensible thermal transmission. The internal thermal gains (*QInt*) were calculated using maximum latent and sensible thermal gains per square metre modulated by occupancy and equipment-use schedules. The thermal losses (*Qinf*, *Qevap*, *Qconv*, *Qcond*) were simulated using the building characteristics observed on-site and assumed (Table 1).

3.4 ANALYSIS OF FINDINGS

The two simulation models were validated comparing the measured field data with the generated model data for a 10-day summer period (1–10 January 2022). The correlation between the measured and modelled data was tested using a Pearson's *R* correlation analysis and visual thermal data comparison. Dwellings H3 and H4 achieved correlations of 0.85 and 0.96 (Pearson's *R*), respectively. Due to the small sample size, the study opted to use descriptive statistics to discuss the efficacy of the adaptation measures to both lower heat stress exposure and limit excessive cold periods in winter as typically reported in informal dwellings (Mabuya & Scholes 2020). The data were analysed using Microsoft Excel and the focus was on ambient temperatures, humidity, humidex and apparent temperatures. Humidex (Hum) and apparent temperatures (AT) were used due to their wide application both locally in South Africa (Garland *et al.* 2015; Kapwata *et al.* 2018; Kimemia *et al.* 2020; Orimoloye *et al.* 2017), and internationally (Almeida *et al.* 2010; Michelozzi *et al.* 2009; Rana *et al.* 2013). The apparent temperature and humidex indicator ranges are noted in Table 2. While there are differences between the two indexes, reporting both contributes to other studies in the Southern African region were limited field data are available.

HUMIDEX INDEX			APPARENT TEMPERATURE INDEX		
INDEX RANGE	WARNING	POSSIBLE HEALTH IMPAIRMENTS	INDEX RANGE	WARNING	POSSIBLE HEALTH IMPAIRMENTS
21–25	Less evident	Fatigue with prolonged exposure	>26		
26–32	Caution	Fatigue	26–31	Caution	Fatigue, discomfort
33–37	Extreme Caution	Muscle cramps, sunstroke, heat exhaustion	32–40	Extreme Caution	Sunstroke, muscle cramps, heat exhaustion
38–48	Danger	Sunstroke, heart failure, sun burn, skin rashes, fainting	41–53	Danger	Sunstroke, heat cramps, heat exhaustion, heatstroke
> 49	Extreme Danger	Heatstroke, heart failure, skin rashes	>54	Extreme Danger	Sunstroke, heatstroke

Table 2: Humidex and apparent temperature index ranges.

Sources: Adapted from United States National Weather Service (cited in Orimoloye *et al.* 2017; and Kapwata *et al.* 2018).

Humidex is calculated using local ambient temperatures and saturated vapour pressure, based on a method developed by Sirangelo *et al.* (2020). This study calculated humidex using dry bulb temperature and relative humidity:

$$Hum = Ta + \frac{5}{9}(e - 10) \tag{2}$$

$$e = \frac{Ur.e_{sat}}{100} \tag{3}$$

$$e_{sat} = 6.112 \times 10^{7.5Ta}_{Ta+237.7} \tag{4}$$

As noted in equations (1–3), Hum is calculated using ambient temperature (Ta) (°C), and calculating the water vapour pressure (*e*) using the relative humidity (Ur) and Ta based on Teten's formula (Sirangelo *et al.* 2020).

Apparent temperature uses Ta, Ur, *e* and air flow (ws) as parameters (Steadman 1994):

$$AT = Ta + 0.33 \times e - 0.7 \times ws - 4.0 \tag{5}$$

Water vapour pressure is calculated using Ur and temperature:

$$e = \frac{Ur}{100} \times 6.105 \times 10 \frac{17.27Ta}{Ta + 237.7} \tag{6}$$

Due to the limited use of operable glazing and poor indoor ventilation rates, similar to a study by Kapwata *et al.* (2018), wind speed was considered negligible.

3.5 PROJECT LIMITATIONS

The project findings are limited to temperate climates such as Tshwane (Koppen–Geiger classification—Cwa) with hot summers and dry winter (StepSA 2020). The project only considered poorly insulated informal housing, which typically does not adhere to basic national building standards. While the sample group is small, the findings can be generalised to other informal dwellings in the region as the analysis of the 10 homes found high similarity in the building characteristics and material use. Finally the thermal improvements can only be ascribed to changes in the building envelope and not any behavioural changes.

4 RESULTS

4.1 FIELD DATA OF DWELLING SAMPLES

A selection of 10 informal dwellings was analysed in terms of their minimum, maximum and mean ambient temperatures (Ta), as well as the indoor heat stress exposure (humidex (HUM) and apparent temperatures (AT) indexes) (Table 3). The Ta conditions over the summer (November–January), autumn (February–April) and winter (May–June) range between 22.4 and 26.7°C. Although the minimum Ta never moved below freezing point (Ta_{min} = 3.1–14.1°C), low indoor temperatures were noted. However, high maximum Ta ranging between 38.7 and 48.5°C were documented. This resulted in a mean humidex index ranging from 29.2 to 34.4, with the percentage of time exposed to *danger to extreme danger* (HUM D-ED) conditions of 7–32%. In terms of AT the resultant mean AT ranges from 23.3 to 28.8°C, with dangerous exposure (*extreme caution to extreme danger*) (AT EC-ED) over the analysis period being 12–34%.

Considering the indoor and outdoor temperatures on a typical summer day reveals three aspects (Figure 7). First, deviation from the outdoor temperatures is predominantly experienced during the daytime. Notably during this period a Ta_{max} of 48.5°C was documented. These temperature increases can predominantly be ascribed to solar radiation exposure and poorly performing envelopes (Figure 7).

DWELLING	INDOOR TEMPERATURE (°C)			HUMIDEX			APPARENT TEMPERATURE (°C)		
	MEAN	MINIMUM	MAXIMUM	MEAN	MAXIMUM	EXPOSURE (%)[a]	MEAN	MAXIMUM	EXPOSURE (%)[b]
H1	24.6	9.0	48.5	31.4	52.4	20%	26.1	52.4	24%
H2	22.4	6.4	42.9	30.2	49.1	16%	24.0	47.4	20%
H3	24.7	10.1	45.3	32.9	50.0	23%	26.8	49.4	25%
H4	23.2	6.8	46.0	29.9	49.3	16%	24.5	48.8	20%
H5	23.7	4.8	46.6	30.8	50.4	17%	25.2	49.7	20%
H6	23.3	7.2	38.7	30.0	43.2	7%	24.5	40.6	13%
H7	25.5	14.7	46.2	33.5	50.7	26%	27.5	50.3	28%
H8	24.0	3.1	47.6	31.2	55.9	24%	25.7	54.6	33%
H9	22.0	4.3	38.9	29.2	45.4	9%	23.3	41.3	12%
H10	26.7	14.1	47.4	34.4	50.6	32%	28.8	50.7	34%

Table 3: Measured indoor conditions of sample homes.

Notes: [a] Humidex = danger to extreme danger range.

[b] Apparent temperature = extreme caution to extreme danger range.

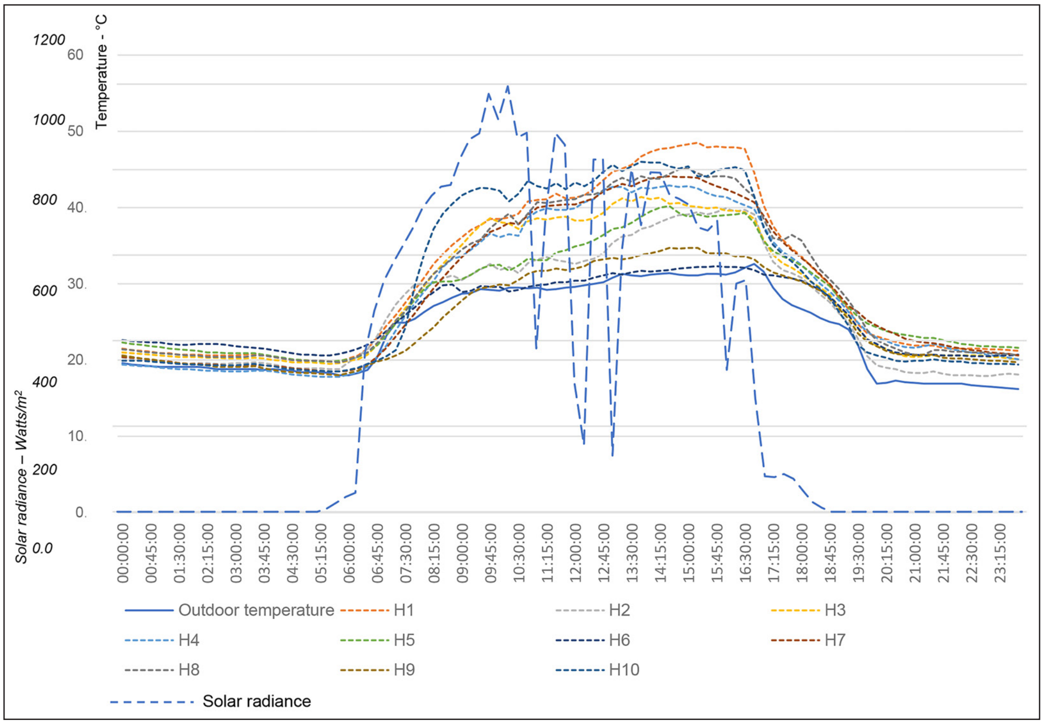

Figure 7: Outdoor and indoor temperatures correlated with local incident solar radiance.

Although the dwellings use similar construction methods, a difference was noted in the minimum and maximum thermal conditions. The minimum temperatures, typically documented in the early mornings and evenings, reveal a mean thermal difference between indoor and outdoor temperatures of 1.79 K with limited deviation between the dwellings (*Z*-scores <1). The maximum temperatures reveal more diverse results, with the thermal differences between the indoor and outdoor ambient temperatures ranging from 2.7 to 16.6 K (mean temperature difference = 9.22 K; high deviation *Z*-scores = between 0.12 and 1.54).

Finally, even though diverse maximum temperatures were documented, Figure 8 reveals that all the dwellings cross the HUM D-ED and AT EC-ED threshold conditions. These findings emphasise the importance of adapting the dwellings.

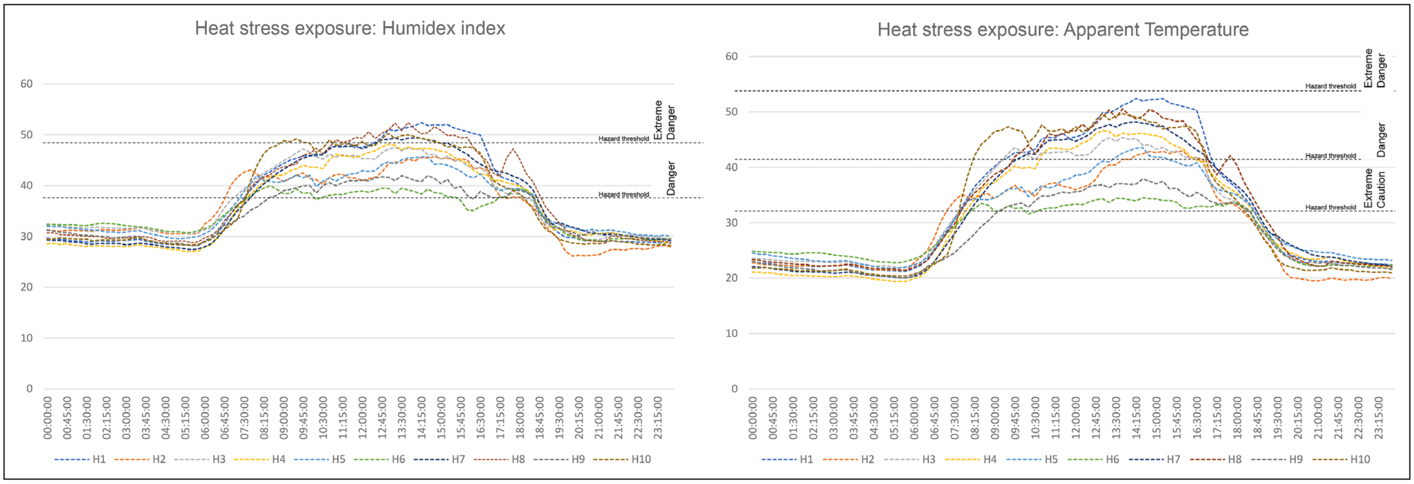

Figure 8: Humidex and apparent temperature exposure on a typical summer day.

4.2 CURRENT AND FUTURE PERFORMANCE OF NON-RETROFITTED DWELLINGS

Two homes (H3 and H4) were selected for the simulation analyses to assess their indoor thermal conditions (Table 4). A comparison between the simulated (full-year analysis) and measured (November–June) data shows that the mean temperatures are slightly lower (2–6%), with the maximum temperatures ranging from 6% lower (H4) to being 16% higher (H3). Conversely the humidex exposure (simulated) is slightly lowered with 4% in each case. While the models show a close statistical correlation between the simulated and measured scenarios (see section 3.4), the difference can be attributed to the models accounting for the generally cooler winter and spring periods.

DWELLING	INDOOR TEMPERATURE (°C)			HUMIDEX			APPARENT TEMPERATURE		
	MEAN	MINIMUM	MAXIMUM	MEAN	MAXIMUM	EXPOSURE[a]	MEAN	MAXIMUM	EXPOSURE[b]
H3	23.1	0.7	54.3	28.6	54.1	19%	23.7	56.0	23%
H4	22.6	0.5	44.6	26.7	47.3	12%	22.9	46.8	19%

Table 4: Simulation findings of dwelling H3 & H4 over a full year period.

Notes: [a] Humidex = danger to extreme danger range.

[b] Apparent temperature = extreme caution to extreme danger range.

In terms of the full-year simulation analysis, both H3 and H4 achieve moderate mean indoor temperatures of 22.6 and 23.1°C, respectively (Table 4). Yet in terms of maximum temperatures, the Ta_{max} conditions differ with close to 10 K, with maximum temperatures of 44.6°C (H4) and 54.3°C (H3). While there are dramatic differences in the Ta_{max} conditions, the HUM and AT condition reveal a closer correlation in terms of the documented performance of both dwellings. H3 performs slightly worse with HUM D-ED for 19% and AT EC-ED conditions for 23% of the time of a full year. H4 experiences HUM D-ED conditions for 12% and AT EC-ED for 19% of the time (Table 4).

The occurrence of extreme heat stress exposure for between 12% and 23% of the time is concerning. Even more worrying are the simulations under the A2 scenario for 2100 climate change: the mean Ta conditions increasing to 26.2–26.3°C for both models (Tables 5 and 6). The heat stress conditions increase dramatically with between 150% and 270%, resulting in HUM D-ED conditions of 40% and 33% and AT EC-ED for 35% and 34% of the time for H3 and H4, respectively. A significant increase in heat exposure is noted with the general ambient temperature range shifting into a higher thermal regime.

4.3 SIMULATION OF HEAT ADAPTATION MEASURES

To date several studies promote using cool roof paints to lower heat stress (Kimemia *et al.* 2020; Kolokotroni *et al.* 2018; Nutkiewicz *et al.* 2022; Vellingiri *et al.* 2020). While the successful use of the technologies is reported, there is limited consensus on its effectiveness in temperate climates with concern that using cool roof paints will result in colder conditions in winter. In response, the simulation assessed two heat stress adaptation measures: (1) painting the complete thermal envelope (*i.e.* external walls and roof) with cool roof paint; and (2) only adjusting the dwelling's roof with cool roof paint and adding an insulated ceiling (Table 7). These changes were identified as economically feasible and easily implementable in existing informal settlements.

DWELLING H3		SIMULATION CONDITION					
		NO INTERVENTION		INTERVENTION 1: ENVELOPE COOL ROOF PAINT		INTERVENTION 2: INSULATION AND ROOF PAINT	
		CURRENT[c]	2100 SCENARIO[d]	CURRENT[c]	2100 SCENARIO[d]	CURRENT[c]	2100 SCENARIO[d]
Temperature	Mean	23.1	26.3	19.9	23.9	22.3	25.7
	Minimum	0.7	5.7	0.6	5.9	2.9	7.6
	Maximum	54.3	56.0	39.7	42.8	41.9	44.9
Humidex	Mean	28.6	34.4	26.0	32.7	28.3	34.2
	Maximum	54.1	58.4	45.2	49.8	47.6	52.1
	Exposure (%)[a]	19%	40%	7%	33%	11%	38%
Apparent temperature	Mean	24.0	28.6	20.7	26.2	23.2	28.1
	Maximum	56.0	60.7	42.0	47.5	45.7	50.8
	Exposure (%)[b]	23%	35%	8%	25%	15%	33%

Table 5: Simulation findings of heat stress adaptation measures for dwelling H3.

Notes: [a] Humidex = danger to extreme danger range.

[b] Apparent temperature = extreme caution to extreme danger range.

[c] Current local climatic conditions.

[d] Future 'A2 2100' scenario.

DWELLING H4		SIMULATION CONDITION					
		NO INTERVENTION		INTERVENTION 1: ENVELOPE COOL ROOF PAINT		INTERVENTION 2: INSULATION AND ROOF PAINT	
		CURRENT[c]	2100 SCENARIO[d]	CURRENT[c]	2100 SCENARIO[d]	CURRENT[c]	2100 SCENARIO[d]
Temperature	Mean	22.6	26.2	21.2	25.1	22.4	26.1
	Minimum	0.51	5.28	0.52	5.29	1.5	6.2
	Maximum	44.6	47.94	40.0.	43.8	40.9	44.7
Humidex	Mean	26.7	32.9	25.6	32.1	26.7	32.9
	Maximum	47.3	52.3	44.7	44.8	45.7	50.6
	Exposure (%)[a]	12%	33%	7%	29%	9%	32%
Apparent temperature	Mean	22.9	27.9	21.5	26.8	22.7	27.8
	Max	46.8	52.4	41.9	48.1	42.8	49.2
	Exposure (%)[b]	19%	34%	12%	29%	16%	34%

Table 6: Simulation findings of heat stress adaptation measures for dwelling H4.

Notes: [a] Humidex = danger to extreme danger range.

[b] Apparent temperature = extreme caution to extreme danger range.

[c] Current local climatic conditions.

[d] Future 'A2 2100' scenario.

RESPONSE	ADJUSTMENTS MADE	REFERENCE
Intervention 1: Complete envelope painted with cool roof paint	Mean aged[a] reflectance: 0.72 Mean aged emittance: 0.89 Mean SRI: 87.17	Cool roofs (2022)
Intervention 2: Roof only insulation added and painted with cool roof paint	Mean aged reflectance: 0.72 Mean aged emittance: 0.89 Mean SRI: 87.17 Insulation: 80 mm Isoboard *R*-value: 3.33 m^2K/W	Cool roofs (2022) Isoboard (2022)

Table 7: Description of the heat stress adaptation measures undertaken in the simulations.

Notes: Mean aged reflectance is derived from the Cool Roof Rating Council which provides validated evaluation of the radiative properties of cool roof products. The study used 'aged' values that represent the radiative properties three years after the products' installation.

SRI = solar reflectance index.

The analysis over a full-year period reveals that under the current climatic conditions painting the whole facade with cool roof paint lowers the HUM D-ED conditions by 63% in H3 and 42% in H4; similarly the AT EC-ED conditions are lowered by 65% in H3 and 37% in H4. This echoes the findings of Kimemia *et al.* (2020) who found a 92% drop in heat stroke conditions after applying cool roof paints to an informal dwelling in Johannesburg, South Africa.

These adaptations are effective in situations with high solar exposure and limited solar control, such as H3 which has no solar shading devices. Potential adverse cooling found Ta conditions below 18°C only increase from 33% to 39% in H3 and from 32% to 34% in H4. Conditions below 10°C only increase with 1% over a full year in both cases.

As a response to the adverse cooling concern, the second strategy only adjusted the roof increasing its reflectivity and insulation capacity (Table 7). This approach was less successful with a HUM D-ED decrease of 42% for H3 and 25% for H4. The AT EC-ED conditions were lowered by 34% in H3 and 15% in H4. The performance under colder temperatures in H3 show the Ta conditions below 18°C and 10°C are lowered by 5% and 4%, respectively, over a full year. In H4 the impact was less with only an improvement of 2% (Ta <18°C and <10°C).

4.4 PERFORMANCE OF ADAPTATION MEASURES UNDER FUTURE CONDITIONS

The findings confirm that both strategies can lower the heat stress exposure for inhabitants under present climatic conditions. Covering the thermal envelope with cool roof paints is the most effective and due to the low thermal capacity of the dwellings has a little effect on the low indoor temperatures.

However, a significant increase in heat stress conditions is identified for the A2 climate scenario (2100). This means the long-term effectiveness of these strategies is insufficient and a serious concern. In terms of assessing intervention 1 under 2100 climate conditions (Table 7) the Hum D-ED conditions are only 17% and 12% lower in H3 and H4, respectively (Tables 5 and 6). Similarly, in terms of the AT EC-ED conditions, improvements of 29% and 15% for H3 and H4, respectively, were noted. Conversely intervention 2 (Table 7) is less successful, only lowering the HUM D-ED conditions by 5% in H3 and 3% in H4. As per the AT conditions, the AT EC-ED conditions in H3 are 6% lower and the H4 simulation shows a negligible improvement.

Focusing on 48-h peak summer and winter periods, using current and future climatic models, the performance of these two strategies is unpacked. Figures 9 and 10 show the increase in average temperatures results in the dwellings being exposed to a generally higher thermal regime. They also reveal that dwellings easily cross the heat stress thermal thresholds of 35°C (Kimemia *et al.* 2020), emphasising the importance of developing the dwelling's thermal or insulative capacity to lower future heat stress exposure.

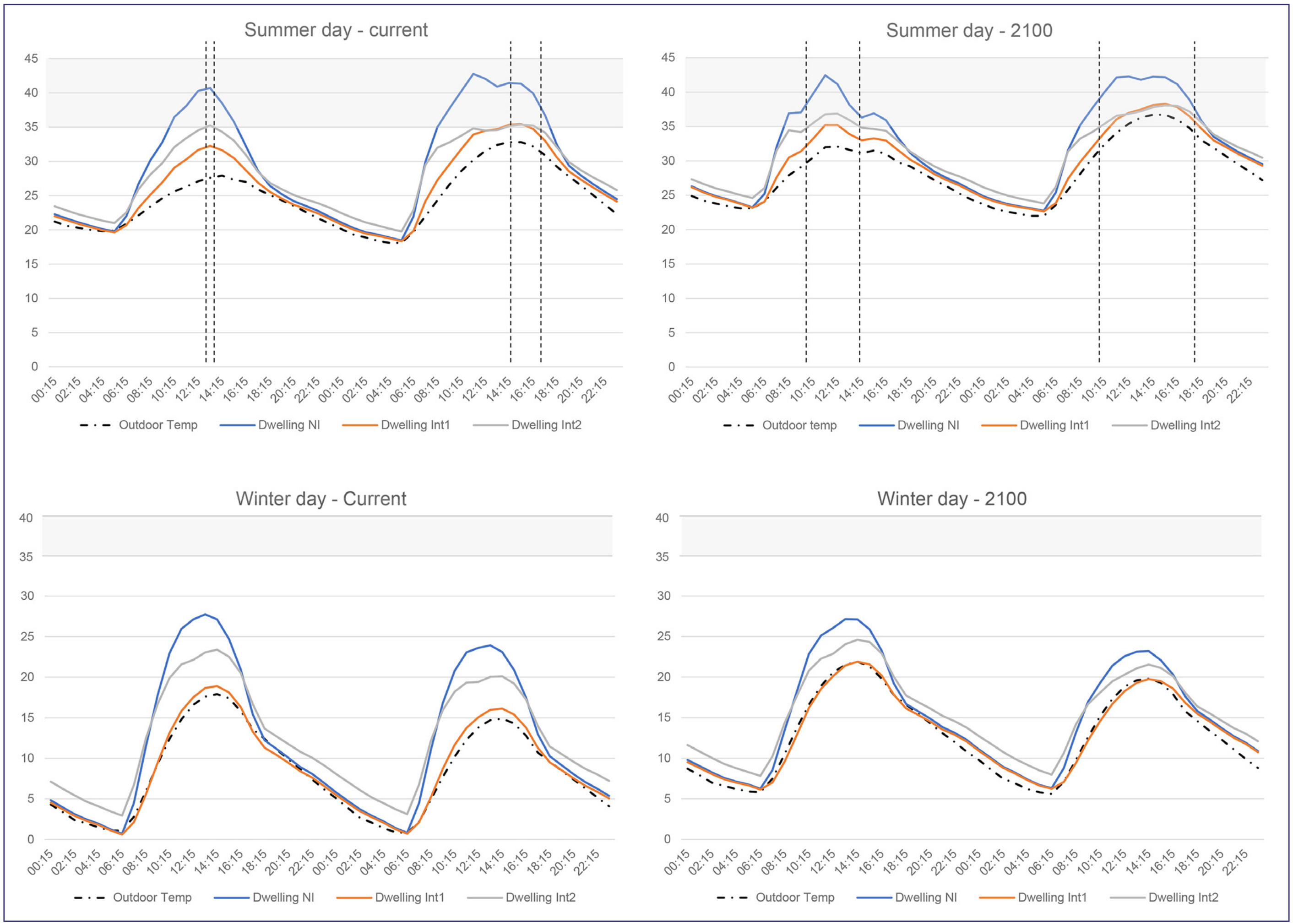

Figure 9: Current and future performance of adaptation measures versus outdoor temperatures for dwelling H3.

Note: Dwelling NI = dwelling simulated with no intervention; Dwelling Int1 = dwelling simulated with intervention 1; Dwelling Int2 = dwelling simulated with intervention 2.

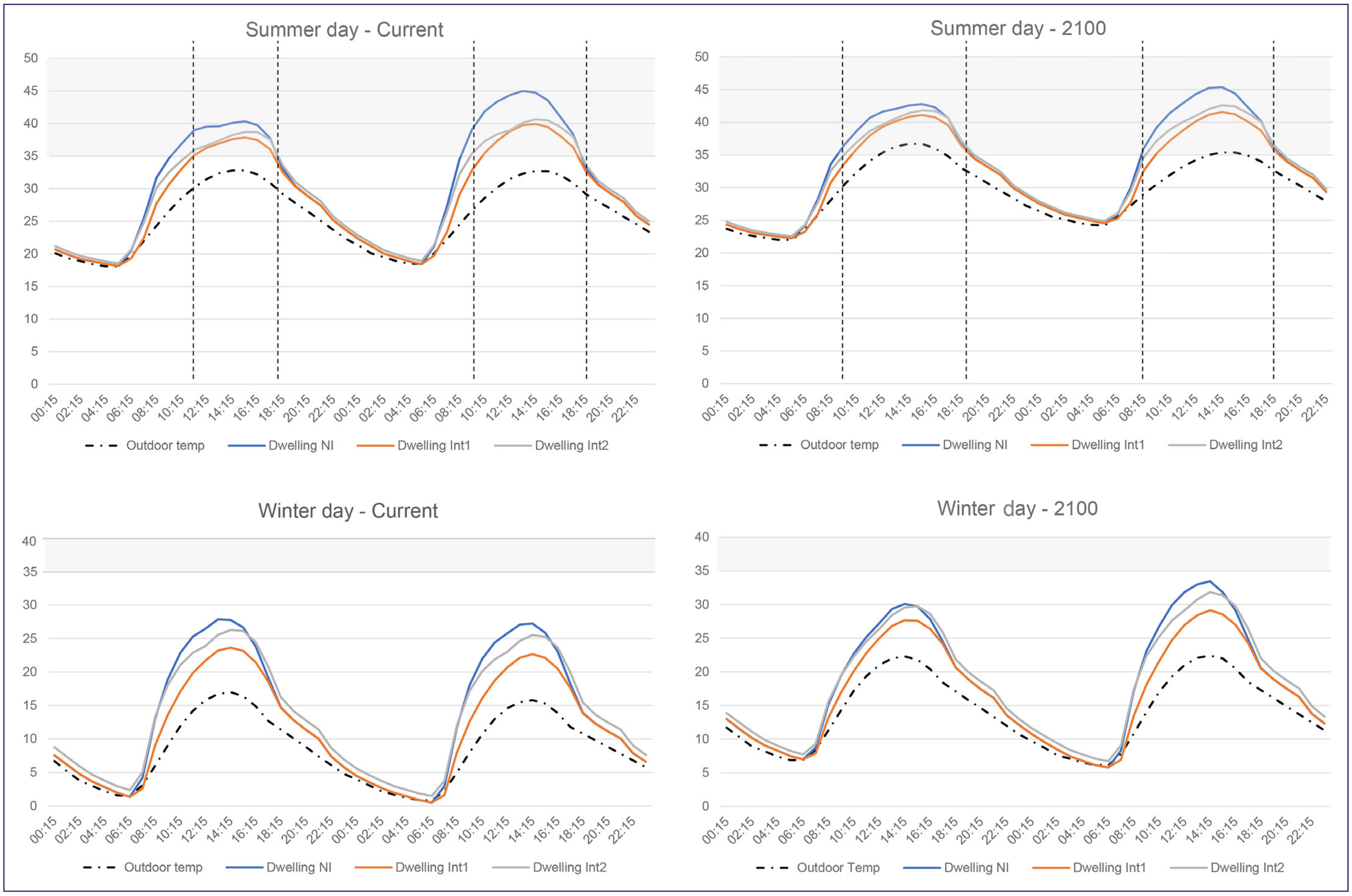

Figure 10: Current and future performance of adaptation measures versus outdoor temperatures for dwelling H4.

Note: Dwelling NI = dwelling simulated with no intervention; Dwelling Int1 = dwelling simulated with intervention 1; Dwelling Int2 = dwelling simulated with intervention 2.

Higher ambient temperatures affect the efficacy of the adaptation measures. Isolating the thermal difference between the non-adapted and adapted models reveals that intervention 1 is 32% (H3) and 27% (H4) less effective, while intervention 2 is 30% (H3) and 39% (H5) less efficient under the 2100 climatic conditions (A2 scenario). This can be ascribed to Fourier's law on isotropic bodies stating higher thermal differences increase thermal transfer. The poorly insulated dwellings conduct more thermal energy into their interiors affecting the efficacy of the adaptations.

Intervention 2 was significantly less effective under the 2100 climatic conditions. During the summer, intervention 2 starts trapping thermal energy early in the mornings while intervention 1 is more effective in dispelling heat and lowering indoor temperatures (Figures 9–11). This prompts one to question the efficacy of half measure adaptations, in this case only providing insulated ceilings without adequate changes to the whole structures as proposed by multiple studies (Mabuya & Scholes 2020; Naicker *et al.* 2017).

5 DISCUSSION

Using cool roof paints in temperate climates will result in cooler daytime indoor environments, (Figures 9 and 10). The maximum indoor ambient temperatures are significantly reduced with between 4.6 K (H4) and 14.6 K (H3). Painting corrugated metal structures with little thermal capacity has little impact on the cool nocturnal indoor temperatures.

Responding to potential adverse cooling, the study also considered alterations to the roof with additional insulation and increasing its reflectivity. This was chosen as a feasible retrofitting intervention without reconstructing the whole dwelling. Under current climatic conditions this strategy is less effective than intervention 1 (cool paint applied to the external envelope). This highlights the impact that the poorly insulated, low thermal mass walls have on the indoor environment. Although the added roof insulation has slightly improved the low morning temperatures, the overall impact is limited.

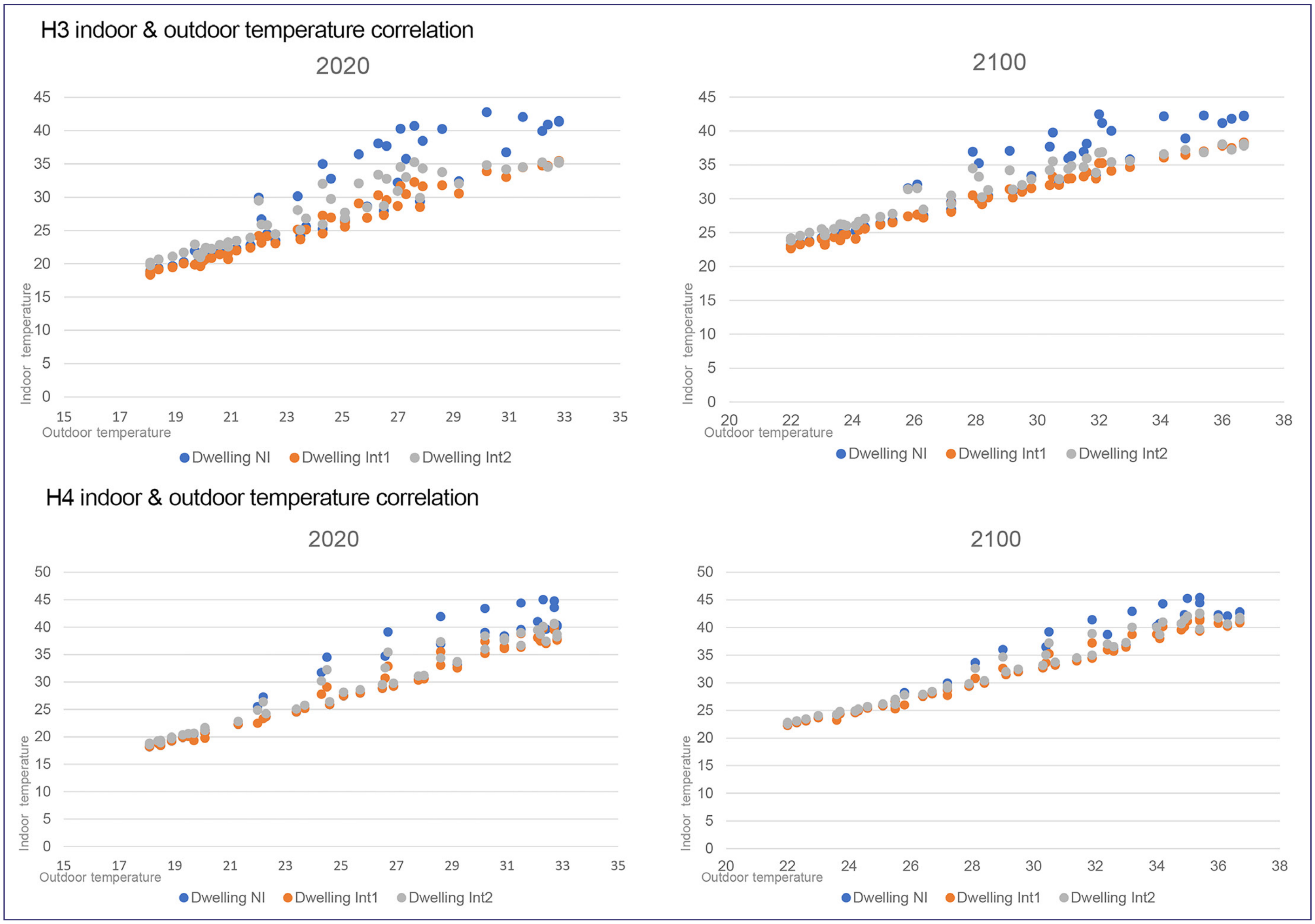

Figure 11: Correlation between outdoor thermal energy and adaptation measures for dwellings H3 and H4.

Note: Dwelling NI = dwelling simulated with no intervention; Dwelling Int1 = dwelling simulated with intervention 1; Dwelling Int2 = dwelling simulated with intervention 2.

As a heat stress adaptation measure, cool roof paint on exposed informal dwellings is highly effective. Interestingly the two structures performed differently, as the dwelling with the added north/north-western-facing veranda (H4) exhibited slightly lower indoor temperatures (compared with H3): Ta_{mean} = 0.4 K lower; Ta_{max} = 9.5 K). The adaptation measures are slightly less effective for H4 than H3. This results in the cool roof adaptation measure lowering the HUM D-ED conditions to 7% for both H3 and H4, while the AT EC-ED conditions were lowered to 8% and 12% for H3 and H4, respectively. This reveals that using cool roof paints surpasses the efficacy of a shaded veranda as cooling structure (implemented in many dwellings), yet the thermal improvement of the shaded verandas must not be neglected.

For future climatic conditions, these interventions were less successful. Although both heat stress adaptation measures result in cooler indoor environments, the second strategy is less effective in limiting heat stress exposure. Only a 12–17% lowering of the HUM D-ED conditions were noted for the cool roof paints covering the whole thermal envelope, while only adjusting the roof (adding thermal insulation reflectivity) leads to only a 3–5% improvement in HUM D-ED conditions. But this will be insufficient to reduce heat stress in a warmer climate or during extreme climate events.

This has implications for practitioners and policymakers to develop multifaceted heat health-response strategies for Southern African informal settlements. This will require more holistic and integrated response measures that (1) improve the building stock, (2) create public cooling zones, (3) establish and grow vegetation coverage, (4) ensure accessibility to potable water during crises and (5) develop awareness campaigns and training programmes to promote behaviour changes and community response strategies during heatwave events (Cheung & Jim 2018; Kapwata *et al.* 2018; Liang *et al.* 2014; Razzak *et al.* 2022).

6 CONCLUSIONS

Responding to the increasing global occurrence of heatwave events and the need to lower heat stress in marginalised communities, this article provides evidence for potential interventions. It shows an immediate potential for success but also their limitations over the medium term due to a warming climate.

This study considered the efficacy of heat stress amelioration measures in informal dwellings in Tshwane, South Africa. The measured indoor thermal conditions, documented in the dwellings during the spring to winter, reveal the existing indoor environments currently expose users to excessive thermal conditions (HUM D-ED and AT EC-ED) for up to a third (8 h) of a typical day.

Simulation analyses of two selected dwellings considered interventions for current and future conditions—based on a future climate scenario (A2 for 2100). The simulation models allowed the research team to address data gaps, and also to simulate structural heat stress amelioration measures. Two strategies proved to be effective under current conditions but were insufficient for future conditions.

From a practical implementation perspective, painting a dwelling's whole envelope with cool roof paint is successful, easy to implement and cost-effective. However, under future climatic conditions, the strategies of improved albedo and insulating the roof are shown to be inadequate for mitigating heat stress. Instead, multilayered and integrated response measures will be needed. The implications for public health policies and strategies are to develop and implement an integrated heat resilience plan.

In terms of further research, the community acceptance, implementation requirements and *in situ* performance of these strategies have to be verified—specifically the performance of ageing cool roof paints in urban conditions with high insolation, dusty conditions and little maintenance capacity.

ACKNOWLEDGEMENTS

The author thanks the honours architecture students at the University of Pretoria who assisted in the project.

AUTHOR AFFILIATION

Jan Marais Hugo orcid.org/0000-0003-4840-2642
Architecture Department, University of Pretoria, Hatfield Campus, Hatfield, ZA

COMPETING INTERESTS

The author has no competing interests to declare.

DATA AVAILABILITY

The data underpinning this project are available at the following online repository: 10.25403/UPresearchdata.21747443.

ETHICAL APPROVAL

Ethics approval (reference number 363/2020) was obtained from the University of Pretoria before undertaking the study.

FUNDING

The project was supported by the United Nations Children's Fund (UNICEF) One Health For Change (UP-OHC) project and is part of the University of Pretoria Built Environment and Public Health Nexus project.

REFERENCES

Adegun, O. B., & **Ayoola, H. A.** (2022). Between the rich and poor: Exposure and adaptation to heat stress across two urban neighbourhoods in Nigeria. *Environment, Development and Sustainability*, 24(10), 11953–11968. DOI: https://doi.org/10.1007/s10668-021-01924-w

Alja'afreh, A., Al Tal, R., & **Ibrahim, A.** (2022). The social role of open spaces in informal settlements in Jordan. *Open House International*, 47(1), 2–16. DOI: https://doi.org/10.1108/OHI-02-2021-0023

Almeida, S. P., Casimiro, E., & **Calheiros, J.** (2010). Effects of apparent temperature on daily mortality in Lisbon and Oporto, Portugal. *Environmental Health: A Global Access Science Source*, 9(1), 1–7. DOI: https://doi.org/10.1186/1476-069X-9-12

Anderson, P., Okereke, C., Rudd, A., & **Parnell, S.** (2013). Regional assessment of Africa. In Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P., McDonald, R., Parnell, S., *et al.* (Eds.), *Urbanization, biodiversity and ecosystem services: Challenges and opportunities* (pp. 453–499). Springer. DOI: https://doi.org/10.1007/978-94-007-7088-1

Baruti, M. M., & **Johansson, E.** (2020). Urban climate urbanites' thermal perception in informal settlements of warm–humid Dar es Salaam, Tanzania. *Urban Climate*, 31(), 100564. DOI: https://doi.org/10.1016/j.uclim.2019.100564

Brandt, S. A., Lim, N. J., Colding, J., & **Barthel, S.** (2021). Mapping flood risk uncertainty zones in support of urban resilience planning. *Urban Planning*, 6(3), 258–271. DOI: https://doi.org/10.17645/up.v6i3.4073

Broersma, S., Fremouw, M., & **Van den Dobbelsteen, A.** (2013). Energy potential mapping: Visualising energy characteristics for the exergetic optimisation of the built environment. *Entropy*, 15(2), 490–506. DOI: https://doi.org/10.3390/e15020490

Chersich, M., Swift, C. P., Edelstein, I., Breetzke, G., Scorgie, F., Schutte, F., & **Wright, C. Y.** (2019). Violence in hot weather: Will climate change exacerbate rates of violence in South Africa? *South Africa Medical Journal*, 109(7), 447–449. DOI: https://doi.org/10.7196/SAMJ.2019.v109i7.14134

Cheung, P. K., & **Jim, C. Y.** (2018). Comparing the cooling effects of a tree and a concrete shelter using PET and UTCI. *Building and Environment*, 130, 49–61. DOI: https://doi.org/10.1016/j.buildenv.2017.12.013

Cool roofs. (2022). *Cool Roof Rating Council. Rated roof products*. https://coolroofs.org/directory/roof

DEA. (2013). *Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa*. Climate Trends and Scenarios for South Africa. https://www.dffe.gov.za/sites/default/files/docs/summary_policymakers_bookV3.pdf

Denscombe, M. (2008). Communities of practice. A research paradigm for the mixed methods approach. *Journal of Mixed Methods Research*, 2(3), 270–283. DOI: https://doi.org/10.1177/1558689808316807

Dodman, D., Archer, D., & **Satterthwaite, D.** (2019). Editorial: Responding to climate change in contexts of urban poverty and informality. *Environment and Urbanization*, 31(1), 3–12. DOI: https://doi.org/10.1177/0956247819830004

Eckstein, D., Kunzel, V., & **Schafer, L.** (2021). *Global climate risk index 2021. Who suffers most from extreme weather events? Weather-related loss events in 2019 and 2000–2019, think tank & research*. German Watch. http://germanwatch.org/en/download/8551.pdf

Garland, R. M., Matooane, M., & **Engelbrecht, F. A.** (2015). Regional projections of extreme apparent temperature days in Africa and the related potential risk to human health. *International Journal of Environmental Research and Public Health*, 12, 12577–12604. DOI: https://doi.org/10.3390/ijerph121012577

Hugo, J., du Plessis, C., & **Masenge, A.** (2021). Retrofitting Southern African cities: A call for appropriate rooftop greenhouse designs as climate adaptation strategy. *Journal of Cleaner Production*, 312, 127663. DOI: https://doi.org/10.1016/j.jclepro.2021.127663

IES. (2018). *Software validation and approval*. https://www.iesve.com/software/software-validation

IPCC. (2000). *Emissions scenarios*. Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/report/emissions-scenarios/

IPCC. (2022). Climate change 2022. Impacts, adaptation and vulnerability. In *Working Group II Contribution to the Sixth Assessment Report on the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/

Isoboard. (2022). *Thermal values*. https://isoboard.com/insulation/r-value/?gclid=Cj0KCQjwn4qWBhCvARIsAFNAMig6mCw0_MNI1rpoaaGHz0y-trHcl4Gmnby7a5UaBYk_W7x1ycLawysaAsmhEALw_wcB

Kapwata, T., Gebreslasie, M. T., & **Wright, C. Y.** (2018). Current and potential future seasonal trends of indoor dwelling temperature and likely health risks in rural Southern Africa. *International Journal of Environmental Research and Public Health*, 15(952), 1–16. DOI: https://doi.org/10.3390/ijerph15050952

Kimemia, D., Van Niekerk, A., Annegarn, H., & **Seedat, M.** (2020). Passive cooling for thermal comfort in informal housing. *Journal of Energy in Southern Africa*, 31(1), 28–39. DOI: https://doi.org/10.17159/2413-3051/2020/v31i1a7689

Kolokotroni, M., Shittu, E., Santos, T., Ramowski, L., Mollard, A., Rowe, K., Wilson, E., Pereira de Brito Filho, J., & **Novieto, D.** (2018). Cool roofs: High tech low cost solution for energy efficiency and thermal comfort in low rise low income houses in high solar radiation countries. *Energy and Buildings*, 176, 58–70. DOI: https://doi.org/10.1016/j.enbuild.2018.07.005

Kotharkar, R., Ramesh, A., & **Bagade, A.** (2018). Urban heat island studies in South Asia: A critical review. *Urban Climate*, 24, 1011–1026. DOI: https://doi.org/10.1016/j.uclim.2017.12.006

Liang, T. C., Hien, W. N., & **Jusuf, S. K.** (2014). Effects of vertical greenery on mean radiant temperature in the tropical urban environment. *Landscape and Urban Planning*, 127, 52–64. DOI: https://doi.org/10.1016/j.landurbplan.2014.04.005

Mabuya, B., & **Scholes, M.** (2020). The three little houses: A comparative study of indoor and ambient temperatures in three low-cost housing types in Gauteng and Mpumalanga, South Africa. *International Journal of Environmental Research and Public Health*, 17(10), 3524. DOI: https://doi.org/10.3390/ijerph17103524

Meteonorm. (2022). *Meteonorm software*. https://meteonorm.com/en/meteonorm-version-8

Meteotest. (2018). *Handbook Part I: Software*. Meteonorm. https://meteonorm.com/assets/downloads/mn73_theory.pdf

Michelozzi, P., Accetta, G., De Sario, M., D'Ippoliti, D., Marino, C., Baccini, M., Biggeri, A., Anderson, H. R., Katsouyanni, K., Ballester, F., Bisanti, L., Cadum, E., Forsberg, B., Forastiere, F., Goodman, P. G., Hojs, A., Kirchmayer, U., Medina, S., Paldy, A., Schindler, C., Sunyer, J., & **Perucci, C. A.** (2009). High temperature and hospitalizations for cardiovascular and respiratory causes in 12 European cities. *American Journal of Respiratory and Critical Care Medicine*, 179(5), 383–389. DOI: https://doi.org/10.1164/rccm.200802-217OC

Mubiwa, B., & **Annegarn, H.** (2013). *Historical spatial change in the Gauteng city-region*. GCRO.

Naicker, N., Teare, J., Balakrishna, Y., Wright, C. Y., & **Mathee, A.** (2017). Indoor temperatures in low cost housing in Johannesburg, South Africa. *International Journal of Environmental Research and Public Health*, 14(11), 1410. DOI: https://doi.org/10.3390/ijerph14111410

Nutkiewicz, A., Mastrucci, A., Rao, N. D., & **Jain, R. K.** (2022). Cool roofs can mitigate cooling energy demand for informal settlement dwellers. *Renewable and Sustainable Energy Reviews*, 159, 112183. DOI: https://doi.org/10.1016/j.rser.2022.112183

Orimoloye, I. R., Mazinyo, S. P., Nel, W., & **Iortyom, E. T.** (2017). Climate variability and heat stress index have increasing potential ill-health and environmental impacts in East London, South Africa. *International Journal of Applied Engineering Research*, 12(17), 6910–6918. http://danida.vnu.edu.vn/cpis/files/Refs/Heat%20Waves/Heat_Stress/Climate%20Variability%20and%20Heat%20Stress%20Index%20have%20Increasing%20Potential%20Ill-health%20and%20Environmental%20Impacts%20in%20the%20East%20London,%20South%20Africa.pdf

Pieterse, E. (2011). Rethinking African urbanism from the slum. *Cities, Health and Well-Being*, November, 1–4. https://lsecities.net/wp-content/uploads/2011/11/2011_chw_5060_Pieterse.pdf

Rana, R., Kusy, B., Jurdak, R., Wall, J., & **Hu, W.** (2013). Feasibility analysis of using humidex as an indoor thermal comfort predictor. *Energy and Buildings*, 64, 17–25. DOI: https://doi.org/10.1016/j.enbuild.2013.04.019

Razzak, J. A., Agrawal, P., Chand, Z., Quraishy, S., Ghaffar, A., & **Hyder, A. A.** (2022). Impact of community education on heat-related health outcomes and heat literacy among low-income communities in Karachi, Pakistan: A randomised controlled trial. *BMJ Global Health*, 7(1), 1–11. DOI: https://doi.org/10.1136/bmjgh-2021-006845

Russo, S., Marchese, A. F., Sillmann, J., & **Immé, G.** (2016). When will unusual heat waves become normal in a warming Africa? *Environmental Research Letters*, 11, 054016. DOI: https://doi.org/10.1088/1748-9326/11/5/054016

SABS Standards Division. (2022). *SANS 10400-XA:2021*. South Africa. https://store.sabs.co.za/catalog/product/view/id/2143705/s/sans-10400-xa-ed-2-00/

Satterthwaite, D., Archer, D., Colenbrander, S., Dodman, D., Hardoy, J., Mitlin, D., & **Patel, S.** (2020). Building resilience to climate change in informal settlements. *One Earth*, 2, 143–156. DOI: https://doi.org/10.1016/j.oneear.2020.02.002

Sherman, M., & **Dickerhoff, D.** (1998). Airtightness of US dwellings. *Paper presented at the AHREA Annual Meeting*, Toronto, ON, Canada. https://www.aivc.org/resource/airtightness-u-s-dwellings

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H. O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., & **Trisos, C. H.** (2021). A framework for complex climate change risk assessment. *One Earth*, 4(4), 489–501. DOI: https://doi.org/10.1016/j.oneear.2021.03.005

Sirangelo, B., Caloiero, T., Coscarelli, R., Ferrari, E., & **Fusto, F.** (2020). Combining stochastic models of air temperature and vapour pressure for the analysis of the bioclimatic comfort through the humidex. *Scientific Reports*, 10(11395), 1–16. DOI: https://doi.org/10.1038/s41598-020-68297-4

Skelhorn, C. P., Levermore, G., & **Lindley, S. J.** (2016). Impacts on cooling energy consumption due to the UHI and vegetation changes in Manchester, UK. *Energy and Buildings*, 122, 150–159. DOI: https://doi.org/10.1016/j.enbuild.2016.01.035

Steadman, R. (1994). Norms of apparent temperature in Australia. *Australian Meteorology Magazine*, 43, 1–16.

StepSA. (2020). *Climate indicators Koppen–Geiger climate classifications*. http://stepsa.org/climate_koppen_geiger.html

Teare, J., Mathee, A., Naicker, N., Swanepoel, C., Kapwata, T., Balakrishna, Y., du Preez, D. J., Millar, D. A., & **Wright, C. Y.** (2020). Dwelling characteristics influence indoor temperature and may pose health threats in LMICs. *Annals of Global Health*, 86(1), 1–13. DOI: https://doi.org/10.5334/aogh.2938

UN. (2019). *World urbanization prospects*. United Nations (UN).

Vellingiri, S., Dutta, P., Singh, S., Sathish, L. M., Pringle, S., & **Brahmbhatt, B.** (2020). Combating climate change-induced heat stress: Assessing cool roofs and its impact on the indoor ambient temperature of the households in the urban slums of Ahmedabad. *Indian Journal of Occupational and International Medicine*, 24(1), 25–29. DOI: https://doi.org/10.4103/ijoem.IJOEM_120_19

Wright, C. Y., Kapwata, T., Jean, D., Wernecke, B., Garland, R. M., Nkosi, V., Landman, W. A., Dyson, L., & **Norval, M.** (2021). Major climate change-induced risks to human health in South Africa. *Environmental Research*, 196, 110973. DOI: https://doi.org/10.1016/j.envres.2021.110973

TO CITE THIS ARTICLE:
Hugo, J. M. (2023). Heat stress: adaptation measures in South African informal settlements. *Buildings and Cities*, 4(1), pp. 55–73. DOI: https://doi.org/10.5334/bc.269

Submitted: 11 September 2022
Accepted: 20 December 2022
Published: 12 January 2023

COPYRIGHT:
© 2023 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See http://creativecommons.org/licenses/by/4.0/.

Buildings and Cities is a peer-reviewed open access journal published by Ubiquity Press.